DRAFT REPORT

Guidelines for Guardrail Implementation

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The Roadside Design Guide's (RDG's) barrier warrants are based on the premise that a traffic barrier should be installed only if it reduces the severity of potential crashes. However, the frequency of run-off-road crashes is not directly related to the severity of potential crashes. Furthermore, the RDG does not provide objective guidance that designers could use to determine what barrier performance level should be implemented and merely suggests using higher performance level barriers when an above average percentage of heavy vehicles or adverse geometrics with poor sight distance are present. The revised roadside barrier warrant procedure, which utilizes the benefit-cost analysis program RSAP, provides an improved method for estimating actual levels of risk associated with run-off-road crashes and their frequencies. The revised guidelines provide a reasonably safe roadside barrier warrant system and will likely reduce the overall level of injuries and fatalities.

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1. INTRODUCTION

The goal of roadside safety devices is to protect motorists from potentially serious hazards located near the travel way. Bridge piers, utility poles, and severe embankments are hazards that if encountered can be deadly. In order to protect motorists, barriers must be placed in front of a roadside obstacle and must be much longer than the hazard in order to limit the risk of a serious accident when vehicles leave the road in advance of the barrier. Unfortunately, barriers also pose a risk to motorists. In fact, guardrails cause approximately 1200 fatalities along the nation's highways annually. Further, accident data analysis indicates that approximately 13 percent of reported guardrail accidents involve rollover and almost 2 percent produce a fatality (1). For lower risk hazards, such as small objects and moderate slopes, the number of serious crashes associated with a guardrail can be greater than the number of similar impacts that would occur without the guardrail. In this situation, guardrail construction would increase the number of injured motorists compared to leaving the hazard unshielded. Clearly, there is an optimum guardrail selection criterion that will produce a minimum number of injury and fatal accidents.

Guardrail warrant recommendations contained in the AASHTO Roadside Design Guide (RDG) (2) are based on a subjective evaluation of the relative severity of striking a roadside obstacle or a barrier. If the consequences of a vehicle striking a fixed object are estimated to be more serious than hitting a traffic barrier, then the barrier is recommended. The current guidelines are presented in the form of a table that offers guidance to designers. Unfortunately, the table incorporates a number of imprecise terms, such as, "judgment decision", "generally required", and "may be warranted".

Existing guidelines for guardrail application allow for a great deal of inconsistency. Two virtually identical sites can be treated much differently, depending upon the discretion of the individual designers. Objective criteria are needed to eliminate inconsistencies and provide optimal safety for all motorists and minimize the number of serious accidents along the roadways.

Further, the RDG does not provide objective guidance that designers could use to determine what barrier performance level should be implemented. Instead, the RDG merely suggests using higher performance level barriers when an above average percentage of heavy truck traffic or adverse geometrics with poor sight distance are present. This very general guidance does not provide any specifics regarding at what truck volumes higher performance level barriers become warranted, nor does it specifically address what the term adverse geometrics should include. Clearly, this type of general guidance directly considers neither the crash frequencies nor the costs associated with the use of higher performance guardrails.

In recognition of the need for better guidance for selecting the appropriate guardrail performance level, the National Cooperative Highway Research Program funded the study described herein.

1.1. Objectives

The objectives of the research included: (1) develop objective guardrail selection guidelines that would provide specific guidance for identifying the most cost beneficial guardrail performance level to be used on any given route; (2) identify when a more detailed analysis is warranted; and (3) present procedures for conducting a more thorough evaluation of guardrail need, when necessary.

2. LITERATURE REVIEW

Ideally highway designers would be provided with detailed guidance for determining when guardrail is needed and the barrier performance level appropriate for any highway route. This sort of guidance must be based upon an economic analysis of guardrail implementation. This type of analysis should consider the benefits of guardrail installation, measured in terms of reductions in accident costs, as well as all direct costs of barrier implementation, including construction, maintenance, and repair.

When safety features first began to be developed, implementation guidelines were based upon the relative severity of the possible alternatives (2). For instance, if a roadside barrier was thought to be a less severe hazard than a roadside hazard, a barrier would be recommended. No effort was directed toward estimating the number or severity of accidents that would occur with or without the barrier. This approach recommends that barrier be installed, irrespective of traffic volume, operating speeds, highway geometrics, or other factors that could affect crash frequency or severity. As a result, this approach caused highway agencies to install guardrail where there was little chance of a serious accident. In order to improve the efficiency of safety expenditures, relative severity methods for guardrail warranting has normally been restricted to high volume, high speed roadways (5, 6).

Cost-effective analysis is another method of evaluating where safety features should be implemented. This technique involves forecasting the annualized cost of the safety device and dividing it by the reduction in risk of serious injuries and/or fatalities along the roadside. These approaches evaluate various alternatives in terms of the cost of each fatality or injury prevented. Safety alternatives with the lowest cost per serious injury or fatality prevented are recommended for implementation. In order to determine if the safety features become warranted, highway agencies must establish a threshold cost-effective value at which safety features will begin to be implemented. These thresholds are normally expressed in terms of maximum costs per fatality or serious injury prevented. Unfortunately, cost-effective threshold values cannot be directly compared to other activities that compete for highway agency funds such as resurfacing, pavement widening, and bridge replacement. As a result, highway agency administrators have little guidance available for selecting the appropriate threshold for cost-effective procedures.

The third method for comparing safety alternatives is benefit-to-cost analysis. These procedures attempt to estimate the dollar value of reductions in injuries and fatalities as well as the direct costs associated with each safety treatment. Results of these studies are normally expressed in terms of the ratio between benefits and costs or B/C ratio. The primary difference between a cost-effective analysis and a benefit-to-cost analysis is that the latter procedure attempts to assign dollar values for motorist injuries and fatalities associated with highway crashes. The ability to express findings in terms of a benefit-to-cost ratio is an important advantage because it allows safety projects to be directly compared to any other type of construction project for which a B/C ratio can be calculated. Thus, benefit-to-cost analysis has become the most common method used for evaluating the need for roadside safety features.

The most difficult problem associated with either cost-effective or benefit-to-cost procedures is the estimation of the frequency and severity of ran-of-road crashes. There are two basic approaches to estimating the frequency and severity of ran-off-road crashes, accident data and encroachment probability.

Accident data based methods utilize historical accident reports to predict future accident frequencies. These techniques fall into two different categories, site-specific and route specific analyses. Site-specific accident data based techniques rely on the accident history at a given location for estimating the frequency and severity of future crashes at that location. Local accident histories intrinsically incorporate the effects of all highway, roadside, and local land-use characteristics for the site under consideration. Thus, whenever accident data is available at a site under consideration, it provides the best available information for supporting an economic analysis of proposed safety improvements. Note that the lack of accident history at a site does not mean there is no risk of future accidents. Instead, it is merely an indicator that crashes at the given site may be relatively infrequent or that crash rates have been unusually low during the recent past. Therefore, alternate techniques must be used to evaluate safety improvements at existing sites when no accident data is available.

The second approach based upon accident data incorporates regional and national accident records collected at similar sites across a wide geographic area. The appeal of this method is the ability to use regression models to directly predict accident frequencies and severities for a given hazard. Unfortunately, this method requires hazards and/or safety treatments to be in place for many years before sufficient accident frequencies can be generated to develop the needed regression models. Further, the hazard specific nature of ran-off-road crashes requires that regional based accident models be developed for every type of hazard and every safety treatment alternative to be evaluated. These limitations generally render regional or national accident based methods impractical for use in the development of guardrail application guidelines where a wide variety of roadside hazards must be considered.

Encroachment probability methods attempt to accomplish this same goal by correlating measured encroachment frequencies to the specific highway characteristics at a given site. The most advanced encroachment probability model software package is the Roadside Safety Analysis Program (RSAP). This procedure incorporates a Monte Carlo simulation to correlate the frequency of roadside encroachments to the frequency and severity of roadside crashes. Vehicle encroachments are randomly simulated one at a time to determine if a crash would occur and the resulting severity and associated crash costs are calculated. The average risk and cost of a crash eventually stabilizes when a sufficient number of encroachments have been simulated. The crash frequency and costs associated with any roadside treatment is then estimated by multiplying encroachment frequency by the average accident risk and cost.

Versatility is the primary advantage of the encroachment probability model. It can be used to analyze crash costs for a wide range of roadside objects, traffic characteristics, and roadside conditions. In fact, encroachment probability models provide the only available method to predict accident frequency for safety features and/or newly constructed or reconstructed roadways.

However, encroachment probability models are not without limitations. Encroachment frequency estimates are based solely upon observations of tire tracks along the roadside. Researchers had no way to distinguish controlled encroachments, where a driver intentionally drives onto the roadside, from uncontrolled encroachments. Further, limitations on data set size and highway geometric data limited the analyses to predicting encroachment frequencies for straight flat sections of roadway. The effects of other factors on encroachment frequency could not be quantified, including parameters such as climate, land use, and roadway curvature. In fact, all of the data was collected during summer months which are free from the influence of winter driving conditions. Wherever possible, the effects of these additional factors have been quantified using accident data.

Because encroachment probability models are intended to predict average crash frequencies, model validation requires analysis of numerous highway sections over significant periods of time. Unfortunately, sufficient funding has not become available to conduct a thorough validation effort (7). Never-the-less, encroachment probability analysis remains the most appropriate method for developing guidelines for developing general guidelines for safety hardware application.

2.1. Encroachment Probability Models

As stated previously, the objective of an encroachment probability model is to relate roadway and traffic characteristics to the expected accident frequency at any given site. The basic assumption behind an encroachment probability based model is that crash frequency is proportional to encroachment frequency. Encroachment frequencies are estimated from historical relationships which relate encroachment frequency on straight sections of roadway to traffic volume and functional class. These basic encroachment frequencies are then adjusted for the effects of roadway geometrics, such as horizontal curvature and grade, using findings from accident studies.

Adjusted encroachment frequency must then be linked to the accident rate that can be expected at any given roadside location. If an encroaching vehicle is assumed to travel along a straight path, an envelope can be described that identifies the region within which a vehicle leaving the roadway will strike the hazard. This region, referred to as the hazard envelope, is shown in Figure 1. The probability that a vehicle of size w, encroaching along a given mile highway at angle θ, speed v, and orientation ψ, will be within the hazard envelope can be calculated as shown in Equation 1:

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

where:

$P(H^{w\,\theta}_{v\,\psi} | E^{w\,\theta}_{v\,\psi})$ = *Probability of a vehicle within the hazard envelope for an encroachment with given vehicle type w, speed v, angle θ, and vehicle orientation ψ.*

L_h = Length of hazard (m)

W_v = Effective width of vehicle (m) = $L_v \sin\psi + W \cos\psi$

L_v = Length of vehicle (m)

W = Width of vehicle (m)

W_h = Width of hazard (m)

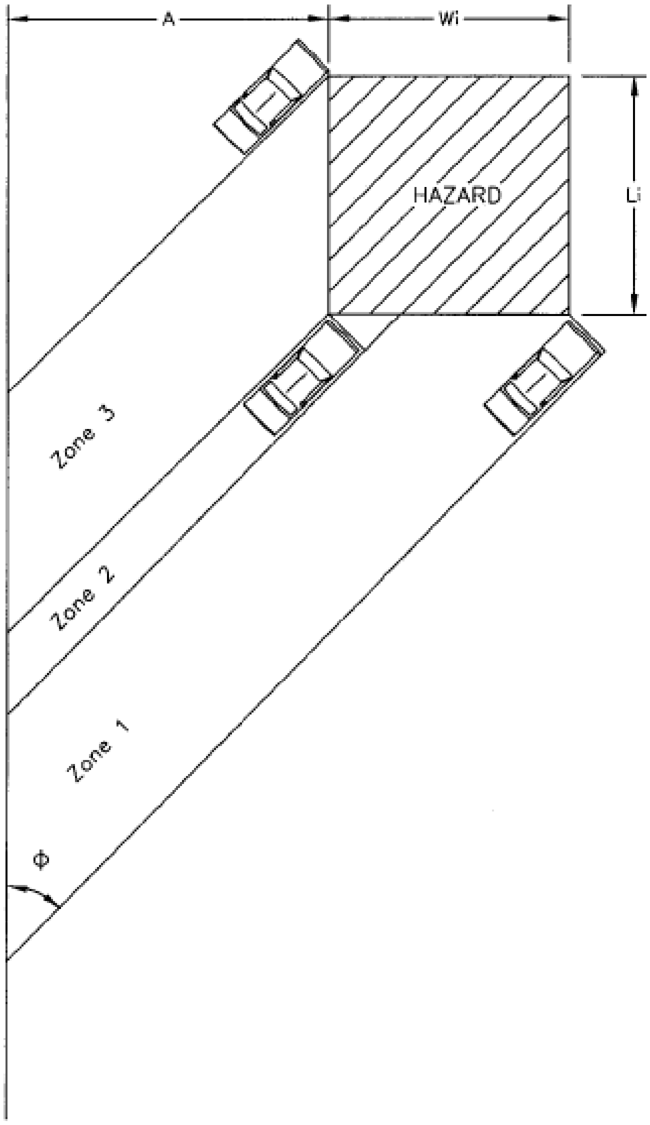


Figure 1. Hazard Envelope

A vehicle leaving the roadway within the hazard envelope will strike the hazard, provided that lateral extent of encroachment is sufficient to reach the hazard. The effective lateral offset of the hazard is different, depending on the zone within which a vehicle encroaches, as shown in Figure 1. Thus, the probability, $P(C^{w\,\theta}_{v\,\psi}|\ E^{w\,\theta}_{v\,\psi})$, that a vehicle of size w, encroaching with a speed v, angle θ, and orientation ψ, is within the hazard envelope and encroaches far enough to impact the hazard, is given by:

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

where:

$P(C^{w\,\theta}_{v\,\psi}|E^{w\,\theta}_{v\,\psi})$ = Probability of a collision for an encroachment with given vehicle type w, speed v, angle θ, and vehicle orientation ψ
L_e = Lateral extent of encroachment
A = Lateral offset to face of hazard (Zone 3)
B = Lateral offset to upstream corner of hazard (Zone 2)
B = $(A + j - 2)$, where j is a variable from 1 to $W_v\cos\theta$
C = Lateral offset to end or width of hazard (Zone 1)
C = $(A + W_v\cos\theta + j - 2)$ where j is a variable from 1 to W_h
$P(L_e \geq A)$ = Probability that an encroachment will reach lateral extent, A
$P(L_e \geq B)$ = Probability that an encroachment will reach lateral extent, B
$P(L_e \geq C)$ = Probability that an encroachment will reach lateral extent, C

The probability that a vehicle will reach a given lateral extent, $P(L_e \geq A)$, can be estimated from lateral extent of travel data collected during encroachment studies. The probability of a collision occurring during an encroachment, P(C|E), then be calculated by summing Equation. 2 over all possible vehicle orientations and sizes and encroachment angles and speeds as shown in Equation 3:

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

where:

$P(C|E)$ = Probability of a collision 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 cost of a single encroachment can be estimated by summing the product of the probability of each type of crash and its estimated cost over all possible crash combinations. Multiplying the cost per encroachment by the encroachment frequency gives an estimate of the annual crash cost as shown in Equation 4. Note that the direct costs associated with roadside crashes, such as barrier repair, can be estimated in the same manner.

$$CC = E_f \sum_{w}\sum_{v}\sum_{\theta}\sum_{\psi} P(E^{w\,\theta}_{v\,\psi}|\, E) * P(C^{w\,\theta}_{v\,\psi}|\, E^{w\,\theta}_{v\,\psi}) * AC(C^{w\,\theta}_{v\,\psi}) \qquad (4)$$

Where

CC = Estimated annual crash cost
E_f = Annual encroachment frequency
$AC(C^{w\,\theta}_{v\,\psi})$ = Accident cost of a collision involving a given vehicle type w, speed v, angle θ, and vehicle orientation Ψ.

Accident costs are normally calculated in a two step process. The severity of a crash is first calculated in terms of either the probability of injury or a severity index (SI). The accident cost is then estimated from the probability of injury or SI values. Encroachment characteristics needed to construct an encroachment probability model and procedures used to estimate accident costs are summarized in the following sections.

2.2. Encroachment Characteristics

There are only three previous studies on encroachment data: Hutchinson and Kennedy (29), Cooper (30), and Calcote (31). The Hutchinson and Kennedy study involved observations of wheel tracks on medians of rural interstate highways in Illinois in the mid 1960 and the Cooper study examined wheel tracks on roadsides of Canadian highways during the summertime in the late 1970s. As shown in Figures 2 and 3, both of these studies found that the encroachment frequency increased very rapidly at low traffic volumes and then either leveled off or declined for volumes in the range of 3000 to 8000 ADT. This unusual shape of the curve has been explained by examining driver behavior. At low traffic volumes, drivers have little contact with other vehicles and tend to drive faster. This combination of factors could lead to a higher incidence of driver error, such as drowsiness, thus resulting in higher encroachment rates. As traffic volumes increase, drivers begin to have more interaction with other traffic, which tends to better identify the roadway and reduce the monotony. These factors may cause the flattening or reduction in encroachment frequency observed for moderate traffic volumes. As traffic volumes continue to increase, the increase in exposure associated with additional vehicles would eventually overcome this effect and lead to higher encroachment rates.

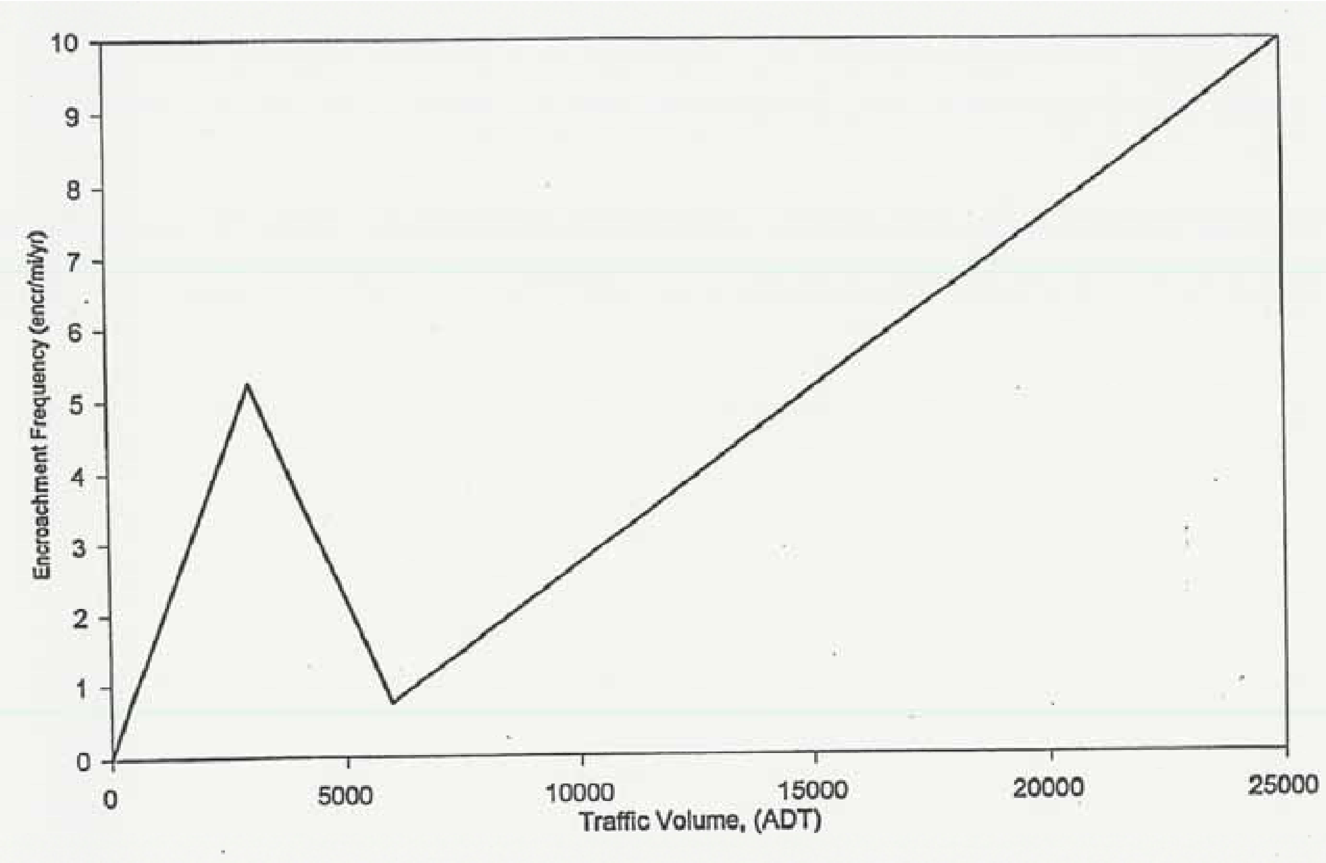


Figure 2. Encroachment Rates from Hutchinson and Kennedy

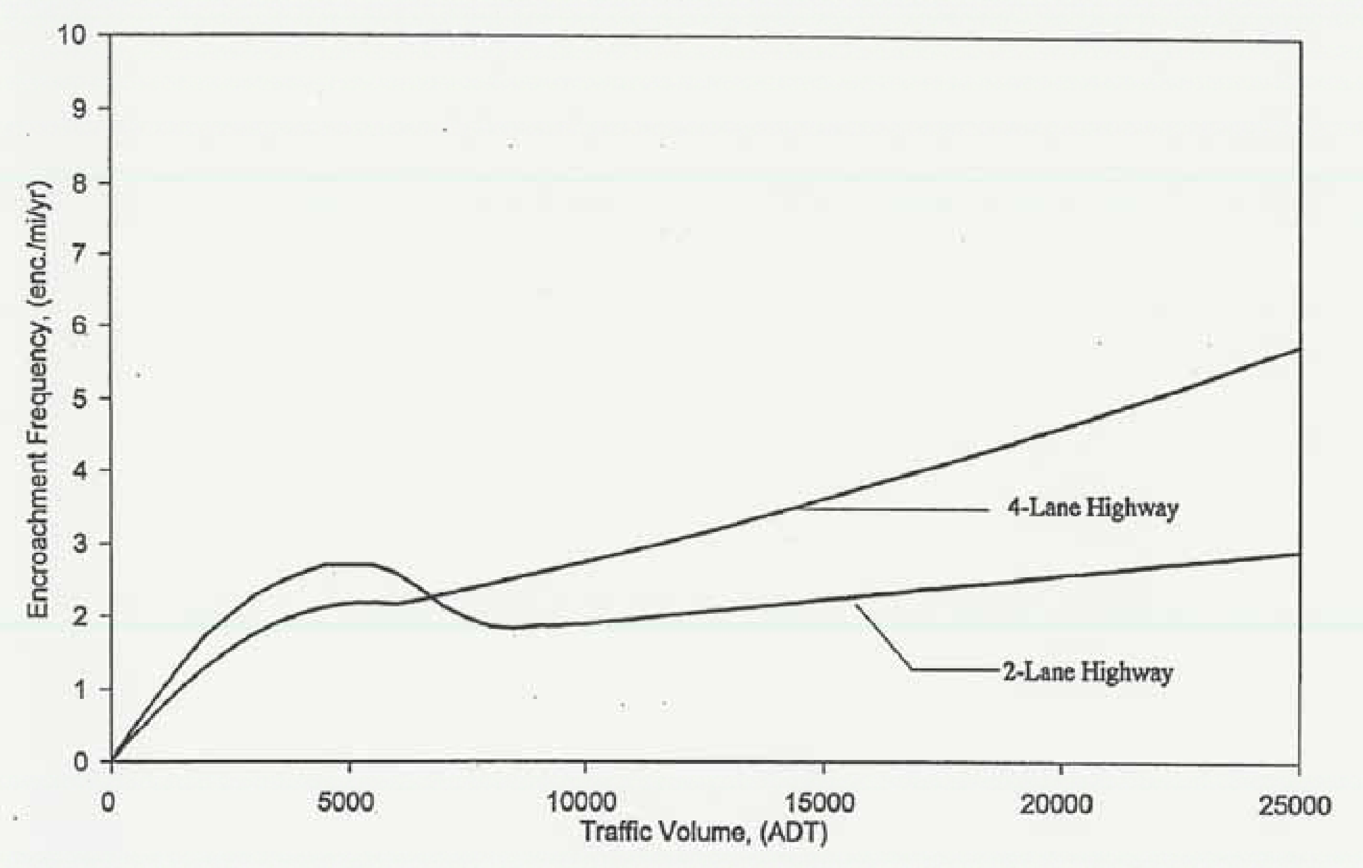


Figure 3. Encroachment Rates from Cooper.

These studies have limitations, including an inability to discern between controlled and uncontrolled encroachments, effects of paved shoulders, the functional classes of highways included in the studies, and the collection periods for the data. Neither Cooper nor Hutchinson and Kennedy could identify control versus uncontrolled encroachments based purely on tire track evidence. Therefore, all tire tracks were recorded and assumed to be uncontrolled. Most of the median shoulders included in the Hutchinson and Kennedy study were on the order of four to six feet (1.2192 to 1.8288 m) while outside shoulders on the highways studied by Cooper ranged from 0 to 13 ft (0 to 3.9624 m). Shoulders mask encroachments that do not extend far from the travelway. The Hutchinson and Kennedy study was limited to interstate freeways in Illinois while the Cooper study incorporated both two-lane and four-lane highways across Canada. Thus, the Hutchinson and Kennedy data is limited to access controlled freeways while the Cooper data generated encroachment frequency estimates for both two-way, two-lane highways and four-lane divided highways. Finally, these two encroachment studies are 30 to 40 years old and were collected during unique time periods. The Hutchinson and Kennedy data were collected when controlled access freeways were first being introduced in Illinois. Drivers were unfamiliar with the operations of these facilities and deliberately driving into the median was believed to have been much more common than today. Although Cooper's study was much later and did not suffer from drivers being unfamiliar with access controlled roadways, all of the data were collected during summer months when traffic volumes are generally higher and winter driving conditions do not influence encroachment frequencies.

Calcote attempted to overcome the major problems with both the Cooper and Hutchinson and Kennedy studies, i.e., some encroachments are not detected due to paved shoulders and that controlled and uncontrolled encroachments are indistinguishable with observing tire tracks (29, 30). This research effort used electronic monitoring along rural highways and time-lapse videography photography along urban freeways. Unfortunately, the electronic monitoring procedure was unsuccessful due to technical problems and the study was limited to time-lapse videography. Although a large number of encroachments were captured by the time-lapse video, researchers were unable to develop an effective method to distinguish between controlled and uncontrolled encroachments. An overwhelming majority of the encroachments recorded involved vehicles drifting 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 cause these encroachments. The researchers chose to restrict the definition of uncontrolled encroachments to vehicles that exhibited sudden changes in vehicle trajectory or hard braking. As a result, 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. As a result, the findings of this study are not very useful.

The encroachment frequency distributions described previously are limited to straight, flat roadway sections. Accident data analysis studies have been used to supplement encroachment frequency data to estimate the effects of highway alignment and profile. The most widely used source of information for adjustment of encroachment rates for horizontal curvature and vertical grade is a study by Wright and Robertson (32). This study analyzed 300 single-vehicle, fixed-object fatal crashes in Georgia and compared fatal crash sites with control sites that were 1 mile upstream of the crash sites. Horizontal curvature was significantly over-represented at the fatal crash sites, with the outside of the curve accounting for 70 percent of the fatal crashes on curves. Downgrades of 2 percent or more were also found to have some effect, but upgrades were not over-represented. The findings from this study, summarized in Figure 4, have been implemented into RSAP and other encroachment probability models.

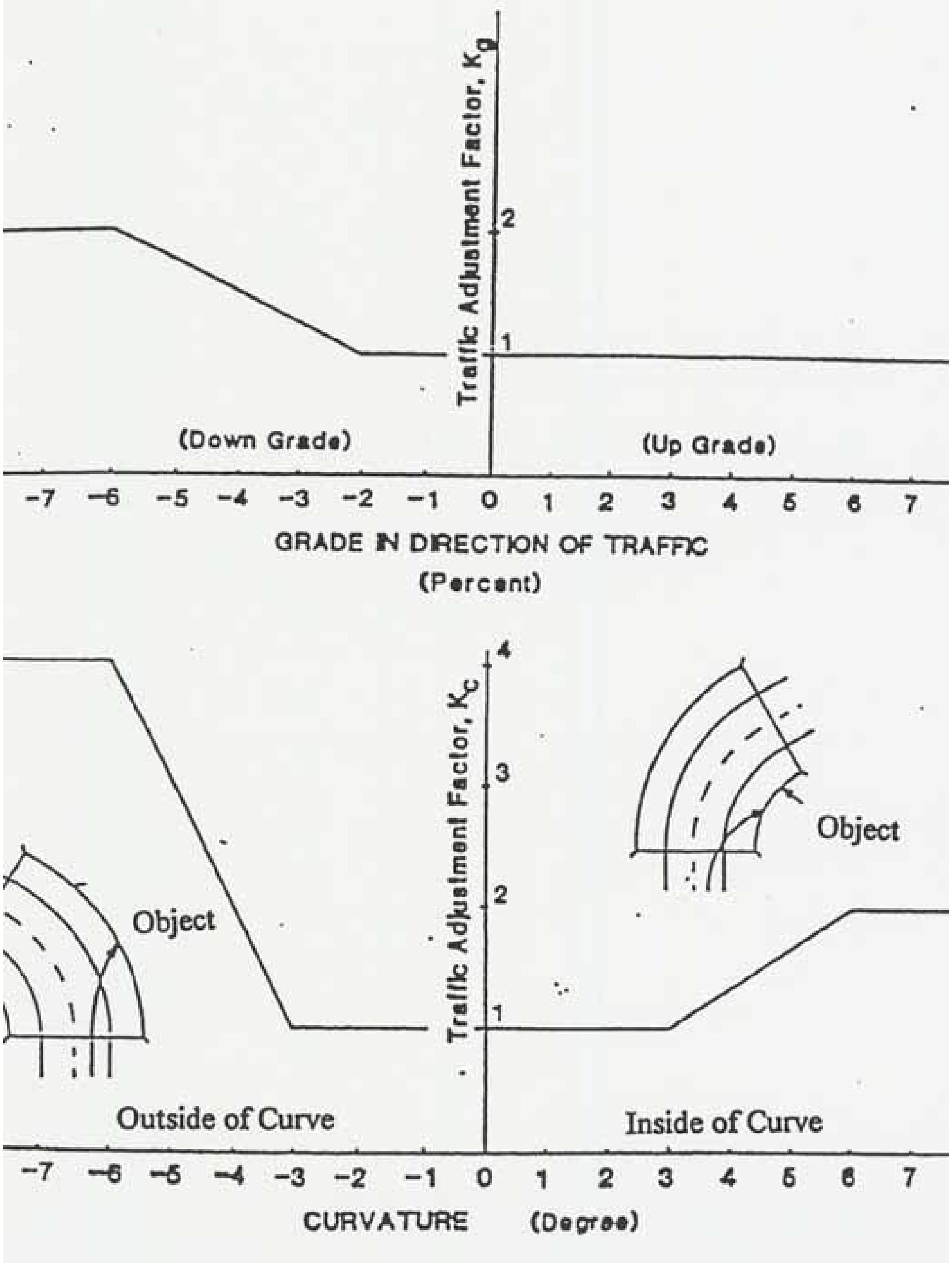


Figure 4. Encroachment Frequency Adjustment Factors for Curvature and Grade

Mak performed an analysis of real-world impact conditions using reconstructed crashes in the mid-1980s (35). 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 RSAP to describe encroachment speeds, angles, and vehicle orientations.

Lateral extent of encroachment distribution is another important parameter in encroachment probability models. Recall that lateral extent distributions are masked by the effects of surfaced shoulders. 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 a lateral extent of 13.2 ft (4 m) or less were under-reported or under-observed due to the presence of paved shoulders. These undetected encroachments explain the almost flat region of the lateral extent of encroachment curves over the first 13.2 ft (4 m). Adjustments for shoulders were developed for the RSAP program by excluding encroachment data from the region where shoulders could have an impact 0 to 13.2 ft (0 to 4 m). The re-analysis of the Cooper encroachment data on the extent of lateral encroachment involved fitting a regression model to lateral extent data beyond 13.2 ft (4 m). A regression model, as shown in Equation 5, with the following form appeared to provide the best fit to the data. The regression coefficients and R^2 values for the equations for both two-lane undivided highways and four-lane divided highways are shown in Table 1.

$$ln(Y) = a + bX \tag{5}$$

where:

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

Table 1. Regression coefficients and R^2-values for highways

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

The y-intercepts, i.e., the percent exceeding 0 ft (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. By definition, the y-intercepts for the lateral extent of encroachment distributions, i.e., percent exceeding lateral extent of 0 ft (0 m), must equal 100 percent. In order to have 100 percent at the y-intercept, all points on the curves are normalized, as shown in Figure 5.

The increase in the y-intercept above 100 percent can be interpreted to represent the extent of under-reporting of encroachments in the 0 to 13.2 ft (0 to 4 m) region. Adjustment factors for encroachment frequency to correct for under-reporting can be obtained by multiplying the Y-intercept by the fraction of observed encroachments that were above 13.2 ft (4 m). The resulting adjustment factors used in RSAP are 2.466 and 1.878 for two-lane undivided and multi-lane divided highways, respectively.

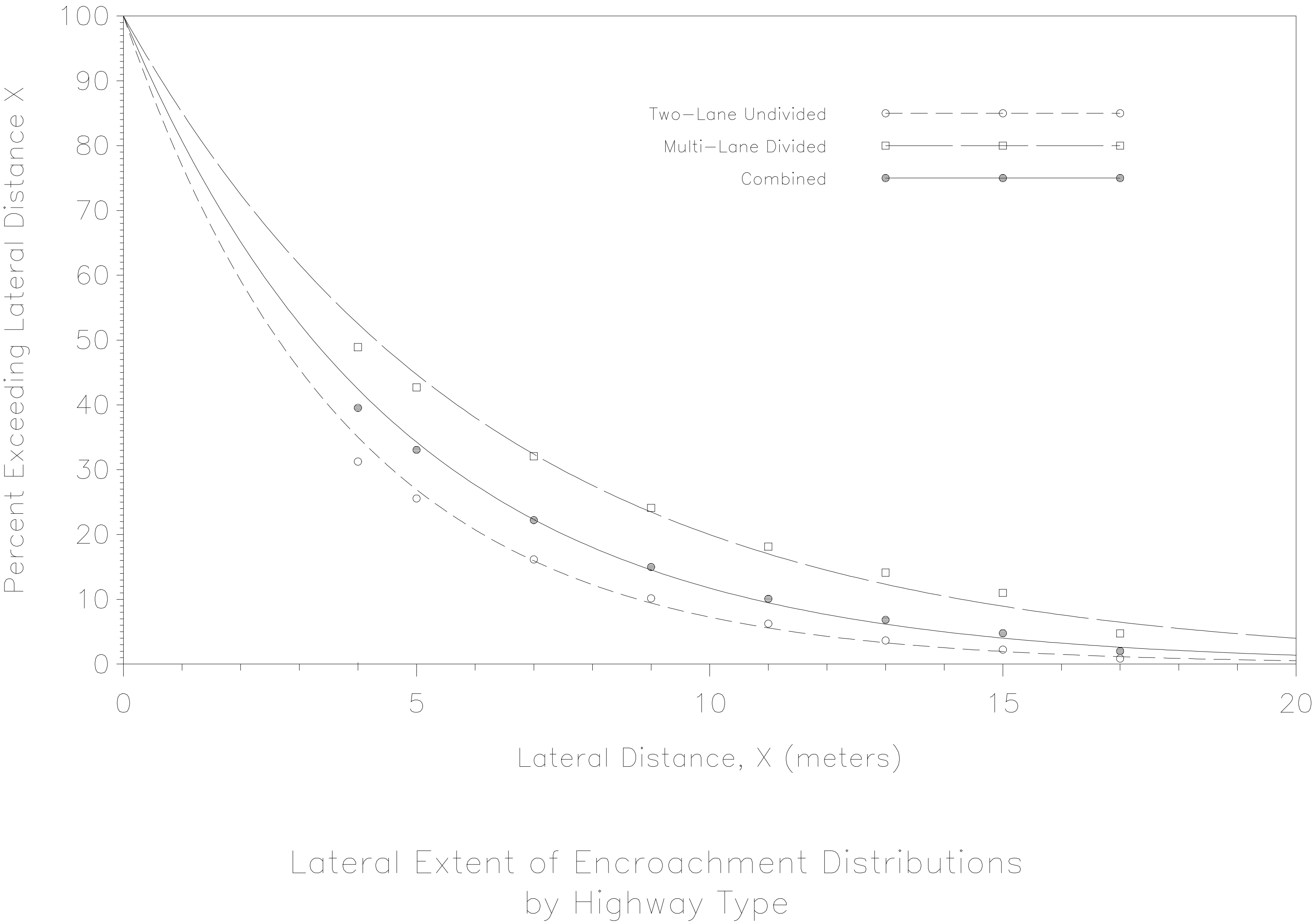


Figure 5. RSAP Lateral Extent of Encroachment Distributions

2.3. Accident Costs

Encroachment probability based economic models must calculate the costs of each predicted accident. A crash severity is assigned for each predicted accident and then cost is calculated based upon the estimated severity level. Although there are several methods for estimating crash severity, the most common method involves developing a link between vehicular impact conditions and Severity Index (SI). SI is a scale of crash severity ranging from 0 to 10. The SI table incorporated into the RSAP Program is presented in Table 2. Note that this table provides a very nonlinear relationship between risk of serious or fatal injury and severity index. RSAP attempts to assign an SI value for each predicted impact based upon the predicted vehicle size, speed, impact angle, and the hazard struck. SI values are generally assumed to have a linear relationship with impact speeds. The nonlinear relationship between SI and probability of injury produces a nonlinear relationship between crash severity and impact speed.

Table 2. Relationships of Severity Indices and Injury Levels

Severity Index (SI)	Injury Level (percent)						
	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

The severity of a crash must be linked to the object struck, as well as the speed, angle, orientation, and vehicle size involved in the accident. Severity calculations are adjusted to fit the type of hazard struck. For example, RSAP first identifies whether an impacting vehicle would be likely to penetrate beyond the accident. For breakaway objects, the penetration is predicted if the impacting vehicle is above a threshold value of kinetic energy. Similarly, longitudinal barriers are predicted to be penetrated when the Impact Severity (IS) of an impact is higher than the limiting value for the barrier test level. IS is calculated as shown in Equation 6.

$$IS = \frac{1}{2}\, m(V \sin\theta)^2 \qquad (6)$$

If feature penetration is predicted to be penetrated, RSAP can utilize different relationships for estimating the severity of impact with the hazard. Further, RSAP estimates the crash severity of the first hazard struck as well as any subsequent hazards in the vehicle's path. The highest severity of any hazard in the vehicle's path is then utilized in the calculation of accident cost.

RSAP also incorporates a rollover algorithm to identify impact conditions under which a vehicle is likely to rollover in front of or over the top of a longitudinal barrier. The rollover routines incorporate simplified impulse and momentum calculations and are primarily intended to be accurate for analyzing heavy truck impacts. Higher severities are assigned to rollover accidents than non-rollover impacts.

RSAP severity estimates are largely based upon SI values presented in Appendix A of the 1996 AASHTO *Roadside Design Guide* (RDG). Note that the SI tables in this document are tabulated by highway design speed. SI versus impact speed relationships were developed for RSAP that generally reproduced the values shown in the 1996 RDG. For each roadside object or feature, a linear regression line was fit through the SI values as a function of speed. These regression lines would always originate at the zero point since an impact speed of zero (0) mph or km/h should not produce any damage to the vehicle or injury to the occupants. The regression was then calibrated by using RSAP to predict average IS values for each of the functional classes of highway used in the program. Predicted severity levels for urban collector, rural collector and urban arterial, rural arterial, and freeways were then compared to values tabulated for design speeds of 31, 43.5, 56, and 71.5 mph (50, 70, 90, and 115 km/h), respectively. This simplistic calibration method helped to iron out some of the inconsistencies within the SI tables shown in the 1996 RDG.

SI values for longitudinal barriers and large vertical drops were treated somewhat differently. Lateral speed, $V_{lat} = V*\sin\theta$, was used instead of impact speed for the SI relationships of longitudinal barriers in order to account for the important effects of angle on impact severity. Further, it was recognized that large vertical drops would not necessarily have an SI of zero for an impact speed of zero because gravity would also play a large role in the probability of injury. Therefore, the regression lines for vertical drops were not fit through the zero point.

The final step in the process of calculating accident costs is to assign dollar values to each of the severity levels shown in Table 2. As summarized in Table 3, RSAP utilizes two standardized cost values, one from the RDG and values recommended by FHWA.

Table 3. Standardized Cost Values

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

2.4. Solution Method

Traditional encroachment probability models utilize a deterministic solution scheme. In other words, these methods calculate accident costs by summing all collision probabilities and costs over all possible combinations of impact conditions. This direct solution method provides the simplest and most accurate sheet your for calculating overall accident costs. However, this technique is limited to models that incorporate straight path encroachments.

RSAP was designed with the intent of incorporating curvilinear encroachment paths when accident data describing these paths became available. In order to accommodate this potential shift in the structure of the hazard envelope, a stochastic solution method became necessary. This technique, called Monte Carlo approach, involves randomly simulating encroachments along the roadside and calculating the resulted accident cost for each simulated encroachment. After stimulating millions of roadside encroachments, the average cost per encroachment will stabilize. The average cost per encroachment can then be multiplied by the encroachment frequency to determine the average annual accident costs at a site.

Although the Monte Carlo approach provides a more flexible solution that can incorporate curvilinear vehicle paths and other modifications that can make encroachment probability models more accurate, the technique does have some limitations. The random sampling approach to simulating encroachments is initiated by a seed number that is determined based on the computer's clock at the time each RSAP run is initiated. As a result, the Monte Carlo procedure will normally give slightly different answers as a run is initiated even though the input may be unchanged. Although these differences are normally very minor, many engineers find the variations unsettling. The variations in answers from one run to the next can be minimized by tightening the convergence checks that must be satisfied before average encroachment cost is considered sufficiently stable.

As summarized previously, RSAP is currently the most sophisticated encroachment probability model available for evaluating the costs of ran-off-road accidents. Therefore, it was selected for use in the development of guardrail implementation guidelines.

2.5. Benefit-To-Cost Analysis

The primary objective of an encroachment probability accident prediction model is to compare the various safety improvement options. The most common method of comparison is to calculate a benefit-to-cost ratio. A benefit-to-cost analysis compares the benefits derived from a safety improvement to the direct costs associated with the improvement. Benefits are measured in terms of reductions in societal costs arising from decreases in the number and/or severity of accidents. Direct costs of a safety improvement include initial installation, maintenance, and accident repair costs. The ratio between differences in the benefits and costs associated with two safety improvements is called the B/C ratio. The calculation of the B/C ratio comparing alternative 2 to alternative 1 is shown in Equation 7.

$$BC_{2-1} = \frac{SC_1 - SC_2}{DC_2 - DC_1} \tag{7}$$

where,

BC_{2-1} = Benefit-to-cost ratio of alternative 2 compared to alternative 1
SC_i = Societal accident costs associated with alternative i
DC_i = Direct costs associated with alternative i

Alternative 2 is normally assumed to be an improvement relative to alternative 1. The predicted benefits are less than the predicted costs if the benefit-to-cost ratio is less than 1.0. Therefore, the improvement is not justifiable and it should not be employed. If the benefit-to-cost ratio for safety improvement is greater than 1.0, the expected benefits are believed to be equal to or greater than the expected costs. A B/C ratio of 1.0 indicates that the benefit to society will be become equal to the direct cost of the construction by the end of the life of the project. B/C ratios for most other construction projects are much higher than 1.0. Implementing safety projects with low B/C ratios produces wasteful expenditures while requiring excessive B/C ratios under values safety. Highway agencies must select the threshold B/C ratios at which safety improvements will be implemented. Most agencies begin to fund safety projects at B/C ratios in the range of 2 to 4.

3. RESEARCH APPROACH

The research described herein attempted to utilize a benefit-to-cost analysis procedure to develop general guidelines for guardrail implementation. The primary goal of this research was to identify the most appropriate guardrail test level based on highway and traffic characteristics. The first step involved identifying the safety treatment options to be evaluated as well as the relevant parameters needed to describe each alternative, including safety treatment layout, construction costs, and accident severities. Next, it was necessary to identify the roadway, roadside, and traffic characteristics of various highway functional classes along with the type and severity of hazards commonly found along each type of roadway. Specific roadway, roadside, and hazard conditions to be analyzed were then assigned to a set of detailed hazard scenarios that form the basis of a benefit-to-cost analysis.

The RSAP program was used to analyze each hazard scenario under a wide variety of roadway and traffic characteristics. These RSAP runs were then tabulated, identify specific locations where various guardrail performance levels should be implemented. These specific guidelines were then generalized to develop route specific recommendations for guardrail performance level for each of five different highway functional classes as a function of traffic volume.

Applications examples of the general route specific guidelines were prepared and documented along with situations under which a more detailed analysis may be warranted. Procedures for implementing a more detailed analysis were also summarized.

The process of identifying input parameters to be used in the RSAP analysis is presented in Chapter 4. Procedures for implementing RSAP are presented in Chapter 5. Chapter 6 describes the process of developing general route specific guidelines, as well as examples of their application. A method for identifying conditions meriting further analysis and the procedures that should be used to conduct such analysis are presented in Chapter 7. Chapter 8 presents conclusions and recommendations.

4. RSAP INPUT

The basic approach to the development of guardrail application guidelines involves identifying the full range of guardrail applications and conducting an economic analysis of a reasonable subset of these conditions. Therefore, it is necessary to determine the types of hazards, proposed guardrail safety treatments, and roadside and roadway conditions commonly found along highways. Other data that must be collected include guardrail and accident costs, guardrail layout, and traffic characteristics. The process used to develop the needed RSAP input data is summarized as follows.

4.1. Roadside Hazards

Guardrails are used to shield motorists from a wide variety of roadside hazards, including point hazards, such as a bridge pier or utility pole, medium-sized hazards, including roadside culverts, and long hazards, such as steep roadside slopes. Previous benefit-to-cost analysis studies of guardrail have shown that the size of the hazard greatly affects the analysis. In order to properly protect motorists, a guardrail must be placed in front of a hazard and must extend upstream of the hazard for some distance. When guardrail is used to treat point hazards, such as a bridge pier, the ratio between guardrail crashes and the number of hazard impacts prevented is very high. Hence, even though the average cost of a guardrail crash may be much lower than the cost of an impact with a hazard, a large increase in crashes may prevent barrier implementation from being cost beneficial. On the other extreme, when guardrail is used to protect long hazards, such as steep roadside embankments, the ratio of guardrail impacts to hazard crashes prevented may approach 1.0. In this situation, the reduced severity of guardrail crashes relative to accidents involving a hazard generally make barrier implementation much more cost beneficial.

The crash severity of roadside hazards can also vary greatly from one location to the next. Guardrail treatment of severe hazards, such as bridge piers and steep roadside slopes, is much more cost beneficial than treatment of moderate hazards, such as small trees and roadside ditches.

In order to develop comprehensive guidelines it was necessary to study a full range of hazard sizes and severity. Two hazard size classifications and three different hazards severities were selected for inclusion in the study. Point hazards were chosen to represent situations of least cost beneficial guardrail applications while long roadside slopes were selected to represent situations where guardrail is most likely to be cost beneficial. It should be noted that long hazars are 4000 ft (1219.2 m) long. Specific hazards selected for each of the six categories are shown in Table 4.

Table 4. Hazard Categories

Category	**Severe**	**Moderately Severe**	**Moderate**
Point Hazard	3' (.9144 m) dia. Bridge Pier	10" (in.) dia. Utility Pole	6" (in.) dia. Tree
Slope Hazard	1.5:1 Slope, 26'(7.9248 m) deep	2:1 Slope, 20' (6.096 m) deep	2.5:1 Slope, 13' (3.9624 m)deep

4.2. Safety Improvement Options And Costs

In order to design any guardrail installation, it is necessary to identify the guardrail and terminal test level and the appropriate guardrail runout length. The first step in selecting the appropriate guardrail test level is to review available barrier systems. Most existing guardrail systems are designed to meet Test Level 3 (TL-3), including strong-post W-beam, box beam, and most cable guardrails. Thrie-beam based guardrails have also been designed and tested to meet TL-4. TL-2 and TL-5 guardrail designs are much less common. The most widely known TL-2 guardrail design is the original weak post W-beam system included in the 1988 AASHTO Roadside Design Guide. Although not normally used in roadside applications, TL-5 median barrier designs have been adapted for use on the roadside. Hence, construction costs for TL-2 and TL-5 barriers can be estimated based upon existing barrier designs. Unfortunately, no guardrail design has yet been developed to meet TL-1 or TL-6. As a result, identifying appropriate costs for these test levels is very difficult. Further, because these designs are not currently available, it is impractical to include them in any barrier selection guidelines. In an effort to provide both a practical and a comprehensive set of guardrail treatment guidelines, Test Levels 2 through 5 (TL-2 through TL-5) guardrails were selected for inclusion in this study.

All available guardrail terminals have been designed to meet Test Levels 2 or 3. Thus, TL-3 terminals had to be utilized for TL3 through TL-5 guardrails and it was necessary to utilize barrier transitions to adapt TL-4 and TL-5 barriers to a TL-3 system before terminating the barrier. Construction costs were obtained from state wide bid tabulations for 7 geographically diverse states. The resulting average cost for the various barriers and terminals are shown in Table 5.

Estimates of transition systems for TL-4 and TL-5 barriers were identified. Costs for transitions from a concrete TL-5 barrier to a TL-3 guardrail terminal were again found on statewide bid tabulations and the costs for a TL-4 to TL-3 transition were estimated using general construction estimation procedures. Costs per foot for both transition systems were found to be approximately equal to the cost of the higher performance barrier. Thus, the cost of a transition system was incorporated by adding an extension of the basic barrier instead of incorporating the guardrail terminal. Note that the transition length was set at 25 ft (7.62 m) and the TL-3 guardrail terminal length was set equal to 37.5 ft (11.43 m).

Table 5. Costs of Guardrails and Terminals

Barrier Type	Cost ($/ft.)	Cost ($/m.)
TL-2 Terminal	1,425.00	4675.20
TL-3 Terminal	2,002.00	6568.24
TL-2	8.90	29.20
TL-3	14.68	48.16
TL-4	21.09	69.19
TL-5	54.58	179.07

4.3. Guardrail Layout

When designing a roadside barrier layout, an engineer must identify the variables shown in Figure 6, including the Lateral Extent of the hazard, L_A, Runout Length, L_R, the offset to the face of the barrier, L_2, the offset to the face of the hazard, L_3, and the flare rate of the guardrail in advance of the hazard. With the exception of L_R, all of these variables are based upon the geometry of the hazard and roadside. The Lateral Extent of the Area of Concern, L_A, is the distance from the edge of the travelway to the far side of the hazard or to the outside edge of the clear zone, L_C, whichever is shorter.

The offset to the face of the barrier is normally controlled by roadside slopes. Guardrails are generally not recommended for placement on roadside slopes steeper than 10:1. For very flat roadsides, the offset to the face of the barrier is limited by barrier deflection during an impact. For the purpose of developing guardrail application guidelines, it was assumed that the barrier is placed as far from the roadway as possible based upon slope geometry and anticipated barrier deflections.

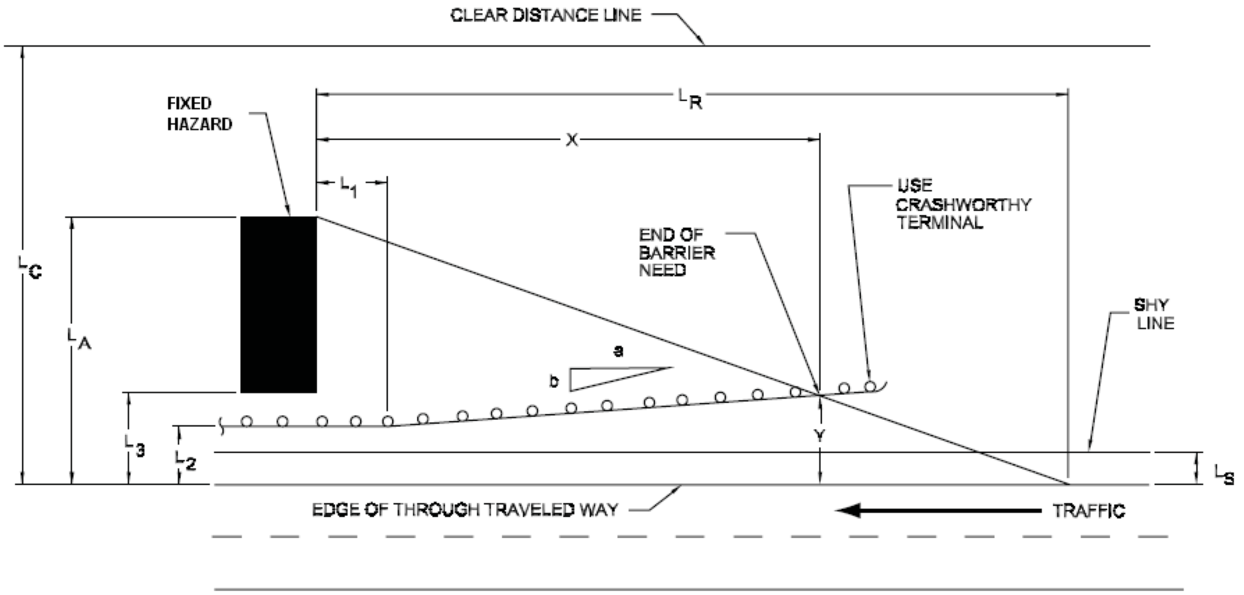


Figure 6. Barrier Layout Variables

The barrier is flared in advance of the hazard in order to reduce the required length and minimize the number of guardrail impacts. Guardrail flare rate is also limited by the need to avoid placing guardrail on roadside slopes steeper than 10:1, as well as RDG limits based on highway design speed. The RDG limits on flare rate are very restrictive and as a result greatly reduce the benefit of implementing a flare configuration. A combination of the fact that roadside slopes are frequently steeper than 10:1 and RDG restrictions have led many states to avoid using any guardrail flare. Thus, in order to simplify the development of guardrail use guidelines, it was decided to utilize only tangent sections of guardrail. This decision greatly reduced the number of different safety treatment alternatives that had to be evaluated. Further, implementation of a guardrail flare should not materially affect the relative benefits nor costs of utilizing higher or lower barrier test level.

Guardrail runout length, L_R, has been the subject of several research papers and much disagreement over the last decade. The primary basis for this disagreement is whether guardrail length should be determined based upon encroachment data collected by Hutchinson and Kennedy or Cooper. Roadside Design Guide procedures are based upon Hutchinson and Kennedy's longitudinal encroachment length data. Cooper's encroachment length data produce runout lengths that are approximately one third shorter than those recommended in the RDG. A 1996 study attempted to conduct a benefit-to-cost analysis to determine the most appropriate guardrail runout lengths. This study found that the most cost beneficial runout lengths were very near values based upon Cooper's data. Further, recently collected data from ran-off-road crashes on high-speed facilities matched Cooper's encroachment length data extremely well. Thus, L_R values obtained from Cooper's data, shown in Table 6, were utilized in the development of guardrail layouts for each hazard configuration.

Table 6. Runout Length, L_r, Based Upon Cooper.

Design Speed mph (km/h)	Runout Length (Lr) given Traffic Volume (ADT)			
	> 3,000 ft (m)	1,700 to 3,000 ft (m)	850 to 1,700 ft (m)	< 850 ft (m)
70 (112.65)	360 (110)	300 (91)	260 (79)	220 (67)
60 (95.56)	260 (79)	210 (64)	180 (55)	170 (52)
50 (80.47)	210 (64)	170 (52)	150 (46)	130 (40)
40 (64.37)	160 (49)	130 (40)	110 (34)	100 (30)
30 (48.28)	110 (34)	90 (27)	80 (24)	70 (21)

4.4. Accident Costs

Transportation agencies primarily utilize one of two sets of accident costs, RDG and FHWA values. RDG values are generally considered to be representative of the direct costs of highway crashes, while FHWA values are intended to be comprehensive and include factors such as a person's willingness to pay to avoid an injury or fatality. FHWA has strongly recommended the use of comprehensive accident costs in order to properly value safety improvements. Therefore, FHWA comprehensive costs have been selected for use in the RSAP analysis. Cost figures were updated to represent 2006 dollars as shown in Table 7.

Table 7. FHWA Comprehensive Accident Costs.

Accident Type	**Accident Costs($) for 2006**
Fatal	3,296,000
Severe Injury	226,600
Moderate Injury	45,320
Minor Injury	23,690
Property Damage Only	2575

4.5. Roadway and Roadside Characteristics

Roadway and roadside geometric parameters, including hazard offset, curvature, grade, and offset to and steepness of roadside slopes, can affect the frequency of ran-off-road crashes. Three of these geometric parameters affect crash frequencies, while a fourth limits guardrail placement options. Hazard offset defines the distance between the edge of the travelway and a roadside obstacle. Obstacles placed closer to the roadway are struck much more often than those placed farther away. Roadway curvature and grade also affect crash frequencies by increasing the number of roadside encroachments. The distance between the edge of the travelway and roadside embankment often controls where guardrail can be placed. The RDG recommends that guardrails be placed on surfaces that have a slope of 10:1 or less. Thus, it is important to determine appropriate ranges for these parameters before guardrail placement guidelines can be developed.

Roadway and roadside geometric parameters are strongly influenced by highway functional class. RSAP includes five different highway functional classes, freeway, urban arterial, urban collector/local, rural arterial, and rural collector/local. The first step in establishing appropriate ranges for the geometric parameters described was to identify minimum values. Some states have established criteria that identify minimum design standards for each highway functional class. Four states, New York, Louisiana, Oregon, and Iowa, were surveyed to identify minimum design standards for each of the five basic functional classes. Note that state design standards do not have a parameter for minimum or maximum hazard offset. However, minimum and maximum hazard offsets are indirectly related to minimum shoulder widths and minimum clear zone widths. Roadside hazards would seldom be allowed to encroach onto the shoulder of a roadway and few highway agencies would consider erecting safety treatments for hazards outside of the clear zone. Minimum design standards, presented in Table 8, represent lower bound values for each of the geometric parameters believed to be important to the development of guardrail application guidelines.

Table 8. Minimum Design Standards

Characteristics	**Rural Local/ Collector**	**Rural Arterial**	**Urban Local/ Collector**	**Urban Arterial**	**Freeway**
Min. Shoulder Width, ft (m)	2 - 8 (0.6 – 2.4)	4 – 8 (1.2 – 2.4)	6 – 8 (1.8 – 2.4)	6 – 10 (1.8 – 3.0)	8 – 12 (2.4 – 3.7)
Min. Clear Zone, ft (m)	7 – 17 (2.1 – 5.2)	6 – 26 (1.8 – 7.9)	8 – 26 (2.4 – 7.9)	9 – 38 (2.7 – 11.6)	10 – 38 (3.0 – 11.6)
Max. Side Slope	2:1 – 6:1	3:1 – 6:1	3:1 – 4:1	3:1 – 6:1	3:1 – 6:1
Max. Horizontal Curvature (degrees)	5 – 8	3 – 6	7 – 37.5	5 – 10	2 – 3
Max. Grade (percent)	4 – 10	3 – 6	7 – 12	5 – 9	3 – 5

Minimum design standards, shown in Table 8, were then utilized to develop typical ranges for important geometric parameters. Although, it is important to evaluate the full range of potential roadway and roadside geometry in order to assure generally applicable guardrail guidelines, it is also necessary to limit the number of geometric combinations to maintain a manageable number of RSAP runs. Note that both curvature and grade have greater effect in one direction than the other. Curves to the left and negative grades have greater effect on encroachment frequencies than curves to the right or upgrades. In order to minimize the number of RSAP runs required, only the limiting conditions of sharp left curve and steep down grade were incorporated into the analysis. Further note guardrail placement was determined by either hazard location or slope offset. Guardrails were placed either 4 ft (1.2 m) in front of the hazard to allow for barrier deflection or 2 feet (0.6096 m) in front of the slope, whichever was closer to the roadway.

Roadway and roadside geometric combinations that were incorporated into the study are shown in Table 9. Recall that the goal of this project is to develop general guidelines for guardrail application. In order to develop these guidelines, it will be necessary to determine the traffic volume at which one guardrail test level becomes cost beneficial compared to another. Further, the relationship between encroachment frequency and traffic volume is not linear. Thus, it is necessary to analyze a sufficient number of traffic volumes for each combination of roadway and roadside geometrics to assure that interpolation between two data points can be relatively accurate. A preliminary evaluation of the variability of the B/C ratio with changes in traffic volume indicated that 11 traffic volumes could sufficiently control the interpolation error. Volume ranges shown in Table 9 were therefore divided into 10 equal segments to produce 11 different traffic volumes. Thus, the variables shown in Table 9 represent 3,300 RSAP runs for each roadside hazard and a total of 19,800 RSAP runs for the entire study.

Table 9. Roadway and Roadside Geometric Combinations.

	Hazard Offset	**Curvature**	**Grade (percent)**	**Slope Offset**	**Volume (1000 ADT)**
Freeway	7,12,18,26,32	0,2L	0,-2	18,12,20	10-100
Rural Arterial	5,8,12,18,24	0,4L	0,-3	18,12,20	5-80
Rural LC	5,8,12,18,24	0,10L	0,-6	3,6,12	5-80
Urban Arterial	5,8,12,18,24	0,6L	0,-3	3,6,12	0.5-5
Urban LC	5,8,12,18,24	0,10L	0,-6	3,6,12	0.5-5

4.6. Traffic Characteristics

The number and size of trucks operating on the nation's roadways varies significantly with highway functional class. In order to accurately evaluate the merits of implementing truck barriers, such as TL-4 and TL-5, it is necessary to identify the truck size distribution and volume for each of the functional classes included in the study. This data was found in a report to the Washington State Department of Transportation and is summarized in Table 10. Data from Table 10 was incorporated into the RSAP analysis for each of the five functional classes included in the study.

Table 10. Truck Volume Distributions by Highway Classification.

Functional Class	**Single-Unit Trucks**	**Combination Trucks**	**Multi-Trailer Trucks**	**Total Trucks**
Rural Interstate	3.5	19	2	24.5
Rural Principal Arterial	3.7	7.4	0.6	11.7
Rural Minor Arterial	3.3	5.2	10	18.5
Rural Major Collector	4.8	2.5	0.1	7.4
Urban Interstate	2.6	5.2	0.7	8.5
Urban-Other Freeways & Expressways	3.7	5.9	1.5	11.1
Urban Principal Arterial	3.2	5.8	0.6	9.6
Urban Minor Arterial	2.4	2.9	0.3	5.6

5. BENEFIT-TO-COST ANALYSIS

The RSAP analysis began with a preliminary evaluation of a small subset of the 19,800 different roadway, roadside, and hazard combinations described in the previous chapter. Roadway and roadside conditions under which guardrail treatment of each of the six roadside hazards included in the study became cost beneficial were identified. This analysis produced some troubling findings. Guardrail treatment of even the most severe point hazard was found never to be cost beneficial. Careful evaluation of these RSAP runs showed that, on freeways, the average Severity Index for guardrail impact was 3.2. When compared to findings from accident data, this SI appeared to be somewhat high.

The validity of average crash severity predictions from RSAP was examined by comparing predicted injury distributions to available guardrail accident data. The NHTSA Traffic Safety Facts was the first source of guardrail crash severity examined. These publications contain data generated from NHTSA's General Estimates System (GES). The GES is designed to be representative of all reported crashes nationwide and therefore includes many crashes on low-speed facilities where both impact speeds and crash severities would be expected to be lower. Based on the fact that it includes lower speed facilities, GES severities would be expected to be significantly lower than RSAP predictions. However, this database is also limited to reported crashes, which should be more severe than the accidents RSAP attempts to predict which include both reported and unreported crashes.

RSAP predictions were also compared to guardrail crash severities from Kansas accident records from 2002 through 2006. The Kansas accident record system was queried to identify all crashes on controlled access freeways where struck guardrail was the first harmful event. By limiting the records to controlled access freeways, it is possible to make a more direct comparison between RSAP predictions for freeway crashes and guardrail crash data. Note however that the Kansas data is still limited to reported crashes which, on average, should be significantly more severe than RSAP predictions. A total of 2,183 accidents were identified that met the criteria.

Average guardrail crash severities from RSAP, Traffic Safety Facts, and Kansas accident data are summarized in
Table 11. Notice that the Kansas data and the NHTSA-GES data are virtually identical with approximately 70 percent PDO, 30 percent injury, and 1 percent fatal accidents. RSAP crash severity appears to be somewhat higher with 40 percent PDO, 58 percent injury, and 1.4 percent fatal accidents. Recall that both the NHTSA-GES and the Kansas accident data omit unreported crashes and therefore should have a higher severity than RSAP.

Table 11. Guardrail Crash Severities

Injury Severity	**RSAP**	**Traffic Safety Facts 2002-2006**	**Kansas 2002-2006**
PDO (percent)	40.4	69.0	70.0
Any Injury (percent)	58.2	30.0	29.4
Fatality (percent)	1.4	1.0	0.64
Possible Injury (percent)	33.2	N/A	10.9
Injury (percent)	23.2	N/A	14.2
Serious Injury (percent)	1.8	N/A	4.3

In order to assure that the reduced severity of guardrail crashes in Kansas was not a result of improper coding of the barrier type, crashes coded as either median barrier or bridge rail were also identified. This effort identified 4,289 median barrier crashes and 705 bridge rail accidents.

Although accident severities with all three barrier types were found to be somewhat similiar, guardrail crash severity was found to be the highest of the three types of crashes.

In order to make a more direct comparison between RSAP predictions and Kansas accident data, injury distributions were converted into accident cost estimates using Table 8 presented in the previous chapter. This effort revealed that RSAP average guardrail crash costs were almost twice the average cost of guardrail crashes on controlled access freeways in Kansas. When taken in light of the fact that RSAP predictions include unreported crashes, the program's average crash costs are quite excessive. Excessive crash severity estimates for guardrail would make the use of guardrail much less cost beneficial by overestimating the number of injuries and fatalities associated with barrier crashes.

The magnitude of unreported accidents varies widely, ranging as low as 10 percent to as high as 80 percent. A recent study of cable median barrier accidents and repairs in Missouri found 4,386 reported accidents and 5,939 barrier repairs. If all repair events are assumed to arise from unreported crashes, this data would indicate that approximately 26 percent of all barrier impacts go unreported data. It is generally believed that cable median barriers are more forgiving than most guardrail systems and more forgiving barriers have a higher proportion of unreported accidents. Hence, it can be argued that less than 26 percent of guardrail crashes go unreported.

Uncertainties, such as the magnitude of unreported guardrail accidents, are often encountered when constructing economic models for evaluating highway safety improvements. These uncertainties are normally addressed with the philosophy that the final analysis should be constructed to err on the side of safety. In the present case, it was decided to adjust guardrail crash costs based on the assumption that 26 percent of guardrail impacts go unreported. This crash cost adjustment was accomplished by assuming that all unreported crashes involved property damage only. RSAP guardrail crash severities were then adjusted to match the revised Kansas guardrail crash cost. This adjustment was accomplished by reducing the crash severity adjustment factor included in RSAP's SI7.dat file from 1.0 to 0.7. The resulting barrier crash severities and costs are summarized in Table 12.

Table 12. Barrier Crash Severities & Costs

Injury Severity	**RSAP Guardrail**	**Adjusted RSAP Guardrail**	**Kansas Guardrail 2002-2006**	**Kansas Median Barrier 2002-2006**	**Kansas Bridge Rail 2002-2006**	**Adjusted Guardrail Severities**
PDO (percent)	40.4	57.0	70.0	70.0	70.0	81.0
Possible Injury (percent)	33.2	28.0	10.9	11.9	14.0	8.1
Injury (percent)	23.2	14.0	14.2	15.7	12.2	10.5
Serious Injury (percent)	1.8	0.5	4.3	2.6	3.0	3.2
Fatality (percent)	1.4	0.5	0.64	0.21	0.43	0.5
Average Cost ($)	69,600	32,000	41,700	24,600	31,600	31,600

The preliminary evaluation runs with RSAP were then repeated. The prior anomalies, wherein guardrail treatment of severe point hazards was not found to be cost beneficial, were eliminated. Based on this positive finding from the preliminary evaluations, the full matrix of 19,800 RSAP runs were completed. Preliminary guidelines for guardrail selection were developed for each combination of highway functional class, hazard offset, curvature, grade, and offset to slope as shown in Table 13. Detailed application guidelines were developed by interpolating traffic volume to identify when one barrier option became cost beneficial over another. Three different sets of guidelines were developed for B/C ratios of 2, 3, and 4. These detailed, site specific, guardrail selection guidelines are presented in Appendices A, B, and C.

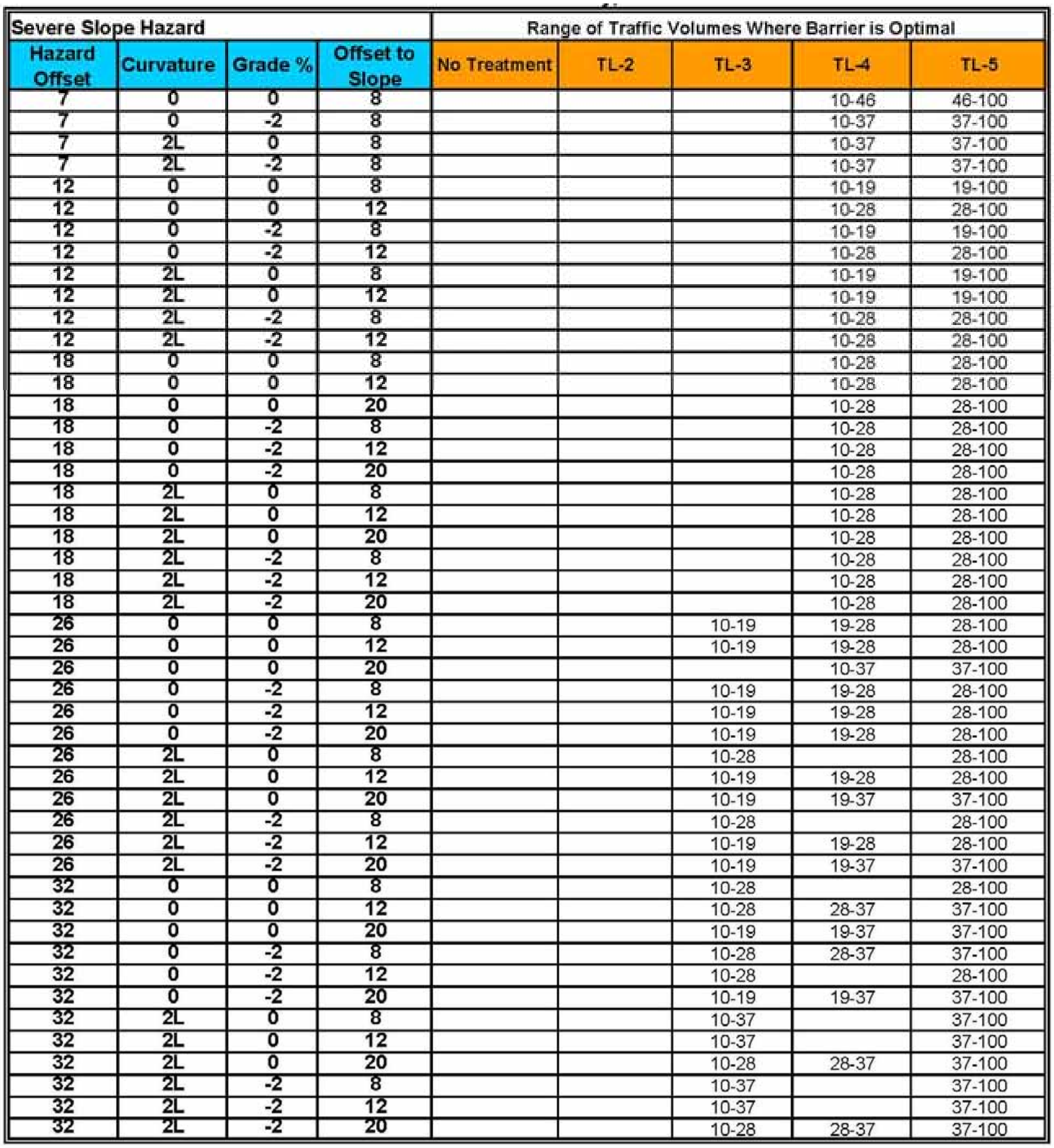
TL-5 barriers were found to be the most cost beneficial option for long, severe and moderately severe hazards adjacent to high volume freeways. Note that the RSAP program incorporates the same impact severity for all barrier test levels. This approach means that the only difference in safety performance for the barriers is the reduction in penetrations and truck rollover crashes associated with the higher test level barriers. Although not apparent in the Kansas data presented in the previous chapter, some accident data has shown that concrete barriers used for TL-5 produce higher probabilities of injury than semi-rigid guardrails commonly used for TL-3.

TL-4 barriers were found to seldom provide the most cost beneficial treatment option. This result was not unexpected because the capacity of a TL-4 barrier is only marginally greater than a TL-3 system. Further, the modest difference in height between TL-3 and TL-4 barriers limits the higher performance barrier's effectiveness in reducing truck rollovers. This finding is a clear indication that TL-4 barriers as defined in NCHRP Report 350 do not have a significant benefit where they are economically viable.

When the site-specific selection guidelines for two different B/C ratios were compared, the effects of requiring a higher B/C ratio were not found to be as significant as originally anticipated. The primary effect was to moderately increase traffic volumes at which higher performance level barriers become more cost beneficial. Rarely did raising the B/C ratio from 2 to 4 move the recommended test level down one step for all traffic volume.

Readers should note that some tables shown in Appendices A, B, and C indicate that as traffic volumes increase, the most cost beneficial option moves from one category to another and then moves back to the original test level at even higher volumes. This, jumping back and forth is an indication that the two barrier treatment options are economically equal. Designers attempting to use the site specific guidelines encountering this situation should look for another basis for selecting the barrier's test level. If the specific site under consideration is more hazardous than the modeled situation, the higher test level barrier should be used. Alternatively, a designer may choose the barrier based upon keeping the barrier test level more uniform over a given length of highway.

Table 13. Guardrail Use Guidelines Freeway, B/C ≥ 2



Severe Slope Hazard				Range of Traffic Volumes Where Barrier is Optimal				
Hazard Offset	Curvature	Grade %	Offset to Slope	No Treatment	TL-2	TL-3	TL-4	TL-5
7	0	0	8				10-46	46-100
7	0	-2	8				10-37	37-100
7	2L	0	8				10-37	37-100
7	2L	-2	8				10-37	37-100
12	0	0	8				10-19	19-100
12	0	0	12				10-28	28-100
12	0	-2	8				10-19	19-100
12	0	-2	12				10-28	28-100
12	2L	0	8				10-19	19-100
12	2L	0	12				10-19	19-100
12	2L	-2	8				10-28	28-100
12	2L	-2	12				10-28	28-100
18	0	0	8				10-28	28-100
18	0	0	12				10-28	28-100
18	0	0	20				10-28	28-100
18	0	-2	8				10-28	28-100
18	0	-2	12				10-28	28-100
18	0	-2	20				10-28	28-100
18	2L	0	8				10-28	28-100
18	2L	0	12				10-28	28-100
18	2L	0	20				10-28	28-100
18	2L	-2	8				10-28	28-100
18	2L	-2	12				10-28	28-100
18	2L	-2	20				10-28	28-100
26	0	0	8			10-19	19-28	28-100
26	0	0	12			10-19	19-28	28-100
26	0	0	20				10-37	37-100
26	0	-2	8			10-19	19-28	28-100
26	0	-2	12			10-19	19-28	28-100
26	0	-2	20			10-19	19-28	28-100
26	2L	0	8			10-28		28-100
26	2L	0	12			10-19	19-28	28-100
26	2L	0	20			10-19	19-37	37-100
26	2L	-2	8			10-28		28-100
26	2L	-2	12			10-19	19-28	28-100
26	2L	-2	20			10-19	19-37	37-100
32	0	0	8			10-28		28-100
32	0	0	12			10-28	28-37	37-100
32	0	0	20			10-19	19-37	37-100
32	0	-2	8			10-28	28-37	37-100
32	0	-2	12			10-28		28-100
32	0	-2	20			10-19	19-37	37-100
32	2L	0	8			10-37		37-100
32	2L	0	12			10-37		37-100
32	2L	0	20			10-28	28-37	37-100
32	2L	-2	8			10-37		37-100
32	2L	-2	12			10-37		37-100
32	2L	-2	20			10-28	28-37	37-100

6. ROUTE-SPECIFIC SELECTION GUIDELINES

The first step in converting the site-specific guardrail selection guidelines shown in Appendices A, B, and C into a route-specific format was to examine the effects of each highway and roadside parameter on the recommended barrier test level. Findings from this examination are summarized below.

Functional Class

Highway functional class was found to have a major impact on the need for higher performance barriers. The RSAP program uses highly functional class as a surrogate for operating speeds. This approach is based on a study by Mak that showed functional class as the best indicator of encroachment speeds associated with ran-off-road crashes. High encroachment speeds greatly increase the number of vehicles that are predicted that penetrate through or over the top of the guardrail system. Thus the benefit of using higher, stronger barriers would be expected to increase significantly when tanks and functional class raise predicted encroachment speeds. This effective close clearly observed when guardrail selection guidelines for freeways are compared to lower functional classes. Higher barrier test levels were found to be consistently more cost beneficial for freeway application than for any other functional class.

Hazard Severity

As presented in Chapter 4, three different hazard severities were included in the study, severe, moderately severe, and moderate. Hazard severity proved to have a significant impact on test level selection. As shown in Table C1, TL-4 or TL-5 barriers were generally found to produce a B/C ratio of 4 or greater when a severe slope hazard was placed within 18 feet (5.5 m) of a freeway with traffic volume of 30,000 ADT or more. When the hazard was replaced with a moderately severe slope, as shown in Table C2, TL-4 barriers dropped off the table and TL-5 barriers do not generally reach a B/C ratio greater than 4 until traffic volume exceeded 60,000 ADT. Finally, when the hazard was changed to a moderate severity slope, only TL-2 barriers were found to have B/C ratios greater than 4. This finding merely reflects the fact that hazard severity has a major impact on the risk of serious injury and fatality whenever a vehicle is predicted to penetrate through or over the guardrail. Recall that the primary benefit of increased guardrail test level is a reduction in the number of vehicles that penetrate through or over the barrier. Whenever the severity of going through the guardrail is increased the benefits of using a stronger guardrail increase commensurately.

Hazard Size

Guardrail shielding of long hazards was found to be much more cost beneficial than treatment of point hazards. When viewed in terms of the benefits associated with a higher barrier test level, this finding is not surprising. As noted above, the benefit of increasing test level is primarily related to the risk of a vehicle striking a roadside hazard after penetrating through or over the barrier. When a vehicle penetrates through or over the portion of any guardrail placed upstream of an object, the risk of the vehicle continuing on to strike the hazard is still relatively modest. However, when a vehicle penetrates through a barrier immediately adjacent to an obstacle, it will almost certainly encounter the hazard. Because of the significantly different risks of a vehicle penetrating through or over the barrier and then striking the hazard, higher test level barriers are shown to be much more cost beneficial when placed adjacent to long hazards.

Hazard Offset

Ran-off-road crash frequencies have been shown to diminish as roadside obstacles are moved farther from the travel way. Thus, the potential benefit of installing guardrail diminishes as hazards are moved further from the travel way. Secondary factor that has the same effect on the benefit of using guardrail is the relationship between guardrail length and the offset to the back of the hazard. Whenever possible, guardrail is placed meeting the adjacent to the hazard. However, whenever roadside slopes steeper than 10:1 are found in front of the hazard, the guardrail must be placed much closer to the roadway. In this situation, the length of guardrail required to adequately shield traffic from the hazard is increased significantly and both the cost of the guardrail installation and the number of impacts with the barrier are increased proportionately. The site-specific guardrail selection guidelines do not show that, for long hazards, offset has as great an effect on test level selection as was originally anticipated. For the long slope hazards included in the study, increasing the offset made only modest increases in the traffic volume at which a higher test level barrier became more cost beneficial. Hazard offset had a much bigger impact on guardrail protection of point hazards. The RSAP analysis showed that increasing hazard offset made lower test level barriers more cost beneficial and for very high offsets made no treatment the most cost beneficial alternative, even on freeways.

Offset to Slope

This parameter is to the distance from the edge of travel way to the beginning of a moderate roadside slope. Although these slopes can cause some accidents, the severities are generally low. The primary effect is related to guardrail placement issues. Guardrails cannot be installed on even modest roadside slopes of 8:1 or steeper. Hence it's a modest roadside slope begins in the edge of the shoulder, the guardrail, must be placed very near the travel way. This location requires more guardrail in order to properly treat the hazard and increases barrier crash frequency. Thus, as the offset to the slope diminishes, so does the benefit of implementing guardrail. This parameter was found to have the greatest effect for hazards with high lateral offsets. In this situation, the increase in guardrail crashes relative to hazard impacts prevented increase significantly when the barrier was moved closer to the roadway. Overall, this parameter was found to be much less important than any of the parameters described above.

Curvature

Highway curvature has been shown to significantly increase the risk of ran-off-road crashes. However, for the economic analysis of guardrail installation, curvature proved to have a relatively limited impact. When the effects of curvature on guardrail protection of long hazards is studied, barrier is found to be only modestly more cost beneficial when the hazard is placed on the outside of a left curve. When the effects of curvature on guardrail benefits are examined for point hazards, just the opposite effect is found. Barrier is found to be less cost beneficial when protecting motorists from point hazards placed outside of a curve. This is this effect is related to the risk of impacting a point hazard when a vehicle encroaches from a curved highway. For straight path encroachments, the risk of encountering a point hazard diminishes as encroachment angle increases. Further, the effective angle of encroachment increases as a vehicle moves away from a curved roadway. This increase in effective encroachment angle reduces the risk of striking small hazards and thereby tends to offset the effects of increased encroachment frequency.

Grade

The effect of down grade on the RSAP analyses of guardrail application was found to be very limited. The RSAP program adjusts encroachment frequency upward to account for the effect a down grade. An increase in encroachment frequency should translate into greater benefits for barrier installation. However, the effects of grade on encroachment frequency is much less than the effect of curvature. Thus, the effects of grade were not considered when developing route-specific guardrail application guidelines.

6.1. Guideline Development

As summarized above, highway functional class, hazard severity, hazard size, and hazard offset were found to be the most important parameters affecting the benefits of implementing higher performance guardrails. These parameters were chosen for evaluation during the process of developing route-specific guidelines. Functional class was found to have such a dramatic impact on the benefit of implementing guardrail that it had to be implemented directly into the guidelines. However, the basic principle behind route-specific guidelines is that only one barrier system will be used for the entire length of a roadway section. Hence, hazard specific parameters, including severity, size, and offset could not be directly implemented into the guidelines.

Hazard severity and size were implemented indirectly by defining roadways in terms typical terrain conditions. The RSAP analysis showed that high-performance barriers were most commonly cost beneficial when installed in front of long severe hazards. These types of hazards are our most commonly found in the form of steep roadside embankments. Steep roadside embankments are seldom encountered along highways across relatively flat terrain. However, severe roadside embankments are found along roadways through rolling terrain.

Implementation of clear zone policy over the last 40 years has produced a largely unobstructed region immediately adjacent to most modern roadways. Most roadside hazards are found outside of this unobstructed region. The size of a typical unobstructed region varies by functional class and from one route to the next. Hazard offset was implemented by defining two ranges of unobstructed zone for each class of highway as shown in Table 14.

Engineering judgment was then used to develop general route-specific guidelines for guardrail use based upon the site specific guidelines presented in Appendices A, B, and C. The resulting route-specific guidelines are presented in Tables 15 through 20. Note that the guidelines developed for relatively flat terrain have been labeled general guidelines and are presented in Tables 15, 17, and 19 for B/C ratios of 2, 3, and 4, respectively. As presented in the previous chapter, the decision of which B/C ratio to implement should be based upon comparisons with B/C ratios common to other types of highway construction projects.

Table 14. Unobstructed Zone Widths

Functional Class	**Classification**	**Unobstructed Zone Width ft (m)**
Freeway	Narrow	<18 (5.5)
	Wide	>18 (5.5)
Rural Arterial	Narrow	<12 (3.7)
	Wide	>12 (3.7)
Rural Collector/Local	Narrow	<8 (2.4)
	Wide	>8 (2.4)
Urban Arterial	Narrow	<8 (2.4)
	Wide	>8 (2.4)
Urban Collector/Local	Narrow	<8 (1.5)
	Wide	>8 (1.5)

Table 15. General Guardrail Use Guidelines, B/C = 2

Functional Class	**Width Class**	**Traffic Volume (1000 ADT)**				
		None	**TL-2**	**TL-3**	**TL-4**	**TL-5**
Freeway	Narrow			0-100		
	Wide			0-100		
Rural Arterial	Narrow		<20	>20		
	Wide		Any			
Rural Collector/Local	Narrow		Any			
	Wide	<1	>1			
Urban Arterial	Narrow		<20	>20		
	Wide		Any			
Urban Collector/Local	Narrow		Any			
	Wide	Any				

Table 16. Rolling Terrain Guardrail Use Guidelines, B/C = 2

Functional Class	**Width Class**	**Traffic Volume (1000 ADT)**				
		None	**TL-2**	**TL-3**	**TL-4**	**TL-5**
Freeway	Narrow				<25	>25
	Wide				<33	>33
Rural Arterial	Narrow			Any		
	Wide			Any		
Rural Collector/Local	Narrow		Any			
	Wide		Any			
Urban Arterial	Narrow			Any		
	Wide			Any		
Urban Collector/Local	Narrow		Any			
	Wide		Any			

Table 17. General Guardrail Use Guidelines, B/C = 3

Functional Class	Width Class	Traffic Volume (1000 ADT)				
		None	**TL-2**	**TL-3**	**TL-**	**TL-**
Freeway	Narrow			Any		
	Wide		<20	>20		
Rural Arterial	Narrow		<35	>35		
	Wide		Any			
Rural Collector/Local	Narrow	<1	>1			
	Wide	Any				
Urban Arterial	Narrow		<30	>30		
	Wide		Any			
Urban Collector/Local	Narrow		Any			
	Wide	Any				

Table 18. Rolling Terrain Guardrail Use Guidelines, B/C = 3

Functional Class	Width Class	Traffic Volume (1000 ADT)				
		None	**TL-2**	**TL-3**	**TL-4**	**TL-5**
Freeway	Narrow				<28	>28
	Wide			<37		>37
Rural Arterial	Narrow			Any		
	Wide			Any		
Rural Collector/Local	Narrow		Any			
	Wide		Any			
Urban Arterial	Narrow			Any		
	Wide			Any		
Urban Collector/Local	Narrow		Any			
	Wide		Any			

Table 19. General Guardrail Use Guidelines, B/C = 4

Functional Class	Width Class	Traffic Volume (1000 ADT)				
		None	TL-2	TL-3	TL-4	TL-5
Freeway	Narrow			Any		
	Wide		<28	>28		
Rural Arterial	Narrow		Any			
	Wide		Any			
Rural Collector/Local	Narrow	<1.5	>1.5			
	Wide	Any				
Urban Arterial	Narrow		<50	>50		
	Wide		Any			
Urban Collector/Local	Narrow	<2	>2			
	Wide	Any				

Table 20. Rolling Terrain Guardrail Use Guidelines, B/C = 4

Functional Class	Width Class	Traffic Volume (1000 ADT)				
		None	TL-2	TL-3	TL-4	TL-5
Freeway	Narrow			<19	19-37	>37
	Wide			<46		>46
Rural Arterial	Narrow			Any		
	Wide		<12	>12		
Rural Collector/Local	Narrow		Any			
	Wide		Any			
Urban Arterial	Narrow			Any		
	Wide		<12	>12		
Urban Collector/Local	Narrow		Any			
	Wide		Any			

6.2. Guideline Application

The route-specific guidelines shown in Tables 15 through 20 can only be implemented after a B/C ratio appropriate for guardrail application is identified. AASHTO or transportation agency administrators should provide highway designers with a recommendation on this subject. After the appropriate B/C ratio is identified, highway designers need only make three decisions in order to determine the guardrail test level appropriate for any given route.

The designer must first determine the type of terrain through which the highway passes. Recall that the terrain classifications are intended to represent the frequency and severity of roadside embankments found adjacent to the highway has characterized in Table 4. Highways in the flat terrain, or the general category, are expected to have very few severe roadside slopes and moderately severe slopes should not be common within the clear zone. A severe slope was represented in the RSAP analysis by a 26 ft (7.9 m) deep embankment with a slope of 1.5:1. A moderately severe roadside slope was represented by a 2:1 embankment that was 20 feet deep. Most of the slope hazards encountered along highways falling into the flat or general category should be flatter or shallower than the definition of a severe slope. It is anticipated that most highways will fall into the flat or general category.

Highways through rolling terrain are expected to have a high proportion of moderately severe and severe roadside slopes within the clear zone. A significant number of these hazards would be expected to be encountered adjacent to almost every mile of the roadway.

A designer must then identify the highway functional class associated with the route being evaluated. Most highway agencies have established functional classifications for all roadways and a designer need only match the agency classification with one of the five classifications included in this study, freeway, rural arterial, rural collector/local, urban arterial, and urban collector/local. Designers must then determine the size of the unobstructed zone adjacent to the highway under consideration. With the exception of bridges, the majority of other hazards to be treated with guardrail should fall outside of the unstructured zone.

After a B/C ratio has been selected and the type of terrain, highway functional class, and size of the unobstructed zone have been identified, a designer can determine the guardrail test level recommended for the highway under consideration directly from Tables 15 to 20. Consider for example a State DOT has selected a B/C ratio of 3 as appropriate for guardrail implementation and a designer needs to identify the barrier test level appropriate for a rural interstate with 25,000 ADT. If he examines the roadway topography and finds few severe or moderately severe slope hazards adjacent to the roadway and the majority of hazards are less than 18 ft (5.5 m) from the edge of the travel way, Table 17 would show that TL-3 guardrail is most appropriate.

7. SUPPLEMENTAL ANALYSIS PROCEDURES

The guardrail selection guidelines presented in the previous chapter can be used to determine the most appropriate guardrail test level for any highway route. Note that these guidelines are appropriate for hazards commonly found along roadways, such as fixed objects and slopes. Supplemental analysis is recommended when unusual hazards, such as deep vertical drops, bodies of water, or a severe slope along a relatively flat terrain, are found within the clear zone. The most accurate and most challenging supplemental procedure is to conduct an RSAP analysis of the specific site. However, this level of effort is not always possible or necessary.

The simplest supplemental analysis involves finding the scenario in Appendix A, B, or C that best fits the particular problem under consideration and reading the recommended solution directly from the appropriate table. Highway engineers should remember that, as mentioned above, when the recommended treatment moves back and forth between treatment options, the two alternatives should be considered economically equivalent. In this situation, designers should look for other criterion upon which to base guardrail test level selection.

Determination of the appropriate guardrail test level for hazards that are significantly more severe than a steep slope is not as straight forward. A simplified analysis can be developed provided the severity index for the new hazard can be estimated. The square of the ratio of severity indices for two hazards can be considered to be roughly proportional to the ratio of average accident cost. Note that increasing the average accident cost for a roadside hazard would produce a roughly proportionate increase in the calculated B/C ratio for guardrail treatment. Thus, if the ratio of severity indices can be estimated, it is possible to identify an effective B/C ratio for the less severe hazard that should provide an equivalent recommended safety treatment for as the more severe hazard at the normal B/C ratio. In this manner an effective lower B/C ratio selection table can be employed to estimate the appropriate treatment for a more severe hazard. The 1996 AASHTO Roadside Design Guide lists severities for a wide variety of hazards, including vertical drops, bodies of water and all hazards used in this study.

The first step in this supplemental analysis is to identify the appropriate comparison hazard from Table 4. The comparison hazard should be chosen first based on size and then severity. For example, a designer encountering a 33 ft (10 m) vertical drop off adjacent to a rural arterial should choose the 1.5:1, 26 ft (8 m) deep slope from Table 4 as the appropriate comparison hazard. Next the Severity Index ratio between the two hazards should be determined. The 1996 RDG shows that for a 100 km/h design speed, appropriate for a rural arterial, the ratio between the severity indices for a 33 ft (10 m) vertical drop and the 1.5:1, 26 ft (8 m) slope is found to be approximately 1.4. The square of this ratio is 1.96 or about 2. This means that the 1.5:1, 26 ft (8 m) slope hazard evaluated at a B/C ratio of approximately ½ of the normal value should provide the appropriate treatment for the more severe hazard situation. In this example, if the highway agency had selected to use a B/C threshold of 4.0, the designer would use site-specific guardrail selection tables for a B/C ratio of 2 instead. Appendix D, site-specific selection guidelines for a B/C ratio of 1.0 has been included to extend the application of this supplemental analysis.

8. CONCLUSIONS AND RECOMMENDATIONS

The performance level selection guidelines presented above should provide objective guidance to help designers determine the most appropriate guardrail test level for any route. Further, site-specific selection guidelines shown in Appendicies A, B, and C provide a more detailed set of guidelines when needed. The site- specific guidelines not only identify what guardrail test level should be incorporated, but also can be used to determine when guardrail use is not cost beneficial.

Supplemental procedures for identifying appropriate guardrail test levels have also been developed. These procedures should expand the applicability of the guardrail selection guidelines to many unusual hazards that cannot be included in development of general procedures. When other supplemental procedures cannot be employed, designers are encouraged to conduct a detailed B/C analysis using the RSAP program.

The guardrail selection guidelines described herein will enable highway engineers to make a more informed judgement regarding what guardrails should be used on any highway route. These procedures should provide an improved level of safety as well as more efficient expenditures of safety funds.

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