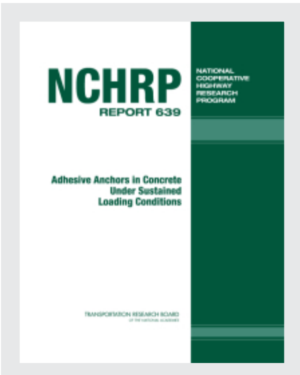

Guidelines for Guardrail Implementation

DETAILS

30 pages | 8.5 x 11 | PAPERBACK
ISBN 978-0-309-11781-4 | DOI 10.17226/14273

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP REPORT 638

Guidelines for Guardrail Implementation

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Subject Areas
Highway and Facility Design

Research sponsored by the American Association of State Highway and Transportation Officials
in cooperation with the Federal Highway Administration

TRANSPORTATION RESEARCH BOARD

WASHINGTON, D.C.
2009
www.TRB.org

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

NCHRP REPORT 638

Project 22-12(02)
ISSN 0077-5614
ISBN: 978-0-309-11781-4
Library of Congress Control Number 2009903448

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are available from:

Transportation Research Board
Business Office
500 Fifth Street, NW
Washington, DC 20001

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Printed in the United States of America

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The authors wish to acknowledge the National Cooperative Highway Research Program for sponsoring this project and the NCHRP Project 22-12 Panel for its guidance. A special thank you is also given to the following individuals at the Midwest Roadside Safety Facility who made a contribution to the completion of this research project:

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FOREWORD

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This report provides guidance on selecting the appropriate barrier performance level for the installation of longitudinal barriers. The report presents performance-level selection guidelines to help designers determine the most appropriate guardrail test level for any route. Further, 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 expand the applicability of the guardrail selection guidelines to many unusual hazards that cannot be included in development of general procedures. The report will be of particular interest to designers with responsibility for designing roadside safety features.

Recent research has promoted the concept of matching highway-safety features to the type of roadway facility and its traffic conditions. According to NCHRP Report 350: Recommended Procedures for the Safety Evaluation of Highway-Safety Features, a safety feature may be developed to meet one of up to six test levels, depending on the type of feature. Further, a feature may be designed for temporary (work zone) or permanent applications. Under this concept, features developed for the lower test levels, which have minimal containment capabilities for heavier vehicles, may be considered applicable for low-speed, low-volume conditions. While the test levels have been defined, recommended guidelines for their application have only been developed for bridge rails. Transportation agencies (federal, state, and local) are being required to make decisions on the use of features without guidelines on the appropriateness of highway-safety features including permanent and temporary traffic barriers, crash cushions, terminals, truck-mounted attenuators, breakaway supports, rumble strips, and cross-sectional elements for specific conditions.

The AASHTO Roadside Design Guide (RDG) provides general guidelines to assist design personnel in determining when specific highway-safety features may be needed. The RDG presents these guidelines in terms of roadside terrain features, traffic volumes, design speed, accident probability, and environmental conditions. It does not, however, provide guidance on the specific type of highway-safety feature most appropriate for combinations of these conditions. Objective guidelines are needed not only to identify site conditions where a safety feature is required but also to identify the most appropriate feature for that site. The guidelines should take into account roadway and traffic conditions, and the characteristics of candidate features (e.g., impact performance, life-cycle costs, durability, and maintainability). Inappropriate selection of a highway-safety feature at a particular site can be detrimental to the overall safety of the roadway or wasteful of scarce resources.

Under NCHRP Project 22-12(2), "Selection Criteria and Guidelines for Highway Safety Features," the University of Nebraska-Lincoln used a benefit-cost analysis procedure to develop general guidelines for guardrail implementation. The safety treatment options to be evaluated were identified as well as the relevant parameters needed to describe each alternative, including safety treatment layout, construction costs, and accident severities. 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 were also identified. 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 Roadside Safety Analysis Program (RSAP) was used to analyze each hazard scenario under a wide variety of roadway and traffic characteristics. These RSAP runs were then tabulated and used to 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 levels for each of five different highway functional classes as a function of traffic volume.

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CHAPTER 1

Introduction

The goal of roadside safety devices is to protect motorists from potentially serious hazards located near the travelway. Bridge piers, utility poles, and severe embankments are hazards that, if encountered, may 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 crash when vehicles leave the road in advance of the barrier. Unfortunately, barriers also pose a risk to motorists. In fact, guardrails cause approximately 1,200 fatalities along the nation's highways annually. Further, crash data analysis indicates that approximately 13% of reported guardrail crashes involve rollover and almost 2% 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 a need for an optimum guardrail selection criterion that will produce a minimum number of injury and fatal crashes.

Guardrail warrant recommendations contained in the AASHTO *Roadside Design Guide* (*RDG*) (*2*) are based on relative severity indices, which were determined by making a subjective evaluation of the relative severities 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 (i.e., "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 help reduce or eliminate inconsistencies and provide optimal safety for all motorists and minimize the number of serious crashes 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, NCHRP funded the study described herein.

Objectives

The objectives of the research included the following:

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.

CHAPTER 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 crash 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 (*3*). 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 crashes that would occur with or without the barrier. This approach recommends that a 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 crash. In order to improve the efficiency of safety expenditures, the relative severity method for guardrail warranting has normally been restricted to high-volume, high-speed roadways (*4, 5*).

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 (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 (*6*). 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-off-road crashes. There are two basic approaches to estimating the frequency and severity of ran-off-road crashes: crash data and encroachment probability (*2*).

Methods based on crash data utilize historical crash reports to predict future crash frequencies. These techniques fall into two different categories: site-specific and route-specific analyses. Techniques based on site-specific crash data rely on the crash history at a given location for estimating the frequency and severity of future crashes at that location. Local crash histories intrinsically incorporate the effects of all highway, roadside, and local land-use characteristics for the site under consideration. Thus, whenever crash 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 crash history at a site does not mean there is no risk of future crashes. 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 crash data is available.

The second approach based upon crash data incorporates regional and national crash 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 crash 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 crash frequencies can be generated to develop the needed regression models. Further, the hazard-specific nature of ran-off-road crashes requires that regionally based crash models be developed for every type of hazard and every safety treatment alternative to be evaluated. These limitations generally render regional or national crash-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 simulated randomly, 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 are then estimated by multiplying encroachment frequency by the average crash 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 crash 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 dataset 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 that are free from the influence of winter driving conditions. Wherever possible, the effects of these additional factors have been quantified using crash 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 (*2*). Nevertheless, encroachment probability analysis remains the most appropriate method for developing general guidelines for safety hardware application.

Encroachment Probability Models

As stated previously, the objective of an encroachment probability model is to relate roadway and traffic characteristics to the expected crash 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 that 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 crash studies.

Adjusted encroachment frequency must then be linked to the crash 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 as follows:

$$P\left(H_{v\psi}^{w\theta} \middle| E_{v\psi}^{w\theta}\right) = (1/5280) * \left[L_h + (W_v/\sin\theta) + W_h \cot\theta\right] \quad (1)$$

where

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

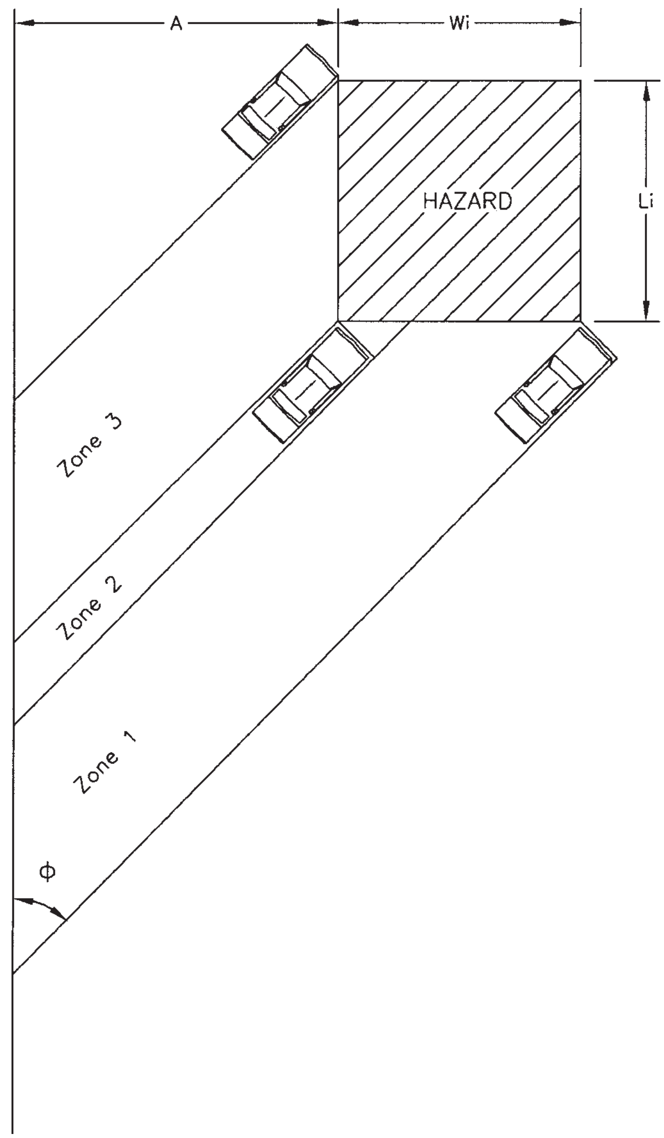
L_h = Length of hazard (ft),

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

L_v = Length of vehicle (ft),

W = Width of vehicle (ft), and

W_h = Width of hazard (ft).



Source: Glennon, J. C., *NCHRP Report No. 148: Roadside Safety Improvement Programs on Freeways—A Cost-Effective Priority Approach,* Transportation Research Board of the National Academies, Washington, D.C., 1974.

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

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

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, and

$P(L_e \geq C)$ = 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, sizes, encroachment angles, and speeds as shown in Equation 3 as follows:

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

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; and

$P(C^{w\theta}_{v\psi}|E^{w\theta}_{v\psi})$ = 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.

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

where

CC = Estimated annual crash cost;

E_f = Annual encroachment frequency; and

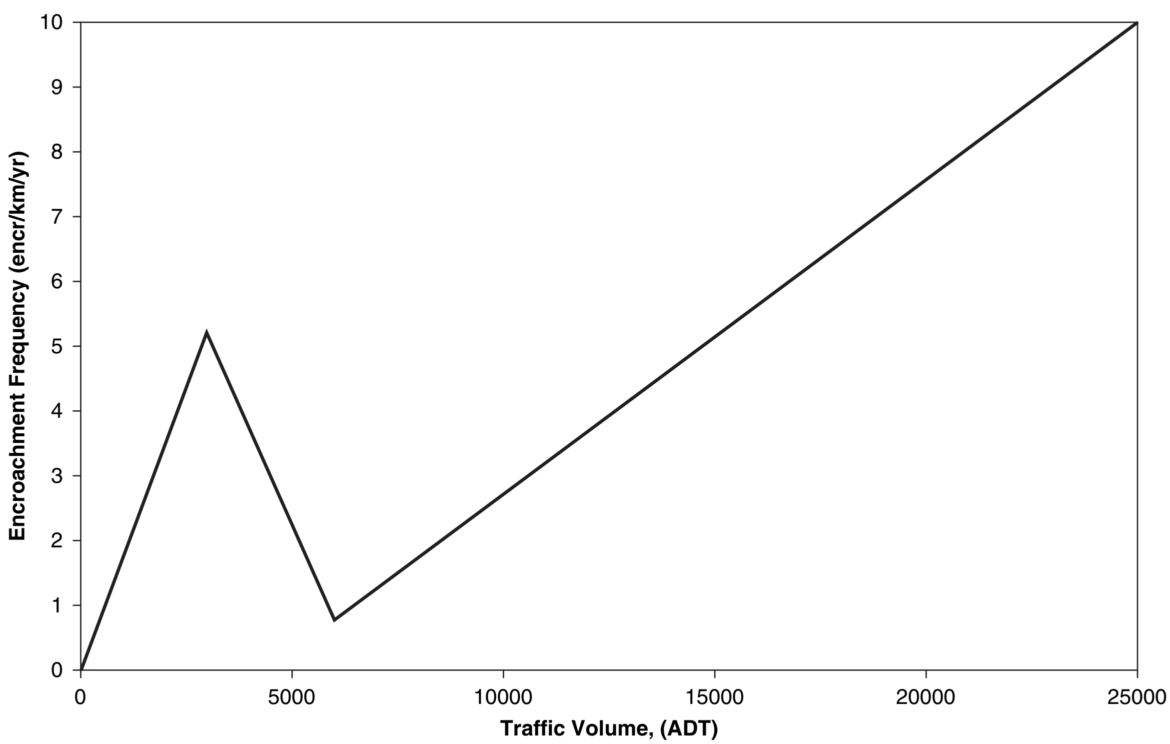
$AC(C^{w\,\theta}_{v\,\Psi})$ = Crash cost of a collision involving a given vehicle type w, speed v, angle θ, and vehicle orientation Ψ.

Crash costs are normally calculated via 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 crash 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 crash costs are summarized in the following sections.

Encroachment Characteristics

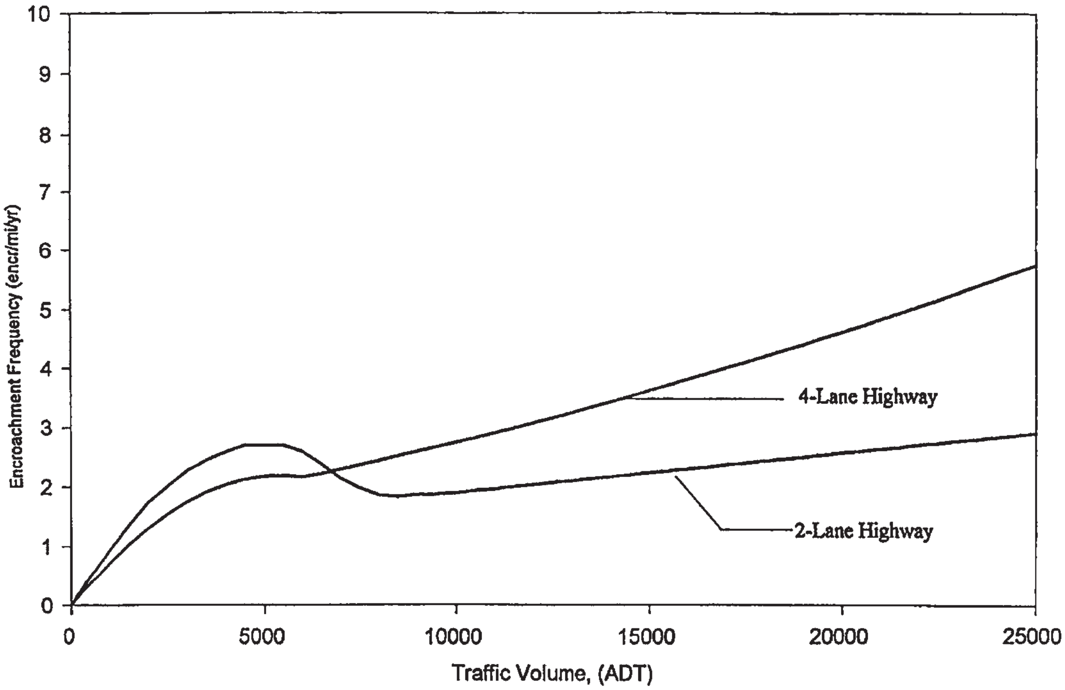
There are only three previous studies on encroachment data: Hutchinson and Kennedy (*7*), Cooper (*8*), and Calcote et al. (*9*). The Hutchinson and Kennedy study involved observations of wheel tracks on medians of rural interstate highways in Illinois in the mid-1960s. The Cooper study examined wheel tracks on roadsides of Canadian highways during summer time in the late 1970s. Calcote et al.'s research effort used electronic monitoring along rural highways and time-lapse video photography along urban freeways. As shown in Figures 2 and 3, both the Hutchinson and Kennedy and Cooper 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 3,000 to 8,000 ADT (average daily traffic). 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.

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 controlled versus uncontrolled encroachments based purely on tire track evidence. Therefore, all tire tracks were recorded and assumed to be uncontrolled. Most of the



Source: Hutchinson, J.W., and Kennedy, T.W., "Medians of Divided Highways—Frequency and Nature of Vehicle Encroachments," *Engineering Experiment Station Bulletin 487*, University of Illinois, June 1966.

Figure 2. Encroachment rates.



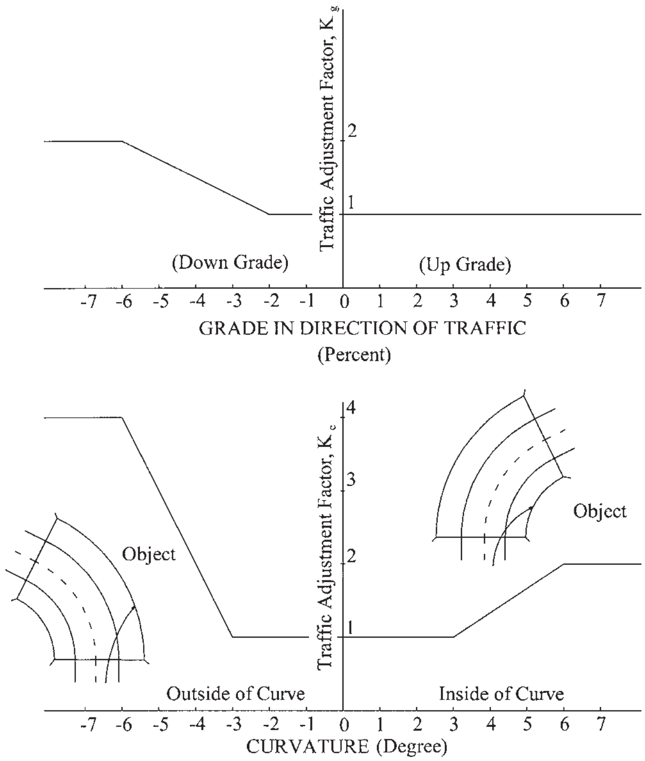
Source: Cooper, P., *Analysis of Roadside Encroachments—Single-Vehicle Run-off-Road Accident Data Analysis for Five Provinces*, B.C. Research, Vancouver, British Columbia, Canada, March 1980.

Figure 3. Encroachment rates.

median shoulders included in the Hutchinson and Kennedy study were on the order of 4 to 6 ft (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, and 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, but 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 was 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 then 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 was collected during summer months when traffic volumes are generally higher and winter driving conditions do not influence encroachment frequencies.

Calcote et al. attempted to overcome the major problems with both the Cooper and Hutchinson and Kennedy studies, namely, some encroachments are not detected due to paved shoulders and that controlled and uncontrolled encroachments are indistinguishable with observing tire tracks (*7, 8*). This research effort used electronic monitoring along rural highways and time-lapse videography 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. Crash 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



Source: Wright, P.H., and Robertson, L., "Priorities for Roadside Hazard Modification: A Study of 300 Fatal Roadside Object Crashes," *Traffic Engineering*, Vol. 46, No. 8, August 1976.

Figure 4. Encroachment frequency adjustment factors for curvature and grade.

for adjustment of encroachment rates for horizontal curvature and vertical grade is a study by Wright and Robertson (*10*). This study analyzed 300 single-vehicle, fixed-object fatal crashes in Georgia and compared fatal crash sites with control sites that were 1 mi 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% of the fatal crashes on curves. Downgrades of 2% 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.

Mak performed an analysis of real-world impact conditions using reconstructed crashes (*11*). 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 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

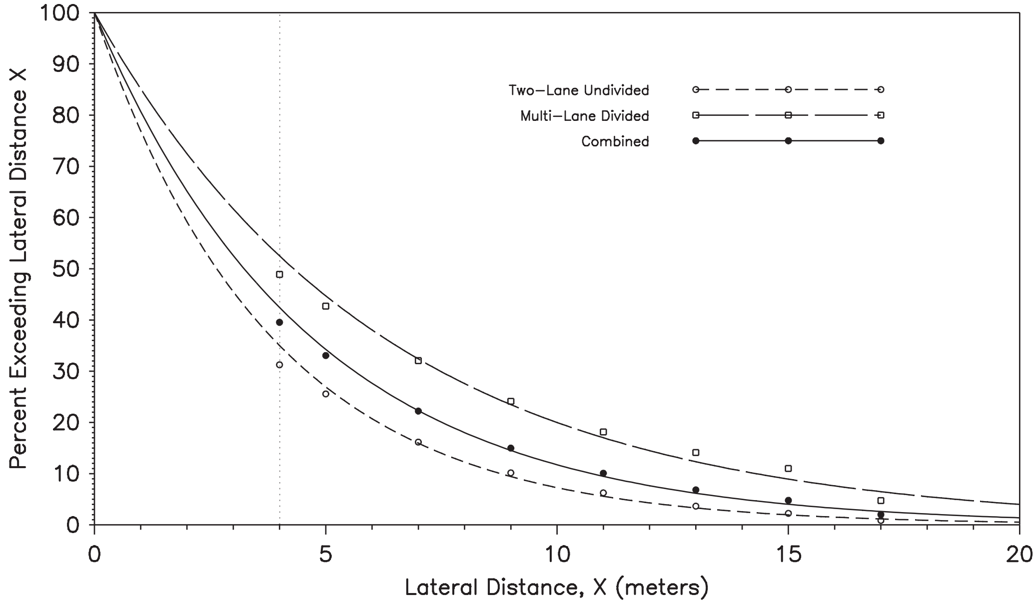
Y = Percent exceeding lateral distance X,
X = Lateral distance, and
a, b = Regression coefficients.

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

The increase in the y-intercept above 100% may 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

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



Source: Mak, K., and Sicking, D., *NCHRP Report No. 492: Roadside Safety Analysis Program (RSAP)—Engineer's Manual*, Transportation Research Board of the National Academies, Washington, D.C., 2003.

Figure 5. RSAP lateral extent of encroachment distributions.

for encroachment frequency to correct for under-reporting can be obtained by multiplying the Y-intercept by the fraction of observed encroachments that were in excess of 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.

Crash Costs

Encroachment-probability-based economic models must calculate the costs of each predicted crash. A crash severity is assigned for each predicted crash 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 RSAP 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

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

Key:
PDO1: Property Damage Only (Level 1); PDO2: Property Damage Only (Level 2); C: Possible or Minor Injury; B: Moderate Injury; A: Severe Injury; and K: Fatal Injury.

probability of injury produces a nonlinear relationship between crash severity and impact speed.

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 crash. 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 crash. 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. Equation 6 provides a calculation for IS.

$$IS = \frac{1}{2} m \left(V \sin\theta \right)^2 \tag{6}$$

If feature penetration is predicted, 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 crash cost.

RSAP also incorporates a rollover algorithm to identify impact conditions under which a vehicle is likely to roll over 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 crashes than non-rollover impacts.

RSAP severity estimates are largely based upon SI values presented in Appendix A of the 1996 AASHTO *RDG* (*2*). Note that the SI tables in this document are tabulated by highway design speed. Speed relationships for SI versus impact 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 resolve 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.

Table 3. Standardized cost values.

Crash Severity	*Roadside Design Guide* Cost ($)	FHWA Comprehensive Cost ($)
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

The final step in the process of calculating crash 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 another with values recommended by FHWA.

Solution Method

Traditional encroachment probability models utilize a deterministic solution scheme. In other words, these methods calculate crash 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 approach for calculating overall crash 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 crash 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 the Monte Carlo approach, involves randomly simulating encroachments along the roadside and calculating the resulting crash 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 crash costs at a site.

Although the Monte Carlo approach provides a 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 crashes. Therefore, it was selected for use in the development of guardrail implementation guidelines.

Benefit-to-Cost Analysis

The primary objective of an encroachment probability crash prediction model is to compare the various safety improvement options (*12*). 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 crashes. Direct costs of a safety improvement include initial installation, maintenance, and crash 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 crash costs associated with alternative i, and
DC_i = Direct costs associated with alternative i.

Generally, Alternative 2 is 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 but 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.

CHAPTER 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 crash 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 program known as RSAP was used to analyze each hazard scenario under a wide variety of roadway and traffic characteristics. These RSAP runs were then tabulated and used to 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 levels for each of five different highway functional classes as a function of traffic volume.

Application examples of the general route-specific guidelines were prepared and documented along with situations that may warrant a more detailed analysis. Procedures for implementing a more detailed analysis also were 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.

CHAPTER 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 crash costs, guardrail layout, and traffic characteristics. The process used to develop the needed RSAP input data is summarized as follows.

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 (such as roadside culverts), and long hazards (such as steep roadside slopes). Previous benefit-to-cost analysis studies of guardrails 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 a steep roadside embankment, the ratio of guardrail impacts to hazard crashes prevented may approach 1.0. In this situation, the reduced severity of guardrail crashes relative to crashes involving a hazard generally make barrier implementation much more cost beneficial.

The crash severity of roadside hazards also can 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 hazard 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 hazards are 4,000 ft (1,219.2 m) long. Specific hazards selected for each of the six categories are shown in Table 4.

Safety Improvement Options and Costs

In order to design any guardrail installation, it is necessary to identify the guardrail, terminal test level, and 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 *RDG* (*13*). 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 Test Levels 1 or 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

Table 4. Hazard categories.

Category	Severe	Moderately Severe	Moderate
Point Hazard	3-ft (.9144-m) diameter bridge pier	10-in. diameter utility pole	6-in. diameter tree
Slope Hazard	1.5:1 slope, 26 ft (7.9248 m) deep	2:1 slope, 20 ft (6.096 m) deep	2.5:1 slope, 13 ft (3.9624 m) deep

and a comprehensive set of guardrail treatment guidelines, 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 TL-3 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 statewide bid tabulations for seven geographically diverse states. The resulting average costs for the various barriers and terminals are shown in Table 5.

Estimates of transition systems for TL-4 and TL-5 barriers were identified. Again, costs for transitions from a concrete TL-5 barrier to a TL-3 guardrail terminal were 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).

Guardrail Layout

When designing a roadside barrier layout, an engineer must identify the variables shown in Figures 6 and 7, including the following:

Table 5. Costs of guardrails and terminals.

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

- Lateral extent of the hazard, L_A,
- Runout length, L_R,
- Offset to the face of the barrier, L_2,
- Offset to the hazard, L_3, and
- Flare rate of the guardrail in advance of the hazard.

In Figure 7, L_s is the offset to slope variable. 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.

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 greatly reduce the benefit of implementing a flare configuration, which is 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 or costs of utilizing a 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

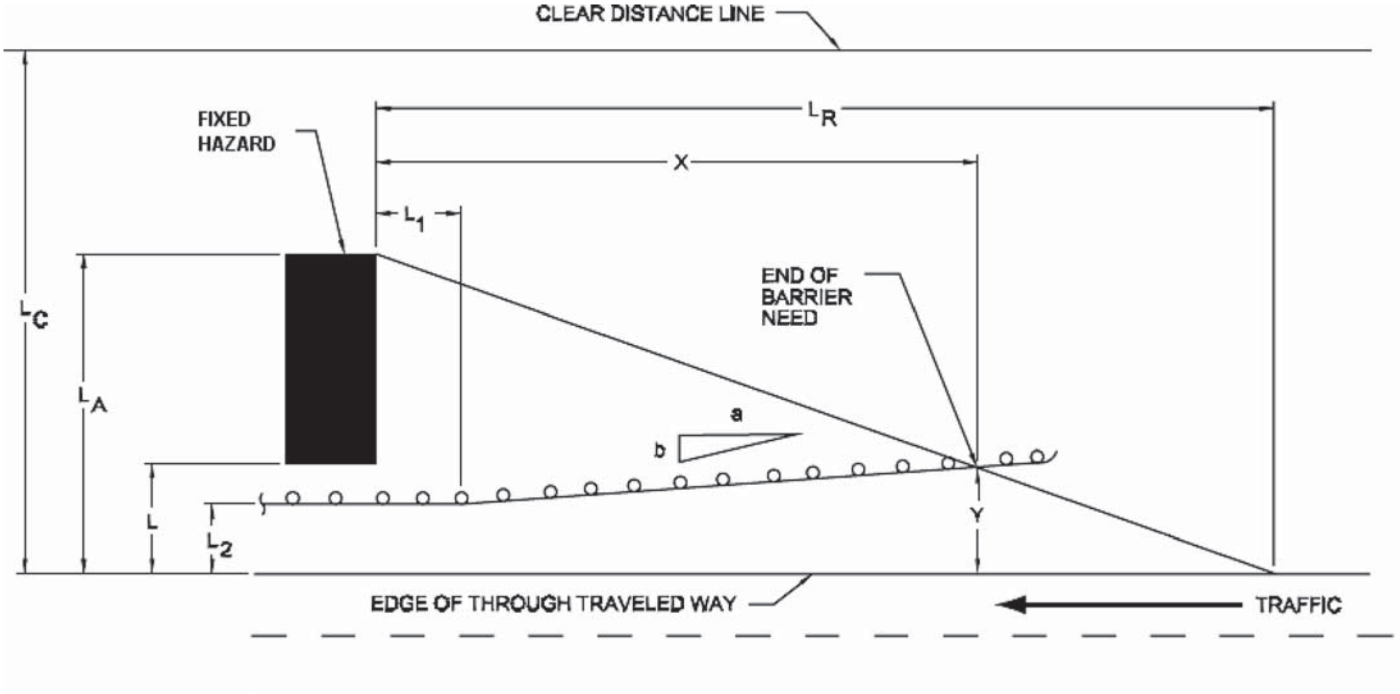


Figure 6. Barrier layout variables for point hazards.

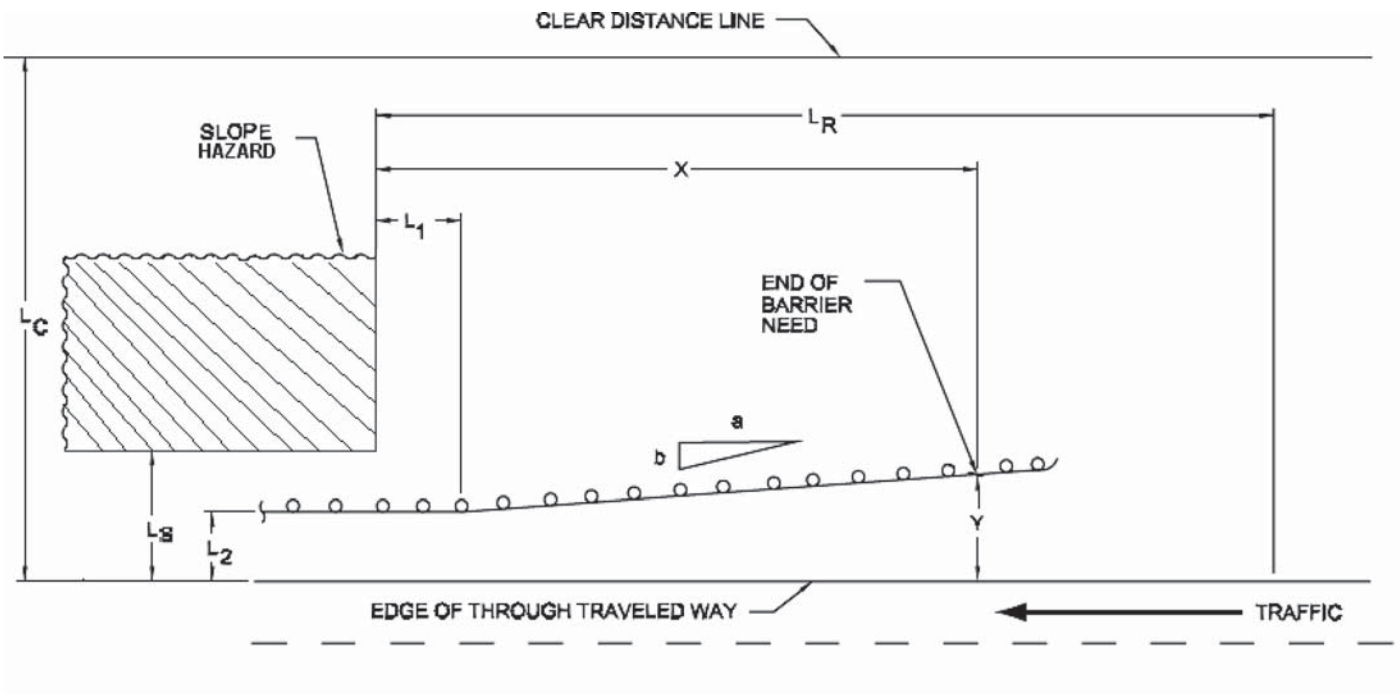


Figure 7. Barrier layout variables for slope hazards.

Table 6. Runout length, L_r.

Design Speed in mph (km/h)	Runout Length (L_R) 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)

Source: Sicking, D.L., and Wolford, D.F., "Development of Guardrail Runout Length Calculation Procedures," NDOR Research Project Number SPR-PL-1(3) P479, University of Nebraska, Lincoln, May 1996.

collected by Hutchinson and Kennedy (*7*) or Cooper (*8*). *RDG* procedures are based upon Hutchinson and Kennedy's longitudinal encroachment length data. Cooper's encroachment length data produced runout lengths that are approximately one-third shorter than those recommended in the *RDG.* A 1996 study (*14*) 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 (*15*) from ran-off-road crashes on high-speed roadways 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.

Crash Costs

Transportation agencies primarily utilize one of two sets of crash costs, *RDG* or FHWA values. *RDG* values are generally considered to be representative of the direct costs of highway crashes; 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 crash 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 crash costs.

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

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 the following 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

Table 8. Minimum design standards.

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

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.

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 a greater effect in one direction than the other. Curves to the left and negative grades have a 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 downgrade 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 ft (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 was to develop general guidelines for guardrail application. In order to develop these guidelines, it is 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.

Functional Class	Hazard Offset	Curvature	Grade (percent)	Slope Offset	Volume (1,000 ADT)
Freeway	7,12,18,26,32	0,2L	0,-2	12,18,20	10-100
Rural Arterial	5,8,12,18,24	0,4L	0,-3	12,18,20	5-80
Rural Local/Collector	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 Local/Collector	5,8,12,18,24	0,10L	0,-6	3,6,12	0.5-5

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 and 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

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 (*16*) 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.

CHAPTER 5

Benefit/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 SI for guardrail impact was 3.2. When compared to findings from crash 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 crash data. NHTSA's *Traffic Safety Facts* (*17*) was the first source of guardrail crash severity examined. Published annually, the *Traffic Safety Facts* 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 low. 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 crashes RSAP attempts to predict and include both reported and unreported crashes.

RSAP predictions were also compared to guardrail crash severities from Kansas crash records from 2002 through 2006. The Kansas crash 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 crashes were identified that met the criteria.

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

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 crashes. Although crash severities with all three barrier types were found to be somewhat similar, 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 crash data, injury distributions were converted into crash 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 considering that RSAP predictions include unreported crashes, the program's average crash costs are quite excessive. Excessive crash severity estimates for guardrails would make the use of guardrails much less cost beneficial by overestimating the number of injuries and fatalities associated with barrier crashes.

The magnitude of unreported crashes varies widely, ranging as low as 10% to as high as 80%. A recent study (*18*) of cable median barrier crashes and repairs in Missouri found 4,386 reported crashes and 5,939 barrier repairs. If all repair events are assumed to arise from unreported crashes, this data would indicate that approximately 26% of all barrier impacts

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

go unreported. 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 crashes. Hence, it can be argued that less than 26% of guardrail crashes go unreported (*19, 20*).

Uncertainties, such as the magnitude of unreported guardrail crashes, 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% 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.

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 was 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 (not provided herein).

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 RSAP 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 crash 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

Table 12. Barrier crash severities and 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

Table 13. Guardrail use guidelines for 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

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* (*21*) 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 (not provided herein) 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.

CHAPTER 6

Route-Specific Selection Guidelines

The first step in converting the site-specific guardrail selection guidelines shown in Appendices A, B, and C (not published herein) 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 in the following sections.

Findings

Functional Class

Highway functional class was found to have a major impact on the need for higher performance barriers. RSAP uses highway functional class as a surrogate for operating speed. This approach is based on a study by Mak, Sicking, and Ross (*22*) 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 to penetrate through or over the top of a guardrail system. Thus the benefit of using higher, stronger barriers would be expected to increase significantly when a higher functional class raises predicted encroachment speeds. This effect is clearly observed when guardrail selection guidelines for freeways are compared to guidelines for 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 (not presented herein), 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 ft (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 (not presented herein), TL-4 barriers dropped off the table, and TL-5 barriers did 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 or 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. When a vehicle penetrates through a barrier immediately adjacent to an obstacle, however, 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 travelway.

Thus, the potential benefit of installing guardrail diminishes as hazards are moved further from the travelway. A 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 immediately 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 increases significantly, and both the cost of the guardrail installation and the number of impacts with the barrier increase proportionately. For long hazards, the site-specific guardrail selection guidelines do not show that 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 that, for very high offsets, made no treatment the most cost beneficial alternative, even on freeways.

Offset to Slope

This parameter is the distance from the edge of travelway to the beginning of a moderate roadside slope. Although these slopes can cause some crashes, 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, if a modest roadside slope begins at the edge of the shoulder, the guardrail must be placed very near the travelway. 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 using 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 reduced calculated B/C ratios when the barrier was moved closer to the roadway. Overall, the offset to slope 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 are studied, a 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 is found. A barrier is found to be less cost beneficial when protecting motorists from point hazards placed outside of a curve. 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 applications was found to be very limited. RSAP adjusts encroachment frequency upward to account for the effect of a down grade. An increase in encroachment frequency should translate into greater benefits for barrier installation. However, the effect 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.

Guideline Development

As summarized previously, 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 of 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 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.

Over the last 40 years, implementation of clear-zone policy has produced a largely unobstructed region immediately adjacent to most modern roadways. Most roadside hazards

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)

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 (not found herein). 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.

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. As described in this section, after the appropriate B/C ratio is identified, highway designers need only make three decisions—determine the type of terrain, identify the highway functional class, and establish size of the unobstructed zone—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 as characterized in Table 4. Highways in 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 ft 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.

Table 15. General guardrail use guidelines, B/C = 2.

Functional Class	Width Class	Traffic Volume (1,000 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 (1,000 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 (1,000 ADT)				
		None	TL-2	TL-3	TL-4	TL-5
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 (1,000 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			

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.

Table 19. General guardrail use guidelines, B/C = 4.

Functional Class	Width Class	Traffic Volume (1,000 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 (1,000 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			

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, that 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 the designer 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 travelway, Table 17 would show that a TL-3 guardrail is the most appropriate. This example shows how the guidelines are to be used but is not situation specific. The following example gives specific numbers to walk a user through each step in the guardrail selection process.

A state has determined that safety projects should begin to be funded when the B/C ratio reaches 4.0. A rural freeway within the state crosses through an area of rolling hills with an average of more than four moderately severe or severe roadside slopes per mile. Further, the freeway has a somewhat constricted right-of-way and most of the roadside hazards are within 18 ft (5.5 m) of the travelway. The design year traffic volume of the highway is 20,000 ADT.

Because of the frequency of moderately severe and severe roadside slopes, the appropriate guardrail test level for this roadway can be determined from Table 20. The first row in this table represents freeways with narrow clear areas. As shown in this row, a traffic volume of 20,000 ADT falls under the TL-4 column. Thus, TL-4 guardrails should be used on this route.

CHAPTER 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 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 (not provided herein) 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 criteria 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 SI for the new hazard can be estimated. The estimated SI can be used to identify an average crash cost using Tables 2 and 7. A hazard can then be chosen from Table 4 that has a similar geometry and its average crash cost can be calculated using these same tables. The ratio of crash costs between the severe hazard and the similarly configured hazard from Table 4 can then be determined. Note that increasing the average crash cost for a roadside hazard should produce a roughly proportionate increase in the calculated B/C ratio for guardrail treatment. Thus, using the ratio of average crash costs, it is possible to identify an effective B/C ratio for the less severe hazard that should provide an equivalent recommended safety treatment for 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. For example, if a highway agency selects a B/C threshold of 4.0 and the ratio of crash costs is approximately 2, a designer could use site-specific guardrail selection tables for a B/C ratio of 2 to accurately determine the appropriate barrier test level. Appendix D (not provided herein), which provides site-specific selection guidelines for a B/C ratio of 1.0, extends the application of this supplemental analysis.

Supplemental Analysis Examples

Example 1

Consider a 33-ft (10-m) deep vertical drop that is placed 22 ft (6.7 m) from a rural arterial highway with a design speed of 70 mph (113 km/hr) and a traffic volume of 5,500 ADT. Further, assume that the highway agency had determined that safety projects should begin to be funded at a B/C ratio of 3.0. For this example, the roadway is a assumed to be straight and flat and the roadside slope leading to the drop-off begins at 10 ft (3.0) from the travelway.

The first step in a supplemental analysis of this extremely severe hazard is to identify the appropriate comparison hazard from Table 4. The comparison hazard should be chosen first based on geometry, measured in terms of length and width, and then severity. In this case, the geometry of a vertical drop-off compares most closely with a steep slope. Thus, the 1.5:1, 26-ft (8-m) deep slope from Table 4 was chosen as the appropriate comparison hazard. Next, the SI for both the actual hazard and the comparison hazard are found in Tables A.13.2 and A.13.1 from the 1996 *RDG* (*2*). The average SI over all surface conditions for the 1.5:1 slope is found to be 6.8 while the SI value of the vertical drop, assuming no water at the bottom, was found to be 9.3.

The average crash cost for these two hazards was then calculated using Tables 2 and 7. Note that linear interpolation was used to estimate probability of injury values from Table 2 and PDO1 and PDO2 categories are assumed to both have average costs of $2,575 as shown in Table 7. The average crash costs were found to be $2.75 million and $0.99 million for the vertical drop-off and steep slope, respectively. The ratio of crash costs was then calculated to be 2.77. When the highway agency threshold B/C value of 3.0 is divided by 2.77, the resulting threshold B/C value for this example is 1.1. The appropriate barrier test level can then be determined by examining Table D7 (not provided herein), which presents RSAP results for a 1.5:1 slope adjacent to a rural arterial when the threshold B/C value is 1.0. Table 21 provides the section of Table D7 that shows Lines 13 and 14, which correspond to a hazard that is placed 18 ft (5.5 m) from the travelway and a roadside slope that begins at 8 and 12 ft (2.4 and 3.7 m) from the highway edgeline. Similarly, Lines 24 and 25 correspond to a hazard that is placed 26 ft (7.9 m) from the travelway and a roadside slope that begins at 8 and 12 ft (2.4 and 3.7 m) from the highway edge line. Because all four lines indicate that TL-3 is the appropriate test level, there is no need for further evaluation. However, if different barriers had been shown for these four lines, engineering judgment would have been necessary to select the appropriate test level. In this case, the barrier class recommended by Line 24 would likely have been most appropriate because the B/C ratio used to develop the table was 1.0 and the target B/C ratio was 1.1. Using a reduced B/C ratio generally has a greater effect on an RSAP analysis than small changes in hazard or slope offset.

Example 2

Consider an irrigation canal adjacent to a rural local/collector highway with a traffic volume of 900 ADT and a design speed of 60 mph (96.5 km/hr). The water in the canal is normally 13.1 ft (4.0 m) deep and it is only 10 ft (3.0 m) from the edge of the travelway. The roadside slope begins at the edgeline and the roadway is relatively straight. Further, assume that the highway agency had determined that safety projects should begin to be funded at a B/C ratio of 2.0.

The comparison hazard chosen for this example must first be chosen based upon geometry. The geometry and severity of a canal again matches most closely to a steep slope. Thus, the 1.5:1, 26-ft (8-m) deep slope from Table 4 was chosen as the appropriate comparison hazard. Next the SI for both the actual hazard and the comparison hazard are found from Tables A.13.2 and A.13.1 from the 1996 *RDG* (*2*). The average SI over all surface conditions for the 1.5:1 slope adjacent to a highway with a 100 km/hr (62 mph) design speed was found to be 6.3 while the SI value of a water depth of 13.1 ft (4 m), assuming no vertical drop, was found to be 7.2.

The average crash cost for these two hazards was then calculated using Tables 2 and 7 using linear interpolation as dis-

Table 21. Excerpt from guardrail use guidelines for rural arterial (Appendix D, Table D7).

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			2.5-50		
7	0	-3	8			2.5-50		
7	4L	0	8			2.5-50		
7	4L	-3	8			2.5-50		
12	0	0	8			2.5-50		
12	0	0	12			2.5-50		
12	0	-3	8			2.5-50		
12	0	-3	12			2.5-50		
12	4L	0	8			2.5-50		
12	4L	0	12			2.5-50		
12	4L	-3	8			2.5-50		
12	4L	-3	12			2.5-50		
18	0	0	8			2.5-50		
18	0	0	12			2.5-50		
18	0	0	20			2.5-50		
18	0	-3	8			2.5-50		
18	0	-3	12			2.5-50		
18	0	-3	20			2.5-50		
18	4L	0	8			2.5-50		
18	4L	0	12			2.5-50		
18	4L	0	20			2.5-50		
18	4L	-3	8			2.5-50		
18	4L	-3	12			2.5-50		
18	4L	-3	20			2.5-50		
26	0	0	8			2.5-50		
26	0	0	12			2.5-50		

Table 22. Excerpt from guardrail use guidelines for rural LC (Appendix D, Table D13).

Rural LC Severe Slope Functional Class				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
5	0	0	3		0.5-5			
5	0	0	6		0.5-5			
5	0	-6	3		0.5-5			
5	0	-6	6		0.5-5			
5	10L	0	3	0.5-0.95	0.95-5			
5	10L	0	6	0.5-2.3	2.3-5			
5	10L	-6	3		0.5-5			
5	10L	-6	6	0.5-0.95	0.95-5			
8	0	0	3		0.5-5			
8	0	0	6		0.5-5			
8	0	0	12		0.5-5			
8	0	-6	3		0.5-5			
8	0	-6	6		0.5-5			
8	0	-6	12		0.5-5			
8	10L	0	3	0.5-1.85, 2.75-4.1	1.85-2.75, 4.1-5			
8	10L	0	6	0.5-1.85	1.85-5			
8	10L	0	12	0.5-0.95	0.95-5			
8	10L	-6	3	0.5-1.85	1.85-5			
8	10L	-6	6		0.5-5			
8	10L	-6	12		0.5-5			
12	0	0	3		0.5-5			

cussed in the prior example. The average crash costs were found to be \$1.2 million and \$0.78 million for the vertical drop-off and steep slope, respectively. The ratio of crash costs was then calculated to be 1.5. When the highway agency threshold B/C value of 2.0 is divided by 1.5, the resulting threshold B/C value for this example is 1.3. The appropriate barrier test level can then be determined by examining Table D13 (not provided herein), which presents RSAP results for a 1.5:1 slope adjacent to a rural local/collector when the threshold B/C value is 1.0. Table 22 provides the section of Table D13 that shows Row 9, which corresponds to a hazard that is placed 8 ft (2.4 m) from the travelway and a roadside slope that begins at 3 ft (0.9 m) from the highway edgeline. Similarly, Line 21 corresponds to a hazard that is placed 12 ft (3.7 m) from the travelway and a roadside slope that begins at 3 ft (0.9 m) from the highway edgeline. Because both lines indicated that TL-2 is the appropriate test level, there is no need for further evaluation. However, if there had been different barriers shown for these lines, engineering judgment would have been necessary to select the appropriate test level with the lowered B/C threshold from a target value of 1.3 to the table value of 1.0 carrying the greatest importance.

CHAPTER 8

Conclusions and Recommendations

The performance level selection guidelines presented in this report should provide objective guidance to help designers determine the most appropriate guardrail test level for any route. Further, site-specific selection guidelines shown in Appendices A, B, C, and D (available from NCHRP for a limited time but not provided herein) 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 also have been developed. These procedures should expand the applicability of the guardrail selection guidelines to many unusual hazards that can not be included in development of general procedures.

It is important to note that the guidelines contained herein are not intended to address unusually dangerous hazards, such as deep water or high vertical dropoffs. Neither the general guidelines, nor the supplemental procedures described herein can be employed to evaluate these unusually severe hazards. In these situations, 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 judgment regarding which 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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Appendices

The following appendices are not published herein but are available for a limited time, from the National Cooperative Highway Research Program.

- Appendix A, Guardrail Use Guidelines for Benefit/Cost = 2
- Appendix B, Guardrail Use Guidelines for Benefit/Cost = 3
- Appendix C, Guardrail Use Guidelines for Benefit/Cost = 4
- Appendix D, Guardrail Use Guidelines for Benefit/Cost = 1

Abbreviations and acronyms used without definitions in TRB publications:

AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	Air Transport Association
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation