A Benefit-Cost Analysis Tool for Assessing Guardrail Needs for Two-Lane Rural Roads in Virginia

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JUSTICE APPIAH, Ph.D.
Research Scientist

BENJAMIN H. COTTRELL, JR., P.E.
Associate Principal Research Scientist

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530 Edgemont Road, Charlottesville, VA 22903-2454
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16. Abstract:

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This study developed such an approach, focusing on low volume, two-lane rural roadways in Virginia. The Roadside Safety Analysis Program (RSAP)—developed under NCHRP Project 22-27 and currently the most sophisticated tool available for conducting cost-effectiveness analysis of roadside safety treatment options—was used to determine expected crash frequencies, severities, and costs for several combinations of hazard scenarios; guardrail treatment options; and relevant roadway, roadside, and traffic characteristics. The results of the RSAP analysis were used to develop a predictive model that relates the input variables to the output response (benefit/cost ratio). The model is implemented in a simple spreadsheet for the quick and efficient evaluation of proposed guardrail treatment options without the need for full-blown RSAP analysis. Application of the spreadsheet tool is demonstrated through example problems.

A comparison of the tool's modeling results with results obtained from RSAP is presented. The comparative results show that benefit/cost ratio estimates provided by the tool are in good agreement with those provided by RSAP. These results indicate that the simplified tool meets the requirements to serve as a surrogate for RSAP analysis and is therefore recommended for benefit/cost evaluations of proposed guardrail treatment options for low volume, two-lane rural roadways in Virginia.

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FINAL REPORT

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Justice Appiah, Ph.D.
Research Scientist

Benjamin H. Cottrell, Jr., P.E.
Associate Principal Research Scientist

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ABSTRACT

Guardrail is installed along the roadside to shield hazards such as steep slopes and bridge piers from vehicles. Although the Virginia Department of Transportation's *Road Design Manual* provides guidance for determining where to install guardrail on new facilities, there is no consistent approach available for evaluating guardrail needs on existing roads that explicitly considers costs and benefits.

This study developed such an approach, focusing on low volume, two-lane rural roadways in Virginia. The Roadside Safety Analysis Program (RSAP)—developed under NCHRP Project 22-27 and currently the most sophisticated tool available for conducting cost-effectiveness analysis of roadside safety treatment options—was used to determine expected crash frequencies, severities, and costs for several combinations of hazard scenarios; guardrail treatment options; and relevant roadway, roadside, and traffic characteristics. The results of the RSAP analysis were used to develop a predictive model that relates the input variables to the output response (benefit/cost ratio). The model is implemented in a simple spreadsheet for the quick and efficient evaluation of proposed guardrail treatment options without the need for full-blown RSAP analysis. Application of the spreadsheet tool is demonstrated through example problems.

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INTRODUCTION

Background

Vehicles may leave the roadway and encroach onto the roadside for many reasons including driver fatigue or distraction; excessive speed; vehicle component failure; and environmental conditions such as ice, rain, and poor visibility (Stephens, 2005). The consequences of roadside encroachments can be severe. Approximately 1,000 people die every month from run-off- road (ROR) crashes on the nation's highways (Virginia Department of Transportation [VDOT], 2015). In Virginia, ROR crashes represent approximately 64% of all roadway crashes (VDOT, 2015). Trees, culverts, embankments, and utility poles are some of the most commonly struck objects. One safety treatment that is widely used involves shielding errant vehicles from roadside hazards using guardrail. However, guardrail itself represents a hazard and should be used only when an engineering study indicates that guardrail installation is warranted.

The American Association of State Highway and Transportation Officials (AASHTO) provides guidelines for guardrail analysis. The AASHTO guardrail warrant recommendations are based on assessing the relative severities of striking a roadside hazard versus striking the guardrail. In general, a guardrail is deemed warranted if it is thought to be a less severe hazard than the roadside hazard being shielded. The AASHTO *Roadside Design Guide* (RDG) provides a hierarchy of safety measures that may be adopted to reduce hazards created by roadside obstacles (AASHTO, 2011). These measures include (1) improving the clear zone; (2) removing or relocating the hazard; (2) shielding the hazard; and (4) delineating the hazard, if nothing else can be done.

Guardrail warranting based solely on subjective evaluation of the relative severities of possible alternatives, with no consideration for crash history, may cause highway agencies to install guardrail where there is little chance of a serious crash. Thus, in order to improve the efficiency of expenditures, the relative severity approach has generally been restricted to high volume high-speed roadways where the probability of crashes may be high (Sicking et al., 2009). The costs involved in the installation, maintenance, and repair of guardrails may often preclude their use on low volume roadways. Even though there might be less frequent crashes on low volume roadways, narrow rights of way and corresponding limitations to the width of clear zone that can be provided mean that the consequences of these crashes can be severe. Therefore, it is important for the guardrail warranting process to take into account both the costs of the guardrail and the expected frequency and severity of crashes into the guardrail. AASHTO encourages the use of such analyses and has been providing analytical tools for implementing benefit/cost (B/C) analysis since the late 1980s (Ray et al., 2012).

Tools for Benefit/Cost Analysis of Roadside Designs

A number of computer models are available for implementing B/C-based guardrail analysis. These programs estimate the benefits of guardrail treatment, measured in terms of expected reductions in crash costs, as well as direct costs including construction, maintenance, and repair. One of the first such programs was the Benefit to Cost Analysis Program (BCAP), which according to Ray et al. (2012) was introduced by the Federal Highway Administration (FHWA) in 1988 and was used in the 1989 AASHTO bridge specification for designing bridge railings. BCAP was not widely accepted because it incorporated inputs for crash frequency and severity prediction that were considered too subjective (Albuquerque et al., 2009).

ROADSIDE, which was provided with the 1989 AASHTO RDG, was the preferred model for B/C analysis in the 1990s (as cited in Ray et al., 2012). It was used, for example, by Arnold (1990) to develop guidelines for guardrails on low volume roads in Virginia and by Rys and Russell (1997) to develop guidelines for such roadways in Kansas. In spite of the popularity of ROADSIDE, it has been suggested that it is inferior to BCAP in terms of the accuracy of the technical results and was in some sense “a step backward in the technical progress of B/C analysis procedures” (Albuquerque et al., 2009).

The Roadside Safety Analysis Program (RSAP) was included in the 2002 revision of the AASHTO RDG as a replacement of the older BCAP and ROADSIDE implementations of the B/C analysis of roadside designs (Ray et al., 2012). The 2002 version of the software used a simulation technique to correlate the frequency of roadside encroachments to the frequency and severity of crashes (Sicking et al., 2009). Stephens (2005) used RSAP to develop barrier guidelines on Federal Lands projects that are low volume facilities, low-speed facilities, or both. It was also used by Sicking et al. (2009) to develop guidance for specifying the necessary guardrail performance level roadways, irrespective of the volume or speed. In 2012, a new version of RSAP, RSAPv3, was released that implements the B/C analysis procedure outlined in the 2011 AASHTO RDG. The program uses a set of probabilistic “encroachment-collision-severity” predictive models to estimate the frequency, severity, and costs of roadside crashes based on user-defined roadway and roadside characteristics (Ray et al., 2012). It is currently the most sophisticated model available for conducting B/C analysis of roadside safety treatments as it incorporates improvements to both data analysis procedures and algorithms “that have been developed in the 10 years since the original release of the software” (Ray et al., 2012).

Problem Statement

Low volume roadways present unique safety challenges. These types of roads typically have restricted rights of way, little or no clear zones, and substandard design features. In addition, because there is less traffic on these roads, drivers are more likely to become inattentive and fatigued. Low volume roads also tend to have a fairly high bridge density, which may exacerbate safety because of the generally restricted conditions and rigid piers and railings.

Design features such as narrow lanes, little or no shoulders, curvilinear alignment, poor delineation, and poor pavement conditions are all directly correlated to poor roadside safety. Right-of-way restrictions on low volume roads may lead to inconsistencies in design such as exceptionally sharp curves on a fairly straight road, abrupt narrowing of lanes, and varying shoulder widths and pavement conditions. All of these features may contribute to roadside crashes.

Even though there is a high likelihood of roadside crashes on low volume roads (because of the generally poor geometric features), the actual number of crashes tends to be low because of the volume of traffic. Nonetheless, when they do occur, crashes on low volume roads tend to be more severe. According to Stephens (2005), the roadside crash fatality rate for rural minor roads is three times the average roadside fatal crash rate for all roads in the United States.

Currently, VDOT's *Road Design Manual* provides guidance for determining locations for guardrail installation (VDOT, 2005). The VDOT guardrail warranting process (1) does not consider crash history; (2) does not differentiate the decision-making process for low volume roads; and (3) is specifically geared toward VDOT's design and construction programs and is often not realistic for maintenance and operations programs. Under the current VDOT guidelines, guardrail installation can be deemed warranted in many locations where installation may be neither feasible nor practical. Guidelines that are based on sound principles of risk versus costs are needed to assist in the evaluation of the need for guardrail for shielding hazards.

AASHTO encourages the use of B/C analysis of treatment alternatives to warrant the use of guardrail and included the RSAP software package in the AASHTO RDG (AASHTO, 2011). Nevertheless, RSAP is "not used as often as it could be" partly because it is "time consuming to enter in data and make sure that the data is correct" (Ray et al., 2012). In addition, many variables affect the results of the RSAP simulations and there can also be considerable expense (time needed) to run the model, especially when several competing alternatives are being analyzed. To overcome some of these challenges and to encourage use within VDOT, it is important that the proposed approach not only provides reliable B/C ratio estimates of proposed guardrail treatment options but also enables quick turnaround analysis of alternatives.

PURPOSE AND SCOPE

The purpose of this study was to develop a simplified procedure for assessing guardrail needs on existing low volume roadways in Virginia based on B/C analysis. The scope included two-lane rural roadways with low volumes (defined in this study as an average daily traffic [ADT] of 4,000 or less) and restricted rights of ways. The ADT threshold of 4,000 was determined through consultations with VDOT staff (D. Totten, P. Hedrich, and G. Harter, unpublished data). A typical roadway of this nature would be a secondary (or local rural) road with a pavement width of 17 to18 ft and an ADT of less than 1,000. However, this study also considered primary roads that met these conditions. The simplified procedure would supplement current VDOT practices for assessing guardrail by adding B/C analysis to aid in managing risk.

METHODS

Overview

The research approach involved simulating a well-designed set of alternative roadway, roadside, and traffic combinations using RSAPv3 probability-based encroachment software. The results of the RSAPv3 analysis were used to develop a predictive model (or emulator) that relates the RSAPv3 inputs to the output response, which for this study was the B/C ratio of shielding a roadside hazard with guardrail versus the do-nothing alternative. In essence, the RSAPv3 guardrail analysis emulator provides a way to approximate B/C analysis of guardrail treatments in RSAPv3 without actually performing a full RSAPv3 design study.

As a closed-form mathematical expression relating RSAPv3 inputs to the output response, the emulator allows for rapid predictions of B/C ratios at user-specified inputs. This is in contrast to a typical RSAPv3 run, which may take 15 minutes to 1 hour to complete (excluding additional time needed to set up the model and check that all inputs are correct). The emulator has been implemented as a simple spreadsheet tool for ease of application.

Five tasks were performed to achieve the objectives of the study.

1. Conduct a literature review.
2. Identify RSAP inputs.
3. Develop an RSAP emulator.
4. Apply the developed emulator.
5. Evaluate the performance of the developed tool.

Task 1: Conduct Literature Review

The literature was reviewed to identify the latest developments regarding the use of guardrail on low volume roads. In particular, the review was done to identify the general elements used to determine the need for guardrail (with the focus on low volume roads) and the specific guidelines already in use by other states. Literature sources, such as the Transportation Research International Documentation (TRID) database, were used to identify the relevant literature.

Task 2: Identify RSAP Inputs

The purpose of this task was to identify the inputs needed for B/C analysis of guardrails in RSAPv3. This involved identifying relevant roadway, roadside, and traffic characteristics. A base RSAPv3 model for guardrail analysis was developed with these variables as input. An important outcome of this task was a list of parameters and their appropriate ranges; these formed the space over which further analyses were done. This task was accomplished through five subtasks:

1. *Identify potential hazards.* Guardrails are used to shield motorists from a wide variety of roadside hazards including, trees, bridge piers and railings, and steep roadside slopes. Crashes involving these different roadside hazards will vary in their level of severity. As a consequence, the B/C ratio of guardrail treatment will vary widely among different roadside hazards. This task sought to identify the range of hazards expected on Virginia's low volume roadways.

2. *Identify guardrail treatment options and costs.* There are a number of guardrail types available for use by VDOT, each with unique performance, cost, and maintenance characteristics. This task compared VDOT guardrail performance to those available in RSAPv3 to ensure that the guardrail and end treatment types selected for use in the study were consistent with the types commonly used on low volume roads in Virginia. The unit costs of these devices were also determined as part of this task.

3. *Determine guardrail layout and costs.* Some key inputs in the RSAPv3 analysis of guardrails are the guardrail length, offsets of the guardrail ends from the roadway, and the use of specific end treatments. This task reviewed how factors such as roadside terrain, flare rate, and length of need (LON) influence guardrail layout on Virginia's low volume roads so that these effects were adequately captured in the configuration used in the base RSAPv3 model. Another important purpose of this task was to determine crash costs appropriate for use in the analysis.

4. *Identify roadway, roadside, and traffic characteristics.* A number of roadway, roadside, and traffic characteristics including hazard offset and geometry, ADT, proportion of heavy vehicles, horizontal curvature, grade, and steepness of (and offset to) roadside slopes can affect the frequency and severity of ROR crashes. The objective of this subtask was to identify such parameters and their appropriate ranges.

5. *Develop base RSAPv3 model.* A model for guardrail B/C analysis was developed in RSAPv3 using the identified parameters as input. This served as a base model for further exploration of the RSAPv3 input-output space.

Task 3: Develop an RSAP Emulator

In this task, B/C analysis of guardrail implementation was performed using RSAPv3 over the range of parameters identified in Task 2. The results of the RSAPv3 runs were tabulated and used to develop a predictive model (or emulator) that relates the RSAPv3 inputs to the output B/C ratios. The development of the emulator consisted of three subtasks:

1. *Experimental design.* This task involved selecting the specific combinations of input values used to perform the RSAPv3 runs. Although it may be important to evaluate the full range of alternative input combinations in order to ensure generally applicable B/C results, it was necessary to limit the number of combinations in order to maintain

a manageable number of RSAPv3 runs. As a consequence, only a subset of possible combinations was analyzed. The selection was done using standard space-filling design methods, which spread the design points as evenly or uniformly (in some sense) as possible over the defined ranges of parameter values so that no phenomenon that might affect the results is overlooked (see Myers et al., 2009).

2. *RSAPv3 runs.* RSAPv3 runs were performed in this task. The software was run using the design points from the previous subtask as input, and the output B/C ratio was recorded for each run. The data generated from the RSAPv3 runs were used for model development in the next subtask.

3. *Model development.* This task developed and evaluated a model of B/C ratio as a function of relevant RSAP inputs using the JMP statistics software (SAS Institute, 2013). Since RSAPv3 is a deterministic model (it produces the same output every time if it is given the same set of inputs), the Gaussian process (GP) model (see Sacks et al., 1989), which is widely used to fit the output from deterministic computer experiments, was used for this task. Model performance was checked using the leave-one-out model validation method (Duda et al., 2001).

Task 4: Application of the Emulator

For convenience and ease of application, the predictive model developed in Task 3 was implemented in a spreadsheet. This task developed a user guide for the spreadsheet tool and provided examples to demonstrate its application.

Task 5: Evaluation of the Developed Tool

The performance of the tool relative to RSAPv3 was evaluated.

RESULTS

Literature Review

Assessment of Guardrail Needs: AASHTO

Guardrail warrants are generally designed to identify only the most severe hazards close to the roadway that merit shielding. Guidelines used by many states are related either directly or indirectly to those specified in the AASHTO RDG (AASHTO, 2011). The guardrail warrant recommendations in the RDG are based on relative severity indices, which were "determined by making a subjective evaluation of the relative severities" of striking a roadside hazard versus striking a guardrail (Sicking et al., 2009). A guardrail is needed only if it is determined that the consequences of striking the hazard would be more serious than those of striking the guardrail.

The first step in the AASHTO RDG guardrail warranting process is to determine the required clear zone because it is generally not necessary to shield hazards located outside the clear zone.

Clear Zone

The clear zone is the unobstructed, traversable area adjacent to the traveled way that is available for the safe recovery of errant vehicles. The provision of an adequate clear zone ensures there is reasonable room for recovery of errant vehicles. In essence, drivers of most errant vehicles can be expected to regain control of their vehicle and return them safely to the pavement without going beyond the clear zone. The AASHTO RDG provides approximate clear zone distances for several combinations of traffic volumes, speeds, and embankment slopes. The AASHTO RDG values have been adopted by VDOT (2005). In addition to these values, the designer may consider site-specific conditions, design speeds, location, and practicality. In all situations the key principle is to "provide the maximum, cost-effective clear zone" (VDOT, 2015).

Roadside Hazards

Once the desired clear zone is determined, fixed objects and roadside features that may be considered hazards within the clear zone are identified. Examples of potential hazards include steep roadside slopes, large trees and boulders, culverts, bridge piers, non-breakaway lighting/signal poles and towers, and above-ground utilities such as telephone pedestals. Trees/shrubs are by far the most commonly struck object type, accounting for almost one-half of all fixed object crashes (AASHTO, 2011).

Hierarchy of Corrective Actions

Even though many obstacles present some degree of risk if struck, the consequences of striking some may not be serious enough to consider shielding them with guardrail. The AASHTO RDG provides a hierarchy of safety measures that may be adopted to reduce hazards created by roadside obstacles. These measures include (1) improving the clear zone; (2) removing or relocating the hazard; (3) shielding the hazard; and (4) delineating the hazard if nothing else can be done. Stephens (2005) noted that low-cost corrective actions may be undertaken for low-severity hazards such as cross culvert end sections with crashworthy grates, if necessary. Further, low-severity hazards often do not justify expenditure of substantial funds for correction, and in fact, in many cases "accepting the risk and leaving the hazard is appropriate" (Stephens, 2005).

For hazards within the clear zone that have the potential for moderately severe or highly severe outcomes when struck, the first treatment priority is to eliminate the hazard. This includes removing items such as small trees, boulders, and jagged rock cuts and re-grading steep slopes and ditches. Potential hazards such as signs and signal supports, utility poles, and endwalls may also be treated by relocating them outside the clear zone or by making them crashworthy. These hazards may be evaluated for possible treatment with guardrail if eliminating them or making them crashworthy is either too expensive or impractical. If none of these treatment options works, then according to the AASHTO RDG, the hazard should be delineated.

Guardrail Warrants

Because guardrail is also a hazard, it is generally recommended that it be used (1) only if improving the clear zone or relocating the hazard is not feasible and (2) only when an engineering study indicates that guardrail installation is warranted. That is, guardrail is installed only if the installation offers less potential hazard than the roadside obstacle or embankment slope.

The AASHTO RDG provides a guardrail warranting guide for roadside embankments that is based on the height of the embankment and the value of the side slope. The criterion (shown in Figure 1) was developed by AASHTO based on studies of the relative severity of encroachments on embankments versus impacts with roadside barriers, but neither considers the probability of an encroachment occurring or the relative cost of installing the guardrail versus leaving the slope unshielded (AASHTO, 2011).

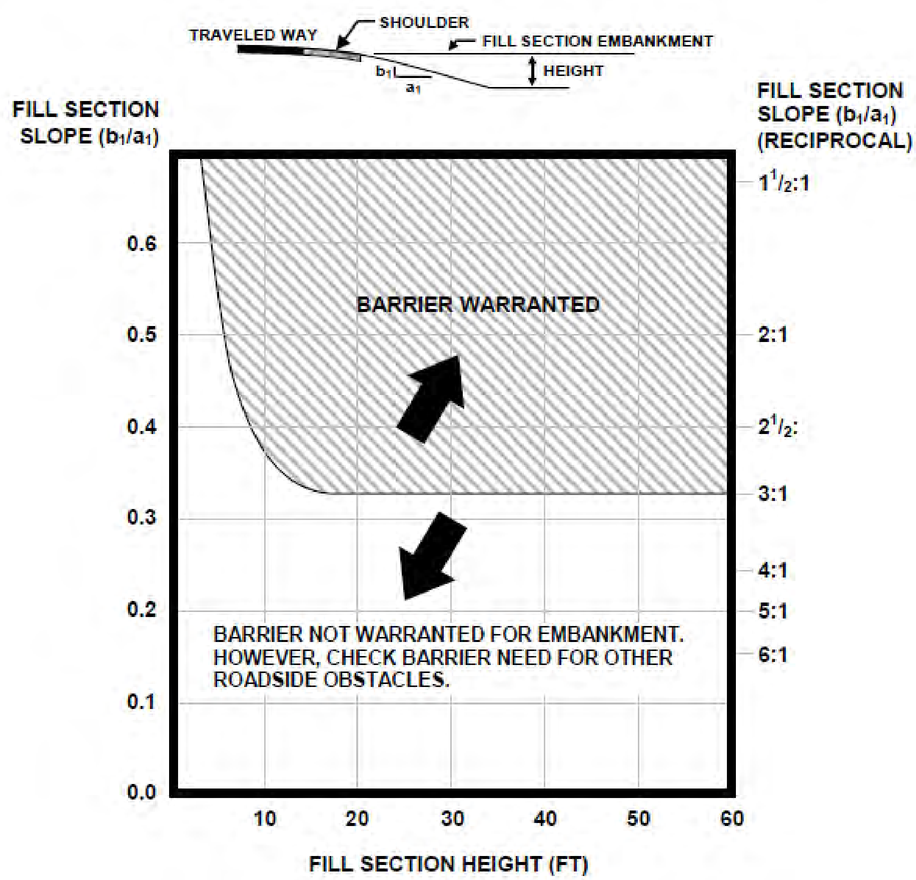


Figure 1. Comparative Risk Warrants for Embankments (VDOT, 2015)

In Virginia, embankments with fill slopes steeper than 3:1 and a height of 7.5 ft or more generally warrant consideration of guardrail (VDOT, 2005). VDOT's *Road Design Manual* also provides a list of "fixed and hazardous objects" that warrant consideration for shielding with guardrail when they are within the clear zone. These include non-breakaway sign supports and lighting/signal posts, bridge piers and parapet ends, retaining walls, culvert headwalls, large trees, etc. (VDOT, 2005).

Subjective Assessment of Guardrail Needs: Stephens (2005)

Stephens (2005) developed guidelines for determining guardrail needs on "Federal Lands projects that are low volume and/or low speed facilities" based on a subjective assessment of potential benefits and a quantitative assessment using RSAP (discussed later).

In the subjective warranting approach, Stephens (2005) categorized common roadside obstacles into three groups as shown in Table1 based on the potential severity of crashes involving these hazards. All "high" severity hazards are considered candidates for shielding with guardrail when located in the clear zone. "Moderate" severity hazards and hazard scenarios that do not fit the descriptions provided in Table 1 are evaluated for the use of guardrail based on additional considerations provided in Table 2.

Even though the approach summarized in Tables 1 and 2 is subjective, Stephens (2005) noted that "it can lead to a reasonable decision concerning the use of guardrail."

Quantitative Assessment of Guardrail Needs

Overview

Roadside safety projects typically must compete for highway funds with other activities such as resurfacing, pavement widening, and bridge widening. Therefore, in order to improve the efficiency of safety expenditures, the relative severity approach of guardrail needs assessment has generally been restricted to high volume high-speed roadways where there is a high likelihood of more frequent crashes (Sicking et al., 2009). Guardrail installation on low volume roads may be difficult to justify economically because of the generally low frequency of crashes on these roads. However, crashes tend to be more severe on these roads. In order to make a more objective assessment of the need for guardrail installation, it is important to consider not only the direct costs of guardrail installation and crash frequencies but also the severity of those crashes.

One common procedure for objective evaluation of competing projects is B/C analysis. With regard to safety projects, B/C analysis procedures attempt to estimate the dollar value of potential reductions in injuries and fatalities and the direct costs associated with implementing the safety treatment. The results of the analyses are typically expressed as the ratio of benefits to costs. The ability to express roadside safety treatment in terms of a B/C ratio allows roadside safety treatments to be compared directly to any other type of project for which a B/C ratio is available.

Table 1. Roadside Hazards and Their Potential Severity

Hazard	Potential Severity		
	L	M	H
A) Fixed Objects			
Bridge piers, abutments and railing ends			X
Boulders, diameter < 1 ft		X	
Boulders, diameter ≥ 1 ft			X
Non-breakaway sign and luminaire supports		X	
Individual trees, 4 in. < diameter < 8 in.	X		
Individual trees, > 8 in.		X	
Groups of trees, individually greater 4 in. diameter			X
Utility poles		X	
B) Cross Drain Culvert Ends			
Exposed culvert ends with no headwalls, diameter ≤ 36 in.		X	
Exposed culvert ends with no headwalls, diameter > 36 in.			X
Sloped culvert ends, diameter < 4 ft	X		
Sloped culvert ends, 4 ft < diameter < 8 ft		X	
Sloped culvert ends, diameter ≥ 8 ft			X
Vertical headwalls, height < 3 ft		X	
Vertical headwalls, height ≥ 3 ft			X
Headwalls with parallel sloped wingwalls, height ≤ 2 ft		X	
Headwalls with parallel sloped wingwalls, height > 2 ft			X
Headwalls with flared and sloped wingwalls, height ≤ 3 ft		X	
Headwalls with flared and sloped wingwalls, height > 3 ft			X
Culvert end sections with crashworthy grates	X		
C) Parallel Drain Culvert Ends			
Exposed culvert ends with no headwalls, diameter < 2 ft	X		
Exposed culvert ends with no headwalls, 2 ft < diameter < 4 ft		X	
Exposed culvert ends with no headwalls, diameter ≥ 4 ft			X
Mitered culvert ends, diameter < 3 ft	X		
Mitered culvert ends, diameter ≥ 3 ft		X	
Vertical headwalls, less than 3 ft above ditch section		X	
Vertical headwalls, 3 ft or higher above ditch section			X
D) Parallel Ditches			
Ditches outside the preferred cross-section in Figures 3.6 and 3.7 of the [AASHTO] RDG and with foreslopes flatter than 3:1	X		
Ditches with foreslopes 3:1 or steeper		X	
E) Slopes			
3:1 foreslope, height < 7 ft	X		
3:1 foreslope, height ≥ 7 ft		X	
2:1 to 5:1 foreslope, height < 13 ft		X	
2:1 to 5:1 foreslope, height ≥ 13 ft			X
Vertical foreslope or fill wall, height < 7 ft		X	
Vertical foreslope or fill wall, height ≥ 7 ft			X
Backslopes that are uneven, or with deep erosion ruts, large rocks, and trees		X	
Vertical backslope with horizontal projections of 4 in. or smaller	X		
Vertical backslope with horizontal projections larger than 4 in.		X	
Downward intersecting slope (traverse to traveled way, such as river bank) 4:1 or steeper, 2 ft < height < 6 ft		X	
Downward intersecting slope (traverse to traveled way, such as river bank) 4:1 or steeper, height ≥ 6 ft			X
Upward intersecting slope (traverse to traveled way, such as an overpass fill) 4:1 to flatter than 1.5:1, height > 1 ft		X	
Upward intersecting slope (traverse to traveled way, such as an overpass fill) 1.5:1 or steeper, height > 1 ft			X
F) Others			
Parallel smooth retaining wall or cut slope	X		
Retaining wall parallel or flared away from approaching traffic flatter than 8:1	X		
Retaining wall parallel or flared away from approaching traffic at 8:1 or steeper		X	
Water, 1ft ≤ depth ≤ 3 ft		X	
Water, depth > 3 ft			X

Source: Stephens (2005). L = low; M = moderate; H = high.

Table 2. Guardrail Warrant Considerations

Consideration	Guardrail More Warranted If:	Guardrail Less Warranted If:
Speed	45 mph or higher	25 mph or lower
Hazard on outside of horizontal curve	1,150 ft or smaller radius	Radius larger than 1,430 ft
Hazard does not fit the descriptions in Table 1	Hazard is more severe	Hazard is less severe
Size of hazard	Very large	Very small
Traffic volume	Above 1,000 vpd	Below 400 vpd
Hazard on inside of horizontal curve	1,150 ft or smaller radius	Radius larger than 1,430 ft
Hazard on a downgrade	5% or greater	Less than 3%
Crash history	Clear crash pattern	No crash pattern
Anticipated cost of barriers	Expected costs are low	Expected costs are high
Roadway cross section	Severe section elements	Good section elements
Multiple hazards exist at the site	Many additional hazards	
Aesthetic impacts		Serious concerns
Environmental impacts		Serious concerns

Source: Stephens (2005). vpd = vehicles per day.

Although it is relatively straightforward to estimate the direct costs of guardrail installation, it is considerably more difficult to quantify the safety benefits associated with the treatment. One significant challenge is determining a reliable estimate of the frequency and severity of ROR crashes. Three basic approaches are available in the literature. The first involves directly using local data regarding crash history. The rationale is that the local crash history inherently involves the aggregate effects of all roadway, roadside, and land use characteristics for the site under consideration. It therefore provides the best available information for supporting a B/C analysis of roadside safety improvements at the site (Sicking et al., 2009). Unfortunately, crash histories are not always available.

The second approach attempts to estimate the expected crash frequency and severity at a study site by modeling crash history data that are available from sites with similar traffic and geometric characteristics. Unfortunately, a model developed for a specific hazard type, a set of roadway and traffic characteristics, and a specific safety treatment option may not be directly transferable to other scenarios. The need for models that are specific to a particular hazard, roadway/traffic, or treatment type renders the approach impractical for use in the development of guardrail application guidelines where a wide variety of roadside hazards must be considered (Sicking et al., 2009). This is further compounded by the observation that the method requires hazards and safety treatments to be in place for many years before sufficient crash data can be generated to develop reliable models.

The third approach, encroachment probability models, assumes that crash frequency is proportional to encroachment frequency. Encroachment frequencies are typically estimated from observed historical relationships that relate encroachment frequency on straight sections of roadway to traffic volume and functional class (e.g., arterial, collector, and local roads). These basic encroachment frequencies are then adjusted for the effects of specific geometric features, such as horizontal curvature and grade (Sicking et al., 2009). The effects of these geometric features are generally quantified using crash data. Encroachment probability models attempt to estimate crash frequencies and severities by correlating measured encroachment frequencies to specific roadway and traffic characteristics.

The expected crash costs for crashes of a given severity are estimated as a product of the encroachment frequency, the likelihood of an encroachment resulting in a crash, the probability of a crash having the specified level of severity, and the unit cost of crashes of such level of severity. Encroachment probability analysis is currently the 'most appropriate method for developing general guidelines for safety hardware application" (Sicking et al., 2009). One reason for this is that encroachment probability models provide the only available method to predict crash frequency for safety features and/or newly constructed or reconstructed roadways. These analyses are typically implemented in a software package. At present, the most advanced encroachment probability model software package is RSAP (Sicking et al., 2009).

Roadside Safety Analysis Program

RSAP was first included in the 2002 revision of the AASHTO RDG as a replacement of the older BCAP and ROADSIDE implementations of the B/C analysis of roadside designs (Ray et al., 2012). The latest version of RSAP, RSAPv3, uses a set of probabilistic "encroachment-collision-severity" predictive models to estimate the frequency, severity, and costs of roadside crashes based on user-defined roadway and roadside characteristics. These are implemented in a systematic approach through four modules, namely, the encroachment module, the crash prediction module, the severity prediction module, and the benefit-to-cost module. A detailed description of each module was provided by Ray et al. (2012).

The encroachment module estimates the frequency at which vehicles can be expected to leave the roadway unintentionally and enter the roadside. This module uses data collected by Cooper in the 1970s to derive the number of roadside encroachments expected per unit length of roadway per year as a function of traffic volume (Ray et al., 2012). The base encroachment rates are based on the assumption of a relatively flat and straight roadway segment but are then adjusted for the effects of horizontal curvature, grade, number of lanes, lane width, access density, and posted speed limit.

A vehicle's trajectory following encroachment is estimated by matching four characteristics of the simulated roadway—roadside cross-section profile, horizontal curve radius, highway vertical grade, and posted speed limit—to those of a historical crash database (Ray et al., 2012). An encroaching vehicle is assumed to follow the same trajectory as that of the crash event in the crash database that occurred on a roadway that matches the simulated roadway most "closely." A set of trajectories that match a pre-specified "closeness" threshold is selected and evaluated for the likelihood of a crash by projecting each trajectory onto the roadside and determining if it intersects the position of any roadside hazard.

The severity prediction module estimates the expected severity of a crash predicted by the crash prediction module. The probability that striking a particular type of roadside hazard under a given set of roadway and traffic conditions will result in severe injury is expressed in terms of a so-called "equivalent fatal crash cost ratio" (EFCCR). The EFCCR is the ratio of the average crash cost calculated for any particular year to the cost of a fatal crash for that same year. Two sets of crash costs (by severity) are available; the AASHTO RDG values (AASHTO, 2011) and the FHWA values (Trottenburg and Rivken, 2013). The AASHTO RDG values are representative of the direct costs of highway crashes, whereas the FHWA values are comprehensive and incorporate a person's willingness to pay to avoid injury or fatality.

For a given roadside hazard, the average crash cost of collisions into the hazard is obtained by (1) determining the distribution of crash severity in a database of police-reported crashes; (2) adjusting to account for unreported crashes; and (3) multiplying the crash cost for each severity level by its relative percentage and summing. For convenience, RSAPv3 also reformulates the EFCCR in terms of a single baseline speed of 65 mph. This allows for direct comparison of hazard severity between different roadside hazards and enables data gathered for a specific hazard at one speed to be used to evaluate the same hazard for situations where speed data are not available (Ray et al., 2012).

The final module in RSAPv3 is the B/C module. This module compares the benefits derived from guardrail installation to the direct costs associated with the improvement by calculating a B/C ratio. The B/C ratio (BCR) is calculated as the ratio between the differences in benefits and costs associated with two safety treatment alternatives as shown in Equation 1.

$$BCR_{1-2} = \frac{CC_1 - CC_2}{DC_2 - DC_1} \qquad \text{[Eq. 1]}$$

where

$BCR_{1\text{-}2}$ = BCR of Alternative 2 with respect to Alternative 1
CC_i = annualized crash cost for Alternative i
DC_i = annualized direct cost for Alternative i.

As shown in Equation 1, benefits are measured in terms of expected reductions in crash costs arising from decreases in the number and/or severity of crashes. The crash cost associated with an alternative is the product of the results of the encroachment, the crash prediction, and the severity prediction modules adjusted for ADT and section length as shown in Equation 2.

$$CC_i = P_E \cdot P_{C|E} \cdot (P_{S|EC} \cdot A_s) \cdot ADT \cdot L_N \qquad \text{[Eq. 2]}$$

where

P_E = probability of an encroachment
$P_{C|E}$ = probability of a crash given an encroachment
$P_{S|CE}$ = probability severity is s given an encroachment results in a crash
A_S = average societal cost of a crash of severity s
L_N = length of roadway segment.

The direct costs of a safety treatment include initial installation, maintenance, and crash repair costs. The direct costs are converted to an annualized cost for calculating the B/C ratio using the project life and the discount rate.

State DOT and Other Agency Assessment Procedures

Stephens (2005) used the 2002 version of RSAP to produce guidelines for warranting guardrail on Federal Lands Highways projects that are low volume and/or low-speed facilities. The main variables considered in developing the guidelines were hazard type and size, hazard offset, traffic volume, traffic growth, horizontal curvature, grade, and speed. First, three sets of adjustment factors were developed for traffic growth, horizontal curvature, and grade. These adjustment factors were used to condense further four of the variables—traffic volume, traffic growth, horizontal curvature, and grade—into a single variable called the "adjusted traffic factor" (ATF). Second, RSAP was run for various combinations of hazard offset, speed, and ATF (for specified hazard types and sizes) to determine the ATF at which the B/C ratio was either 1.0 or 4.0 (no explanation was provided for the choice of this threshold). Third, warranting tables were developed for each modeled hazard type and size; these tables were used to classify the need for guardrail treatment as not warranted (B/C ratio < 1), possibly warranted ($1 \leq$ B/C ratio ≤ 4), or warranted (B/C ratio > 4) based on the values of hazard offset, speed, and ATF.

Sicking et al. (2009) used the 2002 RSAP to develop guidelines for identifying specific locations where guardrail installation may be cost-beneficial and for selecting the appropriate guardrail performance level needed at a given location. First, they identified the safety treatment options to be evaluated and the relevant parameters needed to describe each alternative, including safety treatment layout, construction costs, and accident severities. Second, they identified 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. RSAP was then used to analyze a set of detailed hazard scenarios under a wide variety of specified roadway and traffic characteristics. Third, results of the RSAP runs were used to identify specific locations where various guardrail performance levels should be implemented and then generalized to develop route-specific recommendations for guardrail performance levels for each of five different highway functional classes (freeway, urban arterial, urban collector/local, rural arterial, and rural collector/local) as a function of traffic volume.

CTC & Associates LLC (2011) reviewed guidelines or specifications related to guardrail location for state departments of transportation (DOTs) and found that provisions of the AASHTO RDG underlied the guardrail warrant guidelines of many state DOTs with RSAP seeming to play a lesser role. In particular, they found that "more than half" of the 12 states reviewed had guidelines that included the same height and slope factors associated with embankment warrants as those in the AASHTO RDG. The review also stated that "references to the use of RSAP, or its precursor, ROADSIDE, appear in the design guidelines of Illinois and Indiana DOTs" (CTC & Associates LLC, 2011).

According to Nebraska's *Roadway Design Manual*, guardrail installation is based on cost effectiveness analysis using RSAP. RSAP runs are performed by the head of the roadway design unit or a designee. Shielding a roadside hazard with guardrail is "usually justified" if the hazard is within the clear zone; it is impractical to improve the clear zone; the hazard cannot be economically or practicably removed, relocated, or made breakaway; and the RSAP analysis yields a B/C ratio of 1.0 or greater (Nebraska Department of Roads, 2012).

RSAP Input Factors

This section discusses the process used to determine the combinations of roadway, roadside, and traffic characteristics that were used as input to the RSAP analysis.

Hazard Types and Severity

Guardrails are used to shield motorists from a wide variety of roadside hazards including trees, culverts, bridge piers and railings, and steep roadside slopes. Crashes involving these different roadside hazards will vary in their level of severity. As a consequence, the B/C ratio of guardrail treatment will vary widely among different roadside hazards.

In RSAPv3, crash severities for various roadside features are defined in terms of a dimensionless factor, the EFCCR. The EFCCR is essentially an estimate of the probability that a crash involving the roadside feature results in a fatality (Ray et al., 2012). Roadside features are further divided into three groups, namely, point, line, and area hazards. Point hazards are hazards such as trees, signs, and other hazards that may be reasonably approximated as points in space. Line hazards such as guardrails, tree lines, and other objects may be represented as simple lines, whereas area hazards are terrain-related features such as slopes and ditches that generally result in vehicle rollover when encroached upon.

In order to cover the full range of hazards that may potentially be located in the clear zone, the value of EFCCR used in this study was allowed to vary between 0.01 and 0.25. Roadside features with EFCCR values outside this range were considered as being unlikely candidates for shielding by guardrail. Further, shielding roadside features associated with no or very low severities (e.g., EFCCR < 0.01) with the guardrail is unlikely to be cost-beneficial, whereas roadside hazards associated with a high severity (e.g., EFCCR > 0.25) should generally not be left in the clear zone.

Guardrail Type

A number of guardrail types is available for use on VDOT projects; each has unique performance, cost, aesthetic, and maintenance characteristics. Guardrail performance is generally assessed in terms of one of six test levels specified in NCHRP Report 350 (Ross Jr. et al., 1993). The most common criterion specified by VDOT is Test Level 3 (TL-3), which is based on a 4400/5000-lb pickup truck and an 1800/2420-lb small car impacting the device at 62 mph (VDOT, 2015). Examples of TL-3 approved guardrail systems used on two-lane undivided roadways in Virginia include the weak post cable (VDOT Standard GR-3), the weak post W-beam (GR-8, 8A, 8B, 8C), and the strong post blocked-out W-beam (GR-2, 2A) (VDOT, 2011, 2015). The selection of a particular type of guardrail over another may be influenced by a number of factors including costs, maintainability, repair, guardrail size, dynamic deflection, available end treatments, and any restrictions imposed by the maintaining agency. Aesthetics and environmental concerns may also be considerations in, for example, park and forest settings (Stephens, 2005).

The ends of a guardrail feature protective terminals designed to redirect a vehicle and to minimize the damage to the vehicle and its occupants if hit. These terminals are designed to meet Test Level 1, 2, or 3. Terminal end treatments may be installed parallel to the guardrail (GR-9), flared (GR-7), or buried in backslope (GR-6). Stephens (2005) noted that when a backslope is available, a buried-in-backslope end treatment is usually preferable because then "the end is not exposed, the length of need is not an issue because the hazard is completely cut off, and it is not as sensitive to side slope conditions" (Stephens, 2005). Selection of a satisfactory end treatment is a key part of the barrier selection process as it ensures that the system is as safe as possible. In general the nature of the terrain in advance of, adjacent to, or downstream of the guardrail and possible grading requirements are some of the factors to consider when selecting an end treatment (Stephens, 2005).

For this study, a TL-3 W-beam guardrail was assumed because the GR-2 is the most commonly used guardrail type on low volume roads in Virginia (Arnold, 1990). A generic TL-3 end treatment (the default option in RSAPv3) was assumed on either end of the guardrail (see Ray et al., 2012, for details). As in Sicking et al. (2009), no flare was assumed in the analysis.

Guardrail Layout

Guardrail is normally placed as far from the traveled way as practical without compromising the operating characteristics of the selected guardrail system. The greater the lateral offset the better the chance for an errant driver to recover control of the vehicle. Such placement also reduces the likelihood of the guardrail obscuring a driver's sight distance, particularly at intersections.

Drivers tend to "shy away" from continuous longitudinal obstacles along the roadside, including the guardrail. The distance from the edge of the traveled way beyond which a roadside object will not be perceived as an immediate hazard and result in the driver reducing speed or directing the vehicle away from the barrier is called the shy distance. This theoretical distance is a function of design speed. It is preferable to locate the guardrail at or beyond the shy distance. However, the shy distance is seldom a controlling criterion for guardrail placement, especially for long continuous runs of guardrail placed beyond the perceived shoulder of the roadway. In general, placing a long continuous run of guardrail at a uniform offset distance is not only more aesthetically pleasing but also provides the driver with a feeling of security and comfort when approaching the run (Delaware Department of Transportation, 2004).

Another important consideration in the lateral placement of guardrail is the expected deflection of the selected system. In general, the distance from the guardrail to a rigid roadside object should not be less than the maximum dynamic deflection of the system (e.g., 3 ft for the standard GR-2 guardrail) based on the appropriate test level. If this distance is not available, the AASHTO RDG recommends that the guardrail be stiffened in advance of and alongside the fixed object (AASHTO, 2011). If an embankment area is to be shielded, it is important that the barrier-to-embankment distance is sufficient (desirably a minimum of 1 ft) to support the posts adequately and ensure proper operational characteristics of the barrier. Other factors that influence guardrail layout include (1) terrain effects, (2) flare rate, and (3) LON.

Terrain Effects

The nature of the roadway cross section between the traveled way and the guardrail can have significant effects on the guardrail's performance when hit by an errant vehicle. Generally, guardrail systems perform best when an impacting vehicle has all wheels on the surface and its suspension in a normal position at the point of impact. Two features that often are of concern are curbs and the approach slope because these features may cause a vehicle to vault over a guardrail or strike the guardrail either too high or too low.

Guardrails perform most effectively when they are installed on slopes of 10:1 or flatter. Depending on its speed and encroachment angle, an errant vehicle may go over many standard guardrails or impact them too low if the guardrail is placed on slopes steeper than 10:1. VDOT's Guardrail Installation Training [GRIT] Manual recommends against placing any type of guardrail on slopes steeper than 6:1 (VDOT, 2015). Slopes between 10:1 and 6:1, but no steeper, may be adequate for cable systems. Such slopes may also be used for W-beam systems provided the face of the guardrail is within 2 ft of the hinge point or a minimum of 12 ft beyond the hinge point (see Figure 2). Although installing guardrail on flatter slopes is preferable, Stephens (2005) noted that it may be a reasonable trade-off to accept slopes as steep as 6:1 in front of the guardrail if the speeds are 25 mph or lower.

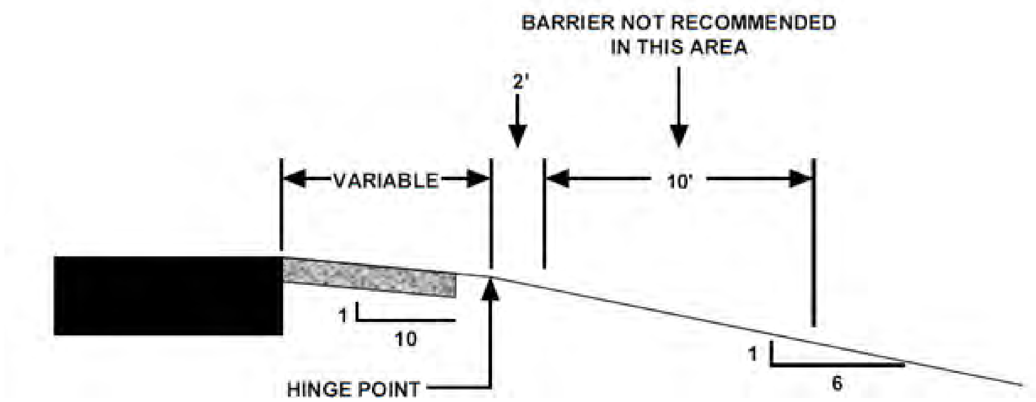


Figure 2. Recommended W-beam Guardrail Location on 6:1 Slope (VDOT, 2015)

Flare Rate

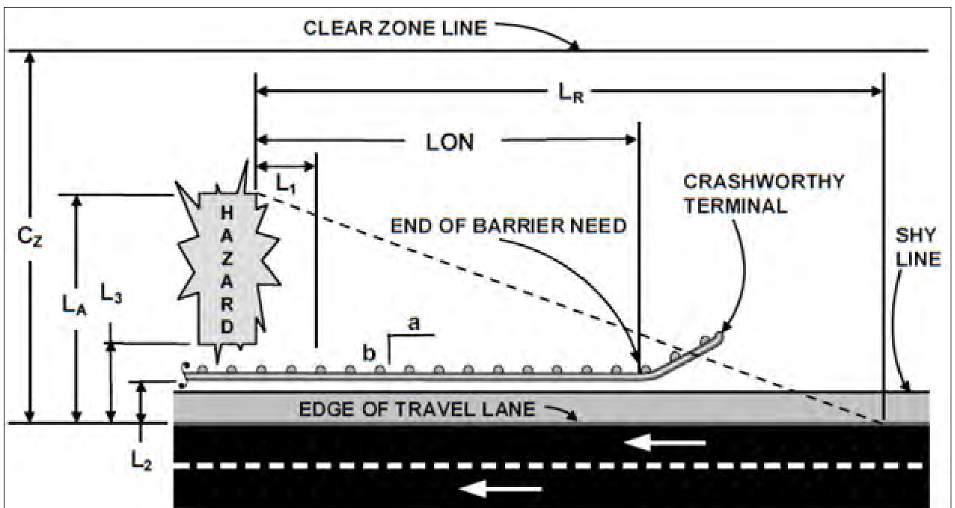
It is common to introduce the guardrail by offsetting the beginning of the installation farther away from the travel way than the normal offset. Flaring the guardrail may reduce cost and improve safety by allowing the terminal section to be located farther away, minimizing the driver's reaction to having an obstacle close to the road, and reducing the total length of barrier needed. There are, however, some disadvantages. For example, the greater the flare rate, the higher the angle at which a barrier can be hit, thereby increasing the severity of crashes. A flared installation may also increase the possibility of a vehicle being redirected back into or across the roadway.

Length of Need

The guardrail LON is the length of guardrail needed upstream of the beginning of the hazard to shield it adequately (see Figure 3). The LON depends on the runout length (L_R), the lateral extent of the hazard (L_A), the flare rate for the tapered section (b/a), and the offset (L_2) of the face of the barrier from the edge of the traveled way.

The general philosophy behind the design process is that if a vehicle leaves the roadway and the driver attempts to steer the vehicle back onto the roadway, the vehicle could end up traveling approximately parallel to, and behind, the guardrail. The design process is intended to allow sufficient room for such a vehicle to come to a stop before striking the hazard. An important part of the layout process is therefore to allow a clear zone behind the barrier upstream of the hazard (Stephens, 2005). The length of this zone, measured longitudinally off the pavement, from the location of the hazard to the point where the vehicle departs from the traveled way, is the runout length, LR. The runout length is a function of speed and traffic volume (AASHTO, 2011).

The lateral extent of the hazard (LA) is the perpendicular distance from the edge of the traveled way to the far side of the hazard or to the outside edge of the clear zone (CZ), whichever is shorter. The tangent length of barrier immediately upstream from the area of concern (L1) is a variable length selected by the designer. Once the variables are selected, the total length of guardrail, without the end treatments, can be calculated using Equation 3.



LON = Length of Need
C_Z = Clear Zone Width
L_A = Distance to back of hazard, Max. = C_Z
L_R = Runout Length
L_1 = Upstream length of Guardrail prior to flare
L_2 = Offset of Guardrail from travelway
L_3 = Distance to front of hazard
a:b = Flare Rate of Guardrail (if applicable)

$$LON = \frac{L_A + (b/a)(L_1) - L_2}{(b/a) + (L_A/L_R)}$$

$$LON\ (No\ Flare) = \frac{L_A - L_2}{L_A / L_R}$$

Figure 3. Layout Variables for Approach Guardrail (VDOT, 2015)

$$LON = \frac{L_A + \frac{b}{a}L_1 - L_2}{\frac{b}{a} + \frac{L_A}{L_R}} \qquad \text{[Eq. 3]}$$

For a parallel installation, with no flare rate, Equation 3 reduces to Equation 4:

$$LON = \frac{L_R(L_A - L_2)}{L_A} \qquad \text{[Eq. 4]}$$

Another approach to determining the length of guardrail needed to shield a hazard is to estimate a specific encroachment angle through cost-effective analysis and install a length of guardrail that will intercept the vehicle's runout path (AASHTO, 2011). One advantage of this approach is that the clear zone behind the LON described earlier may not be an issue because the vehicle's path to the hazard is cut off by the guardrail

Specific Inputs Used to Develop the Base RSAPv3 Model

A number of assumptions were made regarding hazard severity, roadway, roadside and traffic characteristics as well as crash and construction costs. Relevant ranges for the various parameters were determined through a review of the literature and consultations with VDOT staff (D. Totten, P. Hedrich, and G. Harter, unpublished data). The base RSAPv3 model consisted of a two-lane, two-way rural road with 8.5 to 11-ft lanes and 2-ft shoulders. It was modeled as a straight section with vertical grades ranging between -6% and 0%. Positive grades were not modeled because capturing the effects of steep downgrades was considered more critical as roadside encroachments are more likely in the downgrade direction than for upgrade (Sicking et al., 2009). Analyses were done assuming speed limits of 45 mph and 55 mph. Roadway traffic was assumed to consist of a nominal 2% trucks. The analysis ADT was assumed to vary between 50 and 4,000 vehicles.

Slope hazards were not explicitly modeled because the then current version of RSAP, RSAPv3 that was used in this study, did not have such capability. Two workarounds were considered. The first uses the fact that RSAPv3 automatically includes terrain features (e.g. side slopes) specified by the modeler in all of its analyses. With this approach, a roadway segment with specified side slope characteristics is modeled with and without guardrail protection and the B/C ratio noted. Results of this approach seemed counterintuitive, but were consistent with a similar study conducted by the developers of RSAPv3, in that protection by guardrail was always less beneficial than the unprotected alternative (C. Carrigan, unpublished data). The second workaround involved treating the slope hazard as a line hazard (located at the slope break line), thus taking advantage of the fact that line hazards are explicitly modeled in RSAPv3. This approach requires that the value of EFCCR for the side slope is known. Default side slope EFCCR values are not available in RSAPv3 but may be calculated using procedures described in the RSAPv3 Engineer's Manual provided crash data are available (Ray et al., 2012, Appendix B).

Based on the previous discussion, explicit analyses were done only for point hazards and line hazards with the understanding that slope hazards may be treated as line hazards. The diameter of point hazards was allowed to vary between 0.5 and 10 ft, whereas the length of line hazards varied between 10 and 200 ft. Hazards were assumed to be offset a distance between 5 and 20 ft from the edge of the travel way.

The guardrail was located a distance of 3 ft from the edge of the travel way. The length of guardrail (including two end treatments) was varied between 100 and 600 ft. No flaring was assumed. As in Stephens (2005), the length of the analysis segment was assumed equal to 2,000 ft. The guardrail was centered in the segment with the hazard located at the downstream end of the guardrail (along the primary direction of travel). Based on a review of VDOT bid tabulations and input from VDOT's central office and field staff, total construction costs for guardrail were varied between $1,000 and $40,000. A design life of 20 years and a discount rate of 4% were assumed.

The societal cost of a fatal crash was allowed to vary between $4 million and $12 million and projected to grow by 1.07% per year (Trottenburg and Rivken, 2013). These numbers were based on a 2013 U.S. DOT memorandum (Trottenburg and Rivken, 2013) and current VDOT practice. The memorandum suggested that low and high values for the economic value of a statistical life (VSL) of $5.2 million and $12.9 million be used for analyses with the base VSL being $9.1 million. This $9.1 million is also the default value used in RSAPv3. However, the cost of a fatality currently used by VDOT for the Highway Safety Improvement Program is $5 million. A range of $4 million to $12 million was used to capture the current VDOT value of $5 million while allowing for the possibility of an upward review.

RSAPv3 has several input parameters. Some (e.g., percentage of trucks) were set to a constant value, and others were varied over a range. Inputs for parameters not discussed here were set at their default values. The following is a summary of the inputs that were varied over a range and the corresponding ranges used:

1. ADT; range = [50 vpd, 4000 vpd]
2. Vertical grade; range = [-6%, 0%]
3. Lane width; range = [8.5 ft, 11 ft]
4. EFCCR; range = [0.01, 0.25]
5. Hazard size; range = [0.5 ft, 10 ft] for point hazards and [10 ft, 200 ft] for line hazards
6. Hazard offset; range = [5 ft, 20 ft]
7. Length of guardrail; range = [100 ft, 600 ft]
8. Guardrail construction; range = [$1000, $40000]
9. Cost of a fatal crash; range = [$4 million, $12 million].

Even though it may be important to evaluate the full range of inputs in order to ensure generally applicable guardrail guidelines, it was necessary to limit the number of combinations in order to maintain a manageable number of RSAP runs. As a consequence, only a subset of possible combinations was selected for analysis. The selection was done using standard space-filling design methods (see Myers et al., 2009).

The selection of design points and the development of a predictive model that relates the RSAP inputs to the output response (B/C ratio of guardrail use relative to the do-nothing alternative, in this case) are discussed here.

Emulation of RSAP Model

The RSAP model for guardrail analysis discussed in the previous section consists of nine variable inputs. Exploring this multidimensional factor space requires efficient experimentation to gain the most information possible from a limited number of RSAPv3 runs. A convenient approach is to build a surrogate model (or emulator) from these RSAPv3 runs. The emulator is a closed form mathematical expression that relates the input variables to the output response and therefore allows for very fast (microsecond) predictions of new responses at untried inputs. This is in contrast to a typical RSAP run, which may take up to 15 minutes to 1 hour to complete (excluding additional model setup and input checking time).

Experimental Design

A key step in developing an emulator is the selection of specific combinations of input values at which to run RSAPv3 for efficient analysis of the data. It should be noted that RSAPv3 is a deterministic model. Therefore, traditional experimental design techniques based on variance minimization are not applicable because there is no variance to minimize. Further, concepts such as randomization and replication are no longer useful (Jones and Johnson, 2009).

These inherent difficulties have led to the development of families of designs specifically for use with deterministic computer models known collectively as space-filling designs. Examples include the sphere packing design, the uniform design, the Latin hypercube (LH) design, the minimum potential design, the maximum entropy design, and the GP integrated mean-square error design (SAS Institute, 2013). It should be noted that although there is no variance in these deterministic computer experiments, there is a bias (i.e., a difference between the approximation model and the true mathematical function that generates the data) when they are used to develop emulators. The goal of space-filling designs is to bound this bias (SAS Institute, 2013). This is done either by spreading the design points out as far from each other as possible without going outside the experimental boundaries or by spacing the points out evenly over the region of interest. By spreading the points as evenly or uniformly as possible, space-filling design methods increase the likelihood that phenomena that may affect the results are not overlooked.

The LH design is currently the most popular space-filling method. The method maximizes the minimum distance between design points but requires even spacing of the levels of each factor. It is a compromise between the sphere-packing method and the uniform design method. Like the sphere-packing method, the LH method chooses points so as to maximize the minimum distance between design points but with a constraint. The constraint maintains the even spacing between factor levels. For example, in an n x p LH design consisting of n runs for p factors, each factor is divided into as many levels as there are runs in the design. The levels are spaced evenly from the lower bound to the upper bound of the factor. LH samples are formed by randomly permuting individual columns. Thus, there are potentially a very large number of LH samples for any given number of factors and runs. A common selection strategy (called maximin LH) is to generate a large number of random LH samples and choose the one having the largest minimum distance between points.

For this study, the JMP statistics software was used to generate a maximin LH sample consisting of the nine factors identified in the base RSAP model (SAS Institute, 2013). For convenience, a standardized range of [-1, 1] was used for each factor when the LH sample was generated. A total of 120 points was chosen to cover the nine-dimensional parameter space. As noted earlier, this is a compromise in order to have a significantly good coverage of the design space and a significantly low computational cost. There are no specific criteria on sample size. A common rule of thumb is to use about 10 points per dimension.

RSAPv3 Runs

RSAPv3 was run at each of these 120 design points, and the output B/C ratio recorded in each case. The B/C ratios are calculated in RSAPv3 based on Equation 1. Here, benefits are the expected reductions in crash costs before and after guardrail installation. Relevant crashes in the before case are those involving the unshielded hazard. Crashes in the after case include crashes involving the guardrail and those involving the shielded hazard (e.g., if the guardrail is breached). Because the guardrail is closer to the roadway and has a longer span than the hazard it is shielding, there are likely to be more crashes in the after case than in the before case even though these mostly guardrail-related crashes are expected to be of lesser severity. All else being equal, installing the guardrail is expected to be beneficial only if annualized costs for these less severe guardrail crashes are outweighed by annualized costs for the more severe crashes that would occur without the guardrail. In addition, it was assumed for the purposes of this study that the guardrail is offset 3 ft from the edge of the travel way. The farther the hazard to be shielded is from the road, the higher the likelihood that the guardrail installation will actually result in more frequent crashes than would occur if the hazard were left unshielded, which will tend to drive down the B/C ratio.

Because the LH sample consisted of values in the range [-1, 1], all values were transformed back to their original scales before being used as inputs to RSAP in accordance with Equation 5:

$$x_{ik} = x_k^{\min} + \frac{1}{2}(x_k^{\max} - x_k^{\min})(x_{ik}^* + 1) \qquad \text{[Eq. 5]}$$

where

x_{ik} is the *i*th (unstandardized) value of the *k*th factor used in RSAP

x_{ik}^* is the *i*th (standardized) value of the *k*th factor in the LH sample

$x_k^{\min}$ and $x_k^{\max}$ define the minimum and maximum allowable values for the *k*th factor.

Gaussian Process Model

The GP model is often used to fit data from deterministic computer experiments. The GP's appeal stems from the fact that these models provide an exact fit to the computer simulation data. In other words, if the GP prediction function is supplied with an input that matches one of the design points (i.e., training data), it returns the same output as would the computer model (RSAPv3 in this case) with no uncertainty. At other points of interest (in the input space but not used for model development), the function predicts an output response that is an interpolation of the training data and quantifies the uncertainty around the interpolated value.

The GP model is a statistical model adapted from the spatial statistics literature. It was proposed for use as a surrogate model for deterministic computer experiments by Sacks et al. (1989). The GP model treats the deterministic output $\mathbf{y}$ as a realization of a Gaussian stochastic process with mean μ and covariance (Eq. 6)

$$Var(\mathbf{y}) = \sigma^2 \mathbf{R}(\boldsymbol{\theta}) \qquad \text{[Eq. 6]}$$

The correlation matrix $\mathbf{R}(\boldsymbol{\theta})$ may be defined as one of several functional forms including the Gaussian, the exponential, the cubic, and the Bohman functions (see Santner et al., 2003). Two of these functions—the Gaussian and the cubic correlation functions—are available in JMP where the elements of $\mathbf{R}(\boldsymbol{\theta})$ are as defined by Equations 7 and 8, respectively (SAS Institute, 2013).

$$r_{ij} = \exp\left(-\sum_{k=1}^{p} \theta_k (h_k)^2 \right) \qquad \text{[Eq. 7]}$$

$$r_{ij} = \prod_{k=1}^{p} \rho(h_k \mid \theta_k) \qquad \text{[Eq. 8]}$$

where

$$h_k = x_{ik} - x_{jk} \qquad \text{[Eq. 9]}$$

$$\rho(h_k \mid \theta_k) = \begin{cases} 1 - 6(\theta_k h_k)^2 + 6(\theta_k \mid h_k \mid)^3, & \mid h_k \mid \le \dfrac{1}{2\theta_k} \\ 2(1 - \theta_k \mid h_k \mid)^3, & \dfrac{1}{2\theta_k} < \mid h_k \mid \le \dfrac{1}{\theta_k} \\ 0, & \dfrac{1}{\theta_k} < \mid h_k \mid \end{cases} \qquad \text{[Eq. 10]}$$

The parameter $\boldsymbol{\theta}_{(p\times1)}$ specifies the degree of smoothness of the GP model in terms of how far a point needs to go from a design point before the uncertainty becomes appreciable (O'Hagan, 2006). In JMP, the GP model parameters μ, σ^2, and $\boldsymbol{\theta}$ are estimated using the maximum likelihood method (SAS Institute, 2013).

Application to the RSAP Model for Guardrail Needs Analysis

Data

The 120 x 9 LH sample generated earlier and corresponding RSAP outputs were used to develop an emulator for guardrail needs analysis. As noted by Gentle et al. (2004), an LH sample may happen to include outlier scenarios because of the randomness inherent in the design process. Based on the results of the RSAPv3 runs, 2 of the 120 design points were deemed outliers (z-score greater than 3) and were therefore not used in model development.

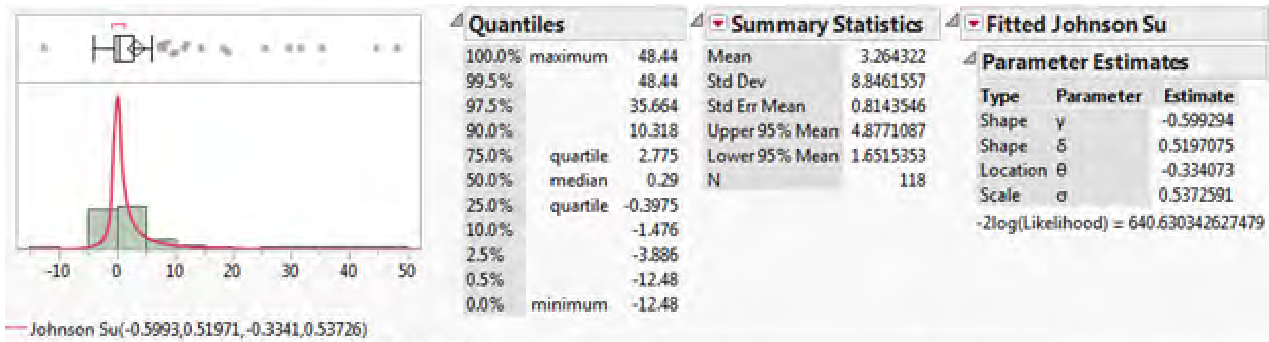
As noted earlier, two speed limit values (45 mph and 55 mph) and two hazard types (point and line hazards) were considered. Thus there was a total of four speed limit–hazard type combinations. For each LH design point, RSAPv3 was run at each of these four speed limit–hazard type combinations for a total of 118 x 4 (= 472) RSAPv3 runs. The results of the RSAPv3 runs including the distributions of B/C ratios, quantiles, and corresponding summary statistics are shown in Figure 4. Also shown for each plot are parameter estimates for an unbounded Johnson (S_U) distribution fit to the B/C ratio data (Law and Kelton, 2000).

The plots in Figure 4 indicate that the output B/C ratios were highly positively skewed with most of the ratios less than 1.0 for point hazards and less than 2.0 for line hazards. The mean B/C ratio when shielding point hazards was 1.9 for the 45 mph speed limit scenario and 3.2 for the 55 mph scenario. The means were 4.6 and 7.6, respectively, when shielding line hazards for the 45 mph segment and the 55 mph segment scenarios.

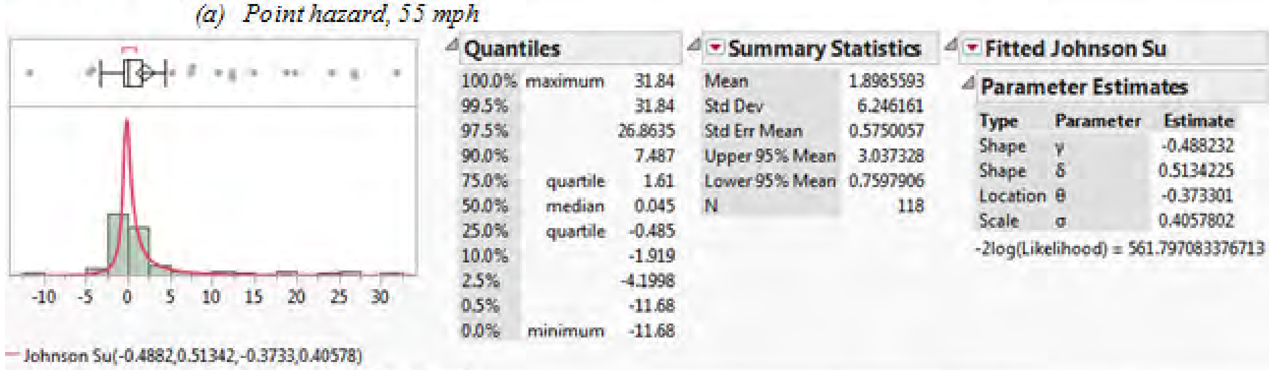
Model Estimation

A predictive model was developed to relate the B/C ratios generated from RSAP to their corresponding inputs. Model estimation was done in two steps. First, a linear regression model was fit to the data and all residuals between individual inputs and their predicted values were recorded; second, a GP model was fit to these residuals. Using a good linear regression model means that much of the variation in the RSAP output B/C ratios, in response to the input variables, is explained by the regression function. The GP is then used to model only the part of the variation that is not explained by the linear regression function. As noted by O'Hagan (2006), this two-step approach tends to result in a "smoother" fit of the data.

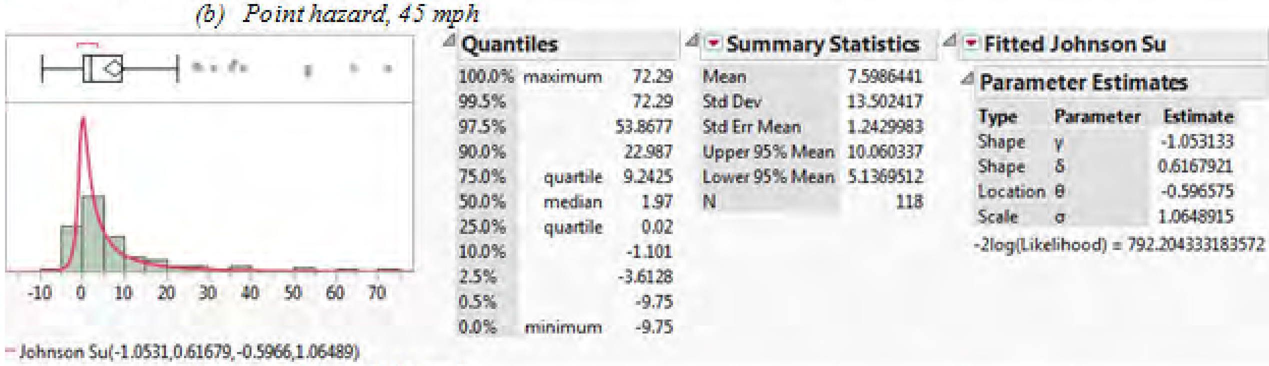
An important assumption of both the linear regression and the GP model is that the output response **y** is normally distributed. However, the distributions of the B/C ratios as shown in Figure 4 were highly skewed and best approximated by the Johnson S_U distribution. As a consequence, the Johnson S_U transformation shown in Equation 11 was applied to transform the data to the normal distribution and to reduce the effects of outliers. The values of the Johnson S_U parameters were estimated using JMP and are also shown in Figure 4.



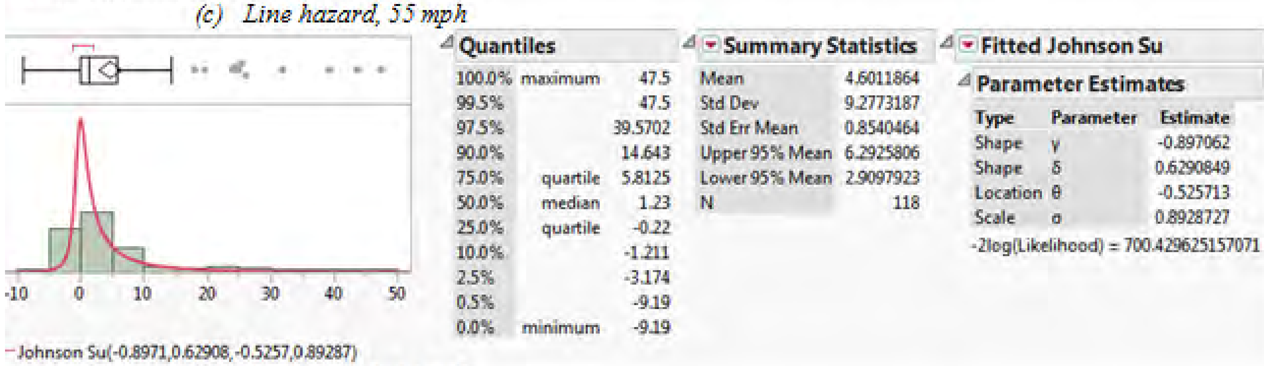
(a) Point hazard, 55 mph



(b) Point hazard, 45 mph



(c) Line hazard, 55 mph



(d) Line hazard, 45 mph

Figure 4. Distributional Characteristics of Benefit-Cost Ratio Output From RSAP Runs

$$z = \gamma + \delta \sinh^{-1}\left(\frac{x-\theta}{\sigma}\right) \quad \text{[Eq. 11]}$$

where

x is the B/C ratio, z its transformed value
γ, δ, θ, and σ are parameters of the Johnson S_U distribution (SAS Institute, 2013).

A regression model was fit to the data with the nine factors identified in the base RSAP model as predictor variables and the B/C ratio as the output response. All model estimation was done using normalized B/C ratios and standardized inputs from the LH sample, in the range [-1, 1]. The results of the regression analysis are summarized in Figure 5.

As can be seen from Figure 5, the signs of the coefficients (Draper and Smith, 1998) suggest that the B/C ratio of using the guardrail tended to increase with increasing ADT, hazard severity (EFCCR), and hazard size but tended to decrease as the other six variables were increased. Further, guardrail use tended to be more cost-beneficial at the higher speed of 55 mph than at 45 mph, and using guardrail to shield line hazards was, on average, more cost-beneficial than using it to shield point hazards.

JMP was used to fit a GP model to residuals obtained from the linear regression model using the cubic correlation structure (the exponential correlation structure was also explored but the cubic structure provided a better fit based on the negative log-likelihood). The results of the GP model estimation are summarized in Figure 6. These results suggest that the fitted surface is fairly "smooth" in all directions—as indicated by the generally low theta values. Therefore, when supplied with an input that is not one of the design points, the input would have to be quite far from a design point before the uncertainty in predictions became appreciable; if the input coincides with a design point, then there is no error in the prediction (O'Hagan, 2006).

Parameter	Estimate	P-Value
Intercept	0.0209	0.6798
ADT	0.0613	0.2304
Grade	-0.4637	<.0001*
Lane Width	-0.1378	0.0079*
Hazard Severity (EFCCR)	0.9475	<.0001*
Hazard Size	0.5417	<.0001*
Hazard Offset	-0.4045	<.0001*
Guardrail Length	-0.2913	<.0001*
Construction Cost	-0.1993	0.0001*
Cost of Fatality	-0.0515	0.3231
Hazard Type (Line = 0, Point = 1)	-0.0001	0.9981
Speed (45 mph = 0, 55 mph = 1)	0.0009	0.9883
Adjusted R-Square	0.597	
*Statistically significant at the 5% level		

Figure 5. Coefficient Estimates for Linear Regression Model

Parameter	Theta	Main Effect	Total Sensitivity
Point Hazard Model			
ADT	0.2094	0.0010	0.1116
Grade	2.5834	0.3106	0.7837
Lane Width	0.0666	0.0008	0.0013
Hazard Severity (EFCCR)	0.3397	0.0300	0.2377
Hazard Size	0.1540	0.0321	0.0506
Hazard Offset	0.3010	0.0063	0.1260
Guardrail Length	0.0100	0.0000	0.0000
Construction Cost	0.2225	0.0135	0.1024
Cost of Fatality	0.0100	0.0000	0.0000
Speed (45 mph = 0, 55 mph = 1)	0.1701	0.0000	0.0176
Mean	-0.0458		
Variance	0.4850		
-2*LogLikelihood	196.99		
Line Hazard Model			
ADT	0.2314	0.0315	0.0891
Grade	0.2846	0.0377	0.0785
Lane Width	0.0100	0.0000	0.0000
Hazard Severity (EFCCR)	0.2788	0.0141	0.0904
Hazard Size	0.7898	0.2375	0.4319
Hazard Offset	0.5964	0.0196	0.1498
Guardrail Length	0.0100	0.0000	0.0000
Construction Cost	0.4301	0.0375	0.1502
Cost of Fatality	0.3439	0.0018	0.1153
Speed (45 mph = 0, 55 mph = 1)	0.0999	0.0002	0.0040
Mean	-0.0225		
Variance	0.4278		
-2*LogLikelihood	119.14		

Figure 6. Gaussian Process Model Estimation Results

Model Validation

The predictive ability of the model was cross-validated using a jackknife technique. That is, the value of each observation (RSAPv3 output) was predicted with estimates of the prediction formula that did not include the observation itself (Myers et al., 2009). A scatter plot of the actual and predicted RSAPv3 output B/C ratios is shown in Figure 7 (B/C ratios shown in the figure are back-transformed from the normalized scale to the original scale).

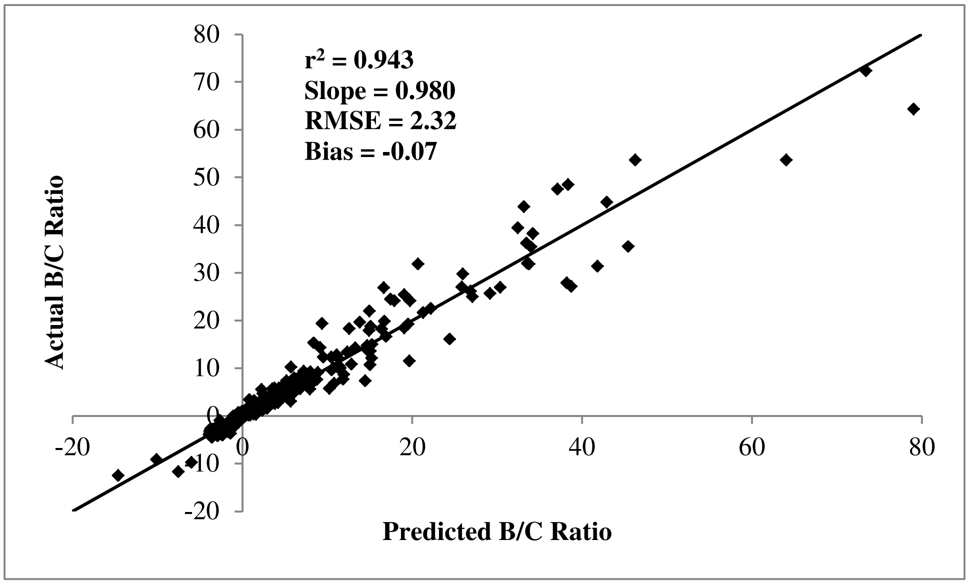


Figure 7. Plot of Actual vs. Predicted RSAPv3 Output B/C Ratio

One measure of the goodness-of-fit is how well the points lie along the 45 degree diagonal line (SAS Institute, 2013). Figure 7 also provides summaries of other measures of "misfit" including the root mean square error (Eq. 12), the slope of the "zero-intercept" least squares regression line (Eq. 13), the bias (Eq. 14) (Durand, 2007), and the square of the Pearson correlation coefficient (Eq. 15) (de Hoon and Eisen, 2002).

Root mean square error, $RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - y_i)^2}$ [Eq. 12]

("Low" values are desirable.)

$$Slope = \frac{\sum_{i=1}^{n} x_i y_i}{\sum_{i=1}^{n}(y_i)^2} \quad \text{[Eq. 13]}$$

(Values close to 1 are desirable.)

$$Bias = \frac{1}{n}\sum_{i=1}^{n}(y_i - x_i) \quad \text{[Eq. 14]}$$

(Values close to 0 are desirable.)

Pearson correlation coefficient, $r = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{x_i - \bar{x}}{s_x}\right)\left(\frac{y_i - \bar{y}}{s_y}\right)$ [Eq. 15] where

$\bar{x}, s_x$ and $\bar{y}, s_y$ are the means and standard deviation estimates, respectively, of the actual and predicted B/C ratios, x_i, y_i.

It may be seen from Figure 7 that most of the points are fairly close to the 45 degree diagonal line, which suggests that the model is a reasonably good fit. This is also supported by the fairly high r^2-value of 0.943 and the small RMSE of 2.32 (relative to a range of 84.77). The bias is also low at -0.07, suggesting that the emulator does not have a tendency to overestimate or underestimate the output response consistently. These metrics suggest that there is a fairly good agreement between the actual (RSAPv3) and the model-predicted B/C ratios. Thus the emulator appears to be a fairly good approximation of the true RSAP input-output relationship and can be useful for making predictions.

Application: Low Volume Road Guardrail Benefit-Cost Analysis Tool

The predictive models developed in this study were implemented in an Excel spreadsheet so as to facilitate application among VDOT engineers. This section describes essential features of this spreadsheet tool and demonstrates its application through examples.

Inputs

The spreadsheet consists of three worksheets: the User Guide, the Severity Calculator, and the Benefit-Cost Ratio Calculator. The User Guide provides a quick overview of the analysis tool. The Severity Calculator is used to quantify the severity of the hazard that is being analyzed in terms of an EFCCR. The actual calculation of a B/C ratio is done using the Benefit-Cost Ratio Calculator.

The following inputs are required and should be entered in the highlighted cells:

1. Average Daily Traffic (ADT). This is the projected two-way average daily traffic in vehicles per day, mid-life of the project. It may be determined from the construction-year ADT using Equation 16:

$$MidLifeADT = ADT_0\left(1+\frac{g}{100}\right)^{\frac{n}{2}} \qquad \text{[Eq. 16]}$$

where

$MidLifeADT$ = mid-life ADT for the roadway
ADT_0 = construction-year ADT
G = annual traffic growth rate (%)
n = design life (assumed equal to 20 years for this study).

The range of values that may be used is 50 to 4,000 vehicles per day.

2. Speed Limit. This is the posted speed limit, in miles per hour, for the section under study. Two speed limit options are available: 45 mph (the lowest available in RSAPv3) and 55 mph.

3. Vertical Grade. This is the vertical grade of the roadway section expressed as a percent. The allowable range is -6% to 0%. The grade may be set to 0% for sections with positive grades.

4. Lane Width. This is the width of the travel lane (one direction only), measured in feet.

5. Hazard Type. This is the type of roadside hazard that is being considered for guardrail treatment. For the purposes of this study, a hazard may be classified as either a point hazard or a line hazard. As discussed earlier, point hazards are roadside hazards that can be reasonably represented as points in space (examples include individual trees and bridge piers); line hazards are those that may be represented as lines (examples include a line of trees and the slope break line of an embankment). Area hazards such as embankments were not explicitly modeled because RSAPv3 did not have this capability. For this study, such hazards were treated as line hazards with the location of the line defined by, for example, the slope-break line. This approach provided B/C output that appeared reasonable and consistent with intuition.

6. Hazard Severity (EFCCR). As is the case in the RSAPv3 model from which the spreadsheet tool was developed, the severity of a roadside hazard is defined in terms of the EFCCR. For a given roadside hazard, the EFCCR essentially is the probability of observing a fatal crash with that hazard at a baseline impact speed of 65 mph. The Severity Calculator provides a method for estimating the EFCCR when crash data are available. Relevant crash data are those involving the roadside feature where there are no events preceding the crashes with the hazard under evaluation (e.g., ROR crashes for which the first harmful event involves the object under evaluation as retrieved from VDOT's crash databases). A detailed description of the EFCCR calculation method is provided in the RSAPv3 Engineer's Manual (Ray et al., 2012, Appendix B).

The method, as implemented in the Severity Calculator, requires the following as input: (1) the distribution of crash records by KABCO crash severity (K = fatal, A = incapacitating injury, B = non-incapacitating injury, C = possible injury, O = property damage only); (2) the posted speed limit; and (3) an estimate of the percentage of crashes involving the hazard that goes unreported. Table 3, from the RSAPv3 Engineer's Manual, provides a summary of the research findings regarding the percentages of unreported crashes (Ray et al., 2012, Appendix B).

Table 3. Summary of Unreported Crash Percentages by Hazard Type

Feature Type		Unreported (%)
Non-breakaway	Utility	12.2
	Luminaire	0.8
	Sign	67.0
	Traffic signal	0.3
Breakaway	Luminaire	7.9
	Sign	5.8
Longitudinal barriers	General	26.0
	Cable median	30.0
	Post-and-beam	50.0
	Concrete	77.0

Source: From the RSAPv3 Engineer's Manual (Ray et al., 2012, Appendix B).

By accounting for unreported crashes, the severity estimation algorithm ensures that the effects of severe crashes are not overrepresented in the analysis. For the purposes of this study, it was assumed that 10% of all crashes are not reported. This seems consistent with the values in Table 3 as the majority of the roadside features listed in Table 3 (especially those with high proportions of unreported crashes) are generally not candidates for shielding with guardrail (VDOT, 2005). The engineer may adjust the default based on local knowledge of the study site. Entering this information into the highlighted cells of the Severity Calculator will yield an estimate of the EFFCR value needed to calculate the B/C ratio.

EFCCR estimation using crash data is the preferred method and is recommended whenever crash records by KABCO crash severity are available. However, in the absence of site-specific crash data, the value of EFCCR may be selected from the fairly extensive library of default values available in RSAPv3. For convenience, a subset of these RSAPv3 defaults was summarized in the Severity Calculator (see Figure 10).

7. Hazard Size. For a line hazard, this is the length of the roadside hazard measured along the direction of travel; for a point hazard, the diameter is used. The allowable ranges of values were 10 to 200 ft for line hazards and 0.5 to 10 ft for point hazards.

8. Hazard Offset. This is the perpendicular distance of the hazard from the edge of the travel way. The allowable range of values was 4 to 20 ft.

9. Length of Guardrail. This is the length of guardrail (including end treatments) required to shield the hazard. The allowable range for this study was 100 to 600 ft.

10. Construction Cost. This is the total construction cost for the guardrail project. The allowable range of values was $1,000 to $40,000.

11. Crash Cost. This is the cost of a fatal crash. The allowable range was $4 million to $12 million.

Entering this information into the highlighted cells yields an estimate of the B/C ratio. This value can then be compared to a pre-established baseline minimum value (for example, 1.0) to determine whether the installation of guardrail is cost-beneficial relative to the do-nothing approach. The spreadsheet tool was designed with and is appropriate for only the allowable ranges stated. If the tool is used for other conditions, the results will not be dependable. A full RSAP analysis may be needed in such situations.

Example Problems

Problem 1

Description. Consider a 2V:1H foreslope that is 20 ft deep and offset 6 ft from the edge of the travel way on a two-lane roadway with 10-ft lanes. The slope is 75 ft long and located parallel to the roadway. The analysis section is assumed to be on a 2% downgrade. The posted speed limit is 45 mph. The present ADT is 750 vehicles with a projected 3% annual growth. Assume that it costs $25 to construct a linear foot of guardrail and a further $4,200 for two end treatments. Assume there has been a total of 13 crashes in the past 3 years: 1 fatal; 4 injury, and 8 property damage only crashes. A preliminary engineering study indicated that a 200-ft-long TL-3 guardrail offset 3 ft from the edge of the travel way may be needed to shield the roadside slope. Assume that the cost of a fatal crash is $5 million and a policy decision has been made that safety projects should be considered for funding only at a B/C ratio starting at 3.0.

Solution.

Step 1: Obtain an estimate of the hazard severity (EFCCR). This is done by entering the provided speed limit and crash data into appropriate cells in the Severity Calculator (see Figure 8). The proportion of unreported crashes is left unchanged at the 10% default because no such information has been provided in the problem statement.

Speed Limit (mph):	45
Crash Data	
(K) Fatal:	1
(A) Incapacitating:	0
(B) Non-Incapacitating	4
(C) Possible Injury	0
(O) Property Damage Only:	8
(Unk) Unknown:	0
Unreported Crashes (%):	10
*Hazard Severity	0.2215

Figure 8. Screen Shot of Part of Severity Calculator

Step 2: Determine the B/C ratio. This is done using the Benefit-Cost Ratio Calculator. The required inputs are as follows:

- $ADT = 750 \times (1 + 3/100)^{10} = 1{,}008$ vehicles
- Speed Limit = 45 mph
- Vertical Grade = -2%
- Lane Width = 10 ft
- Hazard Type = *Line*
- Hazard Severity = 0.2215 (from Step 1)
- Hazard Size = 75 ft
- Hazard Offset = 6 ft
- Guardrail Length = 200 ft
- Construction Cost = $25 \times 200 + 4200$ = \$9,200
- Fatal crash cost = \$5,000,000.

Using these inputs, the B/C ratio is calculated as 9.69 (see Figure 9). Since the predicted B/C ratio is greater than the baseline value of 3.0, shielding by guardrail is considered cost-effective.

ADT:	1008
Speed Limit (mph):	45
Grade (%):	-2
Lane Width (ft.):	10
Hazard Type:	Line
Hazard Severity:	0.2215
Hazard Size (ft.):	75
Hazard Offset (ft.):	6
Guardrail Length (ft):	200
Construction Cost ($):	9200
Fatal Crash Cost ($):	5000000
Benefit-Cost Ratio	9.69

Figure 9. Screen Shot of Part of Benefit-Cost Ratio Calculator

Problem 2

Description. Consider a 3.5-ft-diameter bridge pier that is offset 18 ft from the edge of the travel way on a two-way, two-lane roadway. For this example, the roadway is assumed to be on a flat grade. The posted speed limit is 55 mph. The present ADT is 2,200 vehicles with a projected 3% annual growth. Assume again that it costs \$25 to construct a linear foot of guardrail and a further \$4,200 for two end treatments. There are no crash records available. A preliminary engineering study indicated that a 100-ft-long TL-3 guardrail offset 3 ft from the edge of the travel way may be needed to shield this roadside hazard. Assume also that the cost of a fatal crash is \$5 million and a policy decision has been made that safety projects should be considered for funding only at a B/C ratio starting at 3.0.

Solution.

Step 1: Obtain an estimate of the hazard severity (EFCCR). Since for this example no crash data are available, the RSAPv3 default for bridge piers of 0.1784 listed in the Severity Calculator may be used (see Figure 10).

Hazard Name	Type	Severity
GenericBR	Line	0.0050
BridgeEdge_LowHaz	Line	0.0584
BridgeEdge_MedHaz	Line	0.1584
ClearZoneFence	Line	0.0060
EdgeOfMedian	Line	0.0425
Rock Ledge	Line	0.1800
TreeLine	Line	0.0300
Water	Line	0.0300
GenericAttenuator	Point	0.0120
BridgePierColumn	Point	0.1784
Delineator	Point	0.0020
Generic Fixed Obj	Point	0.1800
Luminaire	Point	0.0130
Mailbox	Point	0.0170
SignsBrkwy	Point	0.0030
SmallWoodSign	Point	0.0030
TrafficSignal	Point	0.0367
Tree	Point	0.0320
UtilityPole	Point	0.0310
GenericRigidWall	Point	0.0035

Figure 10. Screen Shot of Part of Severity Calculator Showing Default EFCCRs. EFCCR = equivalent fatal crash cost ratio.

Step 2: Determine the B/C ratio. The inputs required for the Benefit-Cost Ratio Calculator are as follows:

- $ADT = 2200 \times (1 + 3/100)^{10} = 2{,}957$ vehicles
- Speed Limit = 55 mph
- Grade = 0%
- Lane Width = 10 feet
- Hazard Type = *Point*
- Hazard Severity = 0.1784 (from Step 1)
- Hazard Size = 3.5 ft
- Hazard Offset = 18 ft
- Guardrail Length = 100 ft
- Construction Cost = $25 \times 100 + 4200$ = \$6,700
- Fatal Crash Cost = \$5,000,000.

With these inputs, the predicted B/C ratio is 0.32 (see Figure 11). Since this is less than the baseline value of 3.0, shielding by guardrail is not deemed cost-effective in this example.

ADT:	2957
Speed Limit (mph):	55
Grade (%):	0
Lane Width (ft.):	10
Hazard Type:	Point
Hazard Severity:	0.1784
Hazard Size (ft.):	3.5
Hazard Offset (ft.):	18
Guardrail Length (ft):	100
Construction Cost ($):	6700
Fatal Crash Cost ($):	5000000
Benefit-Cost Ratio	0.32

Figure 11. Screen Shot of Part of Benefit-Cost Ratio Calculator for Problem 2

Performance Evaluation of the Developed Tool

This section reports the results of the evaluation regarding the usefulness of the developed predictive model, named the Low Volume Road Guardrail B/C Analysis Tool, in making decisions about guardrail based on cost-effectiveness. The evaluation examined the general trends of predictions through sensitivity analysis and tested the tool's ability to correctly predict/classify the application of guardrail to new cases (not used for model development) as cost-beneficial or not cost-beneficial.

The Excel Profiler tool in JMP was used to visualize and perform what-if analysis for each of the four hazard type–speed limit scenarios. Snapshots of the prediction profiles generated for each scenario are shown in Figure 12. The B/C ratios indicated in the profiler plots are the predictions made when all inputs were set at values equal to the midpoints of their respective ranges. For each plot, the solid black line shows trends in the predicted response if that variable were to change while all the others were held constant at their current values (i.e., midpoints of their respective range). For example, it may be seen from Figure 12c that in general the B/C ratio of using the guardrail relative to the do-nothing alternative increases as traffic (ADT), hazard severity (EFCCR), hazard size, and the fatal crash cost increases. However, the use of the guardrail generally becomes less cost-beneficial as vertical grade, hazard offset, length of guardrail, and construction costs increase. Further, increasing the width of travel lanes seems to make the guardrail less beneficial but only minimally so. These general trends seem reasonable or consistent with expectations and provide some support for the potential usefulness of the analysis tool as a credible surrogate to RSAPv3 when B/C analysis of guardrail needs on low volume roads is conducted.

The spreadsheet tool was further investigated with respect to its effectiveness in distinguishing cases for which the application of guardrail is potentially cost-beneficial from those for which it is not. To do this, a sample of 180 new cases (45 cases for each speed–hazard type combination) was generated using LH sampling. Each case consisted of a set of values drawn from applicable ranges of the input variables. For each case, RSAPv3 was run and the use of guardrail was classified as cost-beneficial if the output B/C ratio was more than 1 and not cost-beneficial if the B/C ratio was 1 or less. All new cases were also input into the spreadsheet tool, and the B/C predictions made by the tool were noted.

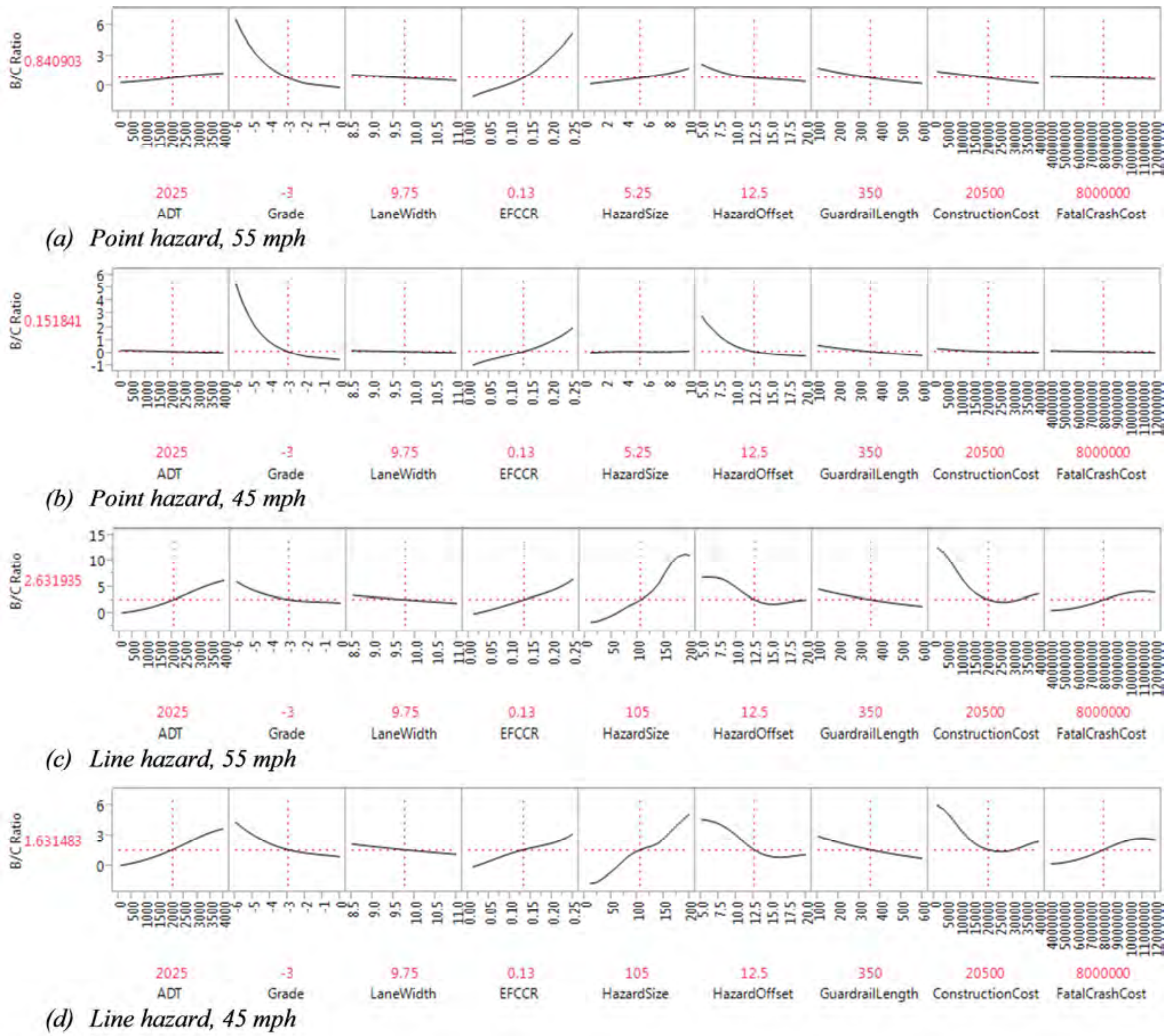


Figure 12. Prediction Profiler Plots for Emulator Inputs and Output B/C Ratio. For each plot, the solid black line shows trends in the predicted response if that variable were to change while all the others were held constant at their current values (i.e., midpoints of their respective range).

Figure 13 is a matrix showing the number of correct and incorrect predictions made by the spreadsheet tool compared to the actual outcomes (RSAPv3 output) in the sample data. The overall accuracy of the predictions was 89.4%. Approximately 90% of actual positive (cost-beneficial) cases were correctly classified as such, and approximately 89% of negative cases were correctly identified as such. The figure also shows that in 12 of the 180 cases the use of guardrail was incorrectly predicted as cost-beneficial and in another 7 cases the use of guardrail was predicted as not being cost-beneficial when in fact it was. Both of these misclassification rates have implications for both VDOT and the road user. For example, the former rate of 6.7% has cost implications, and the latter rate of 3.9% has safety implications and is perhaps more critical. Nevertheless, the estimated rate of 3.9% is fairly low (<5%) and should not detract from the usefulness of the tool in the guardrail application decision-making process.

		Actual (RSAPv3)	
		Not Cost-Beneficial	Cost-Beneficial
Predicted (Spreadsheet Tool)	Cost-Beneficial	12	64
	Not Cost-Beneficial	97	7

Proportion correctly predicted = 0.894

Figure 13. Matrix of Actual and Predicted Outcomes of Guardrail B/C Assessment

CONCLUSIONS

- *The emulator developed in this study appears to be a good statistical approximation of B/C analysis using RSAPv3 software.* A plot of the actual B/C ratios produced by RSAPv3 and the corresponding values predicted with the emulator were reasonably close to the 45 degree line. This conclusion was also supported by the results of other validation metrics such as the r-square and the root mean square error.

- *For ease of use, the emulator was implemented in an Excel spreadsheet titled Low Volume Road Guardrail B/C Analysis Tool. Application of this tool to new data (not used in model development) produced results that were comparable to those produced by RSAPv3.* Sensitivity analysis using the spreadsheet tool yielded trends in predicted B/C ratios with respect to changes in the inputs that were consistent with expectations. The spreadsheet tool was also successful (89.4% accuracy) in distinguishing between new cases where the use of guardrail was known to be beneficial and cases where it was not. Thus, when used together with sound engineering judgment the spreadsheet tool can be a useful aid to assessing the need for guardrail on low volume roads.

- *The spreadsheet tool has high potential for widespread use by VDOT engineers.* Application of the spreadsheet tool produced results that were comparable to those produced by RSAPv3 and did so in a fraction of the time required for a full-blown RSAPv3 analysis. This should allow for objective and quick turnaround evaluation of guardrail treatment options for low volume roads in Virginia.

RECOMMENDATIONS

1. *VDOT's Traffic Engineering Division (TED) should encourage the use and facilitate the further evaluation of the Low Volume Road Guardrail Benefit Cost Analysis Tool developed in this study when considering the need for guardrail at specific locations on existing low volume roadways.*

2. *VDOT staff who use the tool should cooperate with VTRC staff to help evaluate the effectiveness of the tool. Electronic records associated with the use of the tool including a description of each use, the decision made and why it was made, comments, problems, and suggestions for improvement of the tool should be kept and access to such records should be provided to VTRC staff. After the tool has been in use for two years, the Virginia Transportation Research Council should review all comments received and make revisions to the tool if necessary.* This would be conducted as a technical assistance project and reported to VDOT's TED.

BENEFITS AND IMPLEMENTATION

Benefits

This study contributes to VDOT's goal of using data-driven prioritization models to help determine allocations of transportation funding. The study recommendations will encourage a cost-effective decision making process for assessing the need for guardrail installation within VDOT. VDOT engineers should be able to make informed, defendable decisions using the guidelines and have consistent engineering judgment across the state regardless of location.

Implementation

Implementation of the recommendations of this study will involve multiple steps:

1. *Within one month of the report's publication, VTRC in conjunction with the project champions will develop a standardized template of electronic records to be used to track the tool usage.* The template should be vetted through TED and the ATEs.

2. *Within two weeks of the development of the template, VDOT's TED will send an email to the VDOT area traffic engineers (ATEs) encouraging and promoting the use of the Low Volume Road Guardrail Benefit Cost Analysis Tool.* The email will also direct the ATEs to keep the results of each application of the tool using the standardized template through the first two years of use and provide VTRC access to such records.

3. *After two years of implementation, VTRC and TED will evaluate the effectiveness of the tool based on the feedback received from the field users. VTRC and TED may make necessary revisions of the tool and issue additional guidance as needed.*

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