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ABSTRACT

This effort addresses the need for a logic-driven process that the Virginia Department of Transportation can use to allocate resources to run-off-road and fixed-object hazards on diverse secondary road systems. In Virginia, there are approximately 60,000 miles of roadway where guardrail upgrade, installation, or related warning signs or protection may be appropriate to address run-off-road and fixed-object hazards. In this project, an information system was developed to aid the planner in guardrail resource allocation by accounting for the potential crash severities, traffic exposures, costs of treatment, and other factors.

A user manual accompanying the report describes the three developed software packages (database, screening, and site evaluation) in detail, including a demonstration of the software in a case study of New Kent County, Virginia.
INTRODUCTION

Transportation agencies across the nation face the fact that there is not enough available funding to implement all warranted safety improvements. The decisions of what projects to fund must be rational and defensible to minimize undue criticism and lawsuits against the agency. In particular, highway agencies receive limited funding for addressing guardrail needs, which include installation of guardrails in new locations and where existing structures are sub-standard or damaged. Agency officials deciding how to allocate the limited guardrail funding need help to prioritize the hazardous sites for guardrail improvements.

Allocation of guardrail funds in VDOT districts is driven by citizen complaints, familiarity of local engineers with the sites, and crash histories. Once a site is determined to meet the requirements for a guardrail, the funding for that site is placed in a queue of projects waiting for funding. Currently, there is no method for recording hazardous locations and their pertinent information such as citizen complaint history and the severity of site. There is no current method for comparing a guardrail improvement with other guardrail improvements. And, there is no current method for coming up with a broad way of describing the impact a guardrail improvement would have compared to non-guardrail improvement projects.

Prior to the current effort, the Richmond District of VDOT started a database of guardrails installed on interstate and primary systems; the database did not include characterization of the protected or unprotected hazards. Thus a need and opportunity for a decision aid to improve the allocation of limited funding to the maintenance and construction of guardrails and similar categories of assets have been identified. The effort was specifically requested by and developed in collaboration with the Richmond District of VDOT.

PURPOSE AND SCOPE

The current effort develops a risk-cost-benefit decision aid for the screening and evaluation of sites needing guardrail improvements. The effort develops a database and decision aids for an allocation decision where there has heretofore been no process: guardrail installation has traditionally been driven by citizen complaints and recent run-off-road crash histories. Engineers have not heretofore had the tools to compare protected hazards (what has been done) with unprotected hazards (what is proposed). While national standards for guardrail specify the equipment that can be placed at a given hazard, the standards and vehicles traveling the roads have evolved over 50 years, leading to many installed guardrails that do not meet current standards of safety. Thus, there can be the dilemma whether to upgrade older equipment or to address previously unprotected hazards with the limited available funds.

The developed approach is in three parts:

1. **Database.** A database of protected and unprotected run-off-road and fixed-object hazards is specified. For each hazard, a variety of statistics are recorded, including,
for example, a run-off-road severity index, the average daily traffic, and the standard of existing guardrail.

2. **Screening.** A corridor-to-corridor comparison is performed across a region based on corridor-wide crash histories, corridor-average daily traffic, extent of guardrail coverage, and other corridor-aggregate factors. Charts for exploratory data analysis help planners select what corridors are most in need of further study.

3. **Evaluation.** Within a corridor of concern, candidate guardrail sites are able to be compared using alternative benefit-cost ratios. The formulation enables the planner to learn by prioritizing locations alternately based on length and severity of the hazards, vehicles per day, vehicle-miles per day, and cost. Applying alternate sets of constraints and criteria suggests those locations where funding would be most consistent with the needs and values of the locality and the transportation agency.

For Fiscal Year 2001-02, there is $875,000 budgeted for maintenance of guardrail in the Richmond District, representing 1.2% of the asset-maintenance budget. For Fiscal Year 2000-01, there is $613,000 in allocation for new construction of guardrail in the Richmond District for the National Highway System (NHS) and interstate, NHS and non-interstate, and primary road systems, representing 0.8% of the total allocation for construction. These percentages are expected to vary from district to district. The percentages should not be viewed as the only opportunity for cost savings presented by an improved resource allocation to guardrails. Rather, improvements to the allocation of guardrail funding as well as the improved management of other categories of assets such as signs, signals, lighting, pavement, and others, are applicable.

The results of this effort can be integrated with other current VDOT initiatives such as ICAS (Inventory Condition Assessment System). ICAS is a project undertaken by VDOT for the purpose of recording all VDOT investments, such as stop signs, road conditions, etc. The current effort can be integrated with the ICAS effort by having resident engineers surveying the roadways indicate potentially hazardous locations and record pertinent information, such as geographic (GPS) coordinates for the hazard site and its severity. Also, the engineers could record suggested remedial measures for the hazard site, which would also be recorded. Once a complete survey of the roadways has been completed, the methodology for prioritizing guardrail projects can be used to highlight those locations where a guardrail improvement would have the most impact.

**LITERATURE AND PRACTICE REVIEW**

The results of a survey of methods of comparing locations for guardrail installation and upgrade are summarized. Techniques for ranking prospective projects and methods of performing cost-effectiveness analyses are described. Elvik (1995) summarizes over 30 studies of the safety effects of median barriers, guardrails along the edge of the road, and crash cushions (impact attenuators). Sources providing warranting methods for identifying locations in need of guardrail installation or upgrade are also identified. Prioritization and cost-effectiveness tools
are helpful in comparing locations needing guardrail installations or upgrades, while warranting methods merely indicate when a project is justified. It is unlikely that warranting methods would be used for comparing locations. A summary of a survey of state departments of transportation identifying the methodologies used by some states in evaluating locations needing guardrail installation or upgrade is also provided.

**Ranking Techniques**

Kentucky requires highway districts to keep an inventory of all substandard guardrails as well as unshielded locations that meet certain criteria (Pigman and Agent 1991). This inventory provides a listing of locations warranting a guardrail project. A procedure for prioritizing the locations to allocate funds most effectively is described by Pigman and Agent (1989). The method first develops critical rates of run-off-the-road accidents. Next, a screened list of locations with a critical rate of accidents is created, and a hazard-index point system is developed with a field study providing the necessary data. Next, the improvement benefits and costs are determined and the cost-effectiveness of the projects are analyzed. The procedure results in a list of projects recommended to receive funding.

The first step of the procedure is the development of critical accident rates. The critical rates serve as indicators of locations with a particularly high number of accidents. The critical accident rate for a type of roadway section is calculated according to equation (1):

\[
A_c = A_a + K \left( A_a \frac{1}{M} + \frac{1}{2M} \right)^{\frac{1}{2}} \text{accidents/million vehicle miles - sections}
\]

\[
A_a \text{accidents/million vehicles - locations}
\]

where

\( A_c \) = critical accident rate
\( A_a \) = average accident rate, only for accidents where vehicles ran off of the road
\( K \) = constant related to level of statistical significance selected

(\( K = 2.576 \) for a probability of 0.995)

\( M \) = exposure (for sections, \( M \) is in terms of 100 million vehicle - miles,

for spots, \( M \) is in terms of millions of vehicles)

The critical rate factor for each location is then determined by dividing the average accident rate for a given section by the critical accident rate for that type of roadway section. Locations with critical rates greater than 1.0 are evaluated further, while locations with a critical factor less than 1.0 are screened out of the process.
Next a hazard-index point system is described. The system is used to rank the screened list of projects. Each factor in the system is weighted based on its level of perceived relevance. The value for each location for each factor, determined by a field study, is multiplied by the factor’s weight. The terms are then summed to arrive at the score for a given location. The factors included in the hazard-index system and their associated numerical weights are:

1. Number of run-off-the-road accidents (15)
2. Run-off-the-road accident rate (15)
3. Traffic volume (10)
4. Speed limit or prevailing speed (10)
5. Lane and shoulder width (10)
6. Roadside recovery distance (10)
7. Embankment slope (10)
8. Embankment height (10)
9. Culvert presence (5)
10. Subjective roadside hazard rating (5).

Following this analysis, the improvement costs and benefits are determined. The method uses severity levels and costs in the determination of benefits. Costs associated with each accident severity level, as provided by the Federal Highway Administration, along with the accident reduction factors result in an accident reduction benefit for each improvement alternative. It is unclear, however, how adding guardrails reduces the number of accidents. Nevertheless, a cost-effectiveness analysis is subsequently pursued. The method of cost-effectiveness analysis is not described, although the inputs into the budget optimization are given:

- Number of locations to be analyzed
- Budget levels to be considered
- Costs assigned to each accident severity
- Interest rate
- Traffic growth rate
- Accident history
- Alternatives for reducing accidents
- Expected improvement life
- Improvement cost
- Annual maintenance cost
- Expected reduction in accidents due to improvements.

The methodology presented by Pigman and Agent (1989) is valuable in its identification of factors important in the comparison of locations needing a guardrail project. However, although the hazard-index point system suggested provides a quick method for comparing locations, weighted-sum scores have no real basis in decision theory. For example, there is no discussion of the conflicting units among the different factors. Furthermore, there is no basis for assigning a weight to a factor (Pomerol et al. 2000). Weights, once developed, are likely to be used without introspection by subsequent analysts and managers (Frohwein et al. 1999).
AASHTO (1977) suggests a ranking factor for comparing sites for crash cushion installation (equation (2)). In principle, it would be possible to apply the same theory to guardrail sites.

\[
RF = \frac{(1 + NOA) \times ADT \times S}{10,000}
\]

(2)

where

\(RF\) = ranking factor ( (accidents - veh - miles)/(year - day - hour) )

\(NOA\) = number of accidents at the site (accidents per year)

\(ADT\) = averaged daily volume of traffic (vehicles per day)

\(S\) = operating speed of roadway (miles per hour)

Like the weighted-sum scores presented by Pigman and Agent (1989), the value of the ranking factor is its expediency in comparing locations; however, there is no basis in decision theory. Consider the hypothetical data of Table 1 where although \(RF_A = RF_B\), there is no underlying theory to support that a decisionmaker would be indifferent between A and B.

<table>
<thead>
<tr>
<th></th>
<th>NOA</th>
<th>ADT</th>
<th>S</th>
<th>RF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site A</td>
<td>3</td>
<td>20,000</td>
<td>60</td>
<td>480</td>
</tr>
<tr>
<td>Site B</td>
<td>3</td>
<td>40,000</td>
<td>30</td>
<td>480</td>
</tr>
</tbody>
</table>

The ranking factors for these two sites, A and B, are equal, yet it is unlikely that a decision-maker would be indifferent to adding a safety feature to either of the two. Caldwell and Wilson (1999) describe a safety improvement program. Its goal is to identify locations where the largest potential safety benefits can be attained. A section, such as the roadway between two intersections, is given a primary rating factor based on traffic volume and user types such as local, recreational, and tourist. This rating is then adjusted by factors that account for speed, heavy vehicles, and terrain, and the adjusted rating is then used to prioritize the sections. Detailed data collection is not required as each factor is rated subjectively as high, average, or low relative to other road sections in the area.

**Cost-effectiveness Approaches**

A body of research uses cost-effectiveness analyses to evaluate safety improvement projects. In general, these methods compare the costs of the improvements to the benefits derived from the improvements. Mak (1993) provides an overview of methods applying cost-effectiveness procedures to the evaluation of roadside safety improvements, i.e., guardrails. A benefit-cost ratio used for comparing design alternatives is presented in equation (3):
The study makes a distinction between the use of encroachment probability models and accident data-based models as a basis for the cost-effectiveness analysis in equation (3). In accident data-based models, the prediction of roadside accident frequencies is accomplished using multiple regression models. The study indicates that these models are limited in their usefulness because of inherent problems associated with regression analysis. The best model explains only 60% of the variation in accident frequencies. Furthermore, since over 80% of accidents are caused by driver errors, not roadway elements, using these elements as predictors of accident frequency is not tractable. An alternative to accident data-based models is encroachment probability models. Encroachment probability models include three major mechanisms: (1) a method for predicting the frequency of accidents; (2) a method for predicting the severity of accidents; and (3) a method for estimating accident costs and determining the benefit/cost ratio. These mechanisms are applied in equation (4):

\[
B / CRatio_{21} = (B_2 - B_1) / (C_2 - C_1) \tag{3}
\]

*where*

\[
B / CRatio_{21} = \text{Incremental benefit/cost ratio between alternatives 1 and 2;}
\]

\[
B_1, B_2 = \text{Benefits associated with alternatives 1 and 2;}
\]

\[
C_1, C_2 = \text{Costs associated with alternatives 1 and 2}
\]

Accident severities are expressed through severity indices that can be converted to societal or accident costs. Severity indices serve as indicators of the expected injuries consequences of a crash due to some hazard (Hall et al. 1994). The severity index assigned to an object depends on the object’s nature, e.g., strength, size.

Mak et al. (1998) provide a similar methodology using four modules: an encroachment module, an accident prediction module, a severity prediction module, and a benefit-cost module. Equation (5) brings together the modules:

\[
E(C) = \sum_{i=1}^{n} P(E) \times P(A \mid E) \times P(I_i \mid A) \times C(I_i) \tag{4}
\]

*where*

\[
E(C) = \text{Expected accident cost;}
\]

\[
P(E) = \text{Probability of an encroachment;}
\]

\[
P(A \mid E) = \text{Probability of an accident given an encroachment (mechanism (1));}
\]

\[
P(I_i \mid A) = \text{Probability of injury severity } i, \text{ given an accident (mechanism (2)); and}
\]

\[
C(I_i) = \text{Cost associated with injury } i \text{ (mechanism (3))}
\]
The first three modules are incorporated in the calculation. The benefit-cost module is then:

\[
E(AC) = \sum_{i=1}^{n} V \cdot P(E) \cdot P(A \mid E) \cdot P(I_i \mid A) \cdot C(I_i) \tag{5}
\]

where

\(E(AC)\) = Expected accident cost
\(V\) = traffic volume, ADT
\(P(E)\) = Probability of an encroachment (encroachment module)
\(P(A \mid E)\) = Probability of an accident given an encroachment (accident prediction module)
\(P(I_i \mid A)\) = Probability of injury severity \(i\), given an accident (severity prediction module)
\(C(I_i)\) = Cost associated with injury severity \(n\)
\(n\) = number of injury severity levels

\[
BC\ \text{ratio} = \frac{(AC_1 - AC_2)}{(DC_2 - DC_1)} \tag{6}
\]

where

\(AC_1\) = Expected accident cost of project 1
\(AC_2\) = Expected accident cost of project 2
\(DC_1\) = Direct cost of implementing project 1
\(DC_2\) = Direct cost of implementing project 2

There are a few minor differences between Mak et al. (1988) and Mak (1993). Mak et al. (1998) incorporate the traffic volume in the calculation of the expected accident cost. Second, the benefit-cost ratio of Mak et al. (1998) is slightly altered from that of Mak (1993). The ratio in Mak et al. (1998) shows that the expected accident cost should be less for the project that has a higher direct cost, forcing the ratio to be non-negative.

Glennon (1974) presents a slightly different cost-effectiveness approach based on a hazard model. The model considers:

1. Vehicular roadside encroachment frequencies
2. The percentile distribution for the lateral displacement of encroaching vehicles
3. The lateral placement of the roadside obstacle
4. The size of the obstacle
5. The accident severity associated with the obstacle.

The model is then:
The ratio in equation (7) compares the annualized cost of the improvement under consideration to the hazard reduction achieved by the improvement. This ratio can then be compared to the ratios of other proposed guardrail projects. The hazard score is given by one of two relationships.

The first relationship is:

\[
H = V \times P(E) \times P(C \mid E) \times P(I \mid C)
\]

where

- \(H\) = hazard index (expected number of fatal plus nonfatal injury accidents per year)
- \(V\) = vehicle exposure (number of vehicles per year passing through the section)
- \(P(E)\) = probability that a vehicle will encroach on the roadside within section \(L\); encroachments per vehicle
- \(P(C \mid E)\) = probability of a collision given that an encroachment has occurred; accidents per encroachment
- \(P(I \mid C)\) = probability of an injury (fatal or nonfatal) accident given a collision; fatal plus nonfatal injury accidents per year

This model is very similar to equation (4) given by Mak (1993). A second formula is given for calculating the hazard reduction of a given improvement [equation (9)].

Assuming an 11-degree encroachment angle and a 6-foot average vehicle length allows Figure 1 to be used to determine the necessary probabilities.

Equation (9) considers the properties of the roadside in determining the necessary probabilities. For example, the probability of a collision given an encroachment is a function of the vehicle’s lateral displacement: the distance from the roadside that the vehicle travels, the lateral placement of the obstacle; the distance from the roadside where the obstacle is placed, and the size of the obstacle: its length and width. These factors allow equation (9), a simple formula to use in real practice, to be applied to decisions.

Using Figure 1 with equation (9), the hazard reduction achieved by an improvement is determined. This is found by determining the hazard before the guardrail is added and subtracting the hazard after the guardrail is installed. Equation (7) is now applied to make a comparison of locations needing a guardrail project. The reduced severity of colliding with a guardrail versus the object or slope being shielded will be coupled with an increased probability
of colliding with the guardrail because the value of \( s \), the lateral placement of obstacle, is now reduced.

\[
H = \frac{E_f \cdot S}{10,560} \left\{ \left[ l \cdot P[y \geq s] \right] + 31.4 \cdot P[y \geq (s + 3)] + \frac{5.14 \cdot w}{n} \sum_{j=1}^{n} P[y \geq \left( s + 6 \cdot \frac{w \cdot (2j - 1)}{2n} \right)] \right\}
\]

where

\( E_f \) = encroachment frequency (number of roadside encroachments per year)

\( S \) = severity index (number of fatal and nonfatal injury accidents per total accidents)

\( l \) = longitudinal length of the roadside obstacle (feet)

\( P[y \geq \ldots] \) = probability of a vehicle lateral displacement greater than some value, as taken from Figure 1

\( y \) = lateral displacement of encroaching vehicle (feet)

\( s \) = lateral placement of obstacle (feet)

\( w \) = lateral width of the roadside obstacle (feet)

\( n \) = number of analysis increments for the hazard associated with the obstacle width. A reasonable subdivision is that, for widths up to 4 feet, each 2.5 feet of width is represented as one increment

\( j \) = number of the obstacle-width increment under consideration

\[ \sum \]

**Figure 1.** Probability of a vehicle’s lateral displacement being greater than \( X \) feet.
AASHTO (1996) presents a cost-effectiveness procedure. The technique calculates the total present worth of accident costs and highway department costs incurred over the life of the project. Equation (10) is the formula used in calculating the total present worth:

\[
TPW = C_a(K_i) + C_i + ARC + C_m(K_i) - C_s(K_j)
\]

10

where

- \(C_a\) = Accident cost based on initial collision frequency
- \(C_i\) = Installation cost
- \(C_m\) = Annual maintenance cost
- \(C_s\) = Salvage value of feature being studied
- \(K_c\) = Factor to account for project life, discount rate, and traffic growth rate
- \(K_i\) = Factor to account for the project life and the discount rate
- \(K_j\) = Factor to account for the project life
- \(ARC\) = Present worth of accident repair costs = \(\sum K_c * C_d * f\)
- \(C_d\) = Average collision damage repair costs for sides, corners, and face
- \(C\) = Initial collision frequencies for sides, corners, and face

To use AASHTO (1996) for comparing locations needing guardrail projects, one would compare the total present worth of each of the locations. The accuracy of the methodology can be questioned because of the uncertainties involved in estimating the average collision damage repair costs, initial collision frequencies, and other factors. The selection process should be supplemented by engineering judgment and experience.

The methodology presented in AASHTO (1996) is based on work done in AASHTO (1977). In the procedure, the total present worth cost for each alternative is determined, allowing a comparison to be made. Equation (11) gives the total present worth cost.

As is the case with the procedure presented in AASHTO (1996), the uncertainties involved in estimating these factors raise doubts with regard to the usefulness of the methodology. Indeed, this is the case with all cost-effectiveness procedures that use estimates of encroachment frequencies, collision frequencies, and/or accident severities.

**Warranting Methods**

Another body of research identifies when guardrail projects are warranted. Instead of comparing locations, these methods tell an analyst if a given location is justified in receiving a guardrail upgrade or an installation. Therefore, it is difficult to use a warranting method to compare locations needing guardrail installation or upgrade. One may envision that comparisons could be made by considering which locations more strongly warrant guardrails.
\[
C_s = (C_i) + (C_d * f * T) + (C_{OVD} * f * K_r) + (C_m * K_r) - (C_s * K_j)
\]

where

- \(C_i\) = Installation cost
- \(C_d\) = Average collision damage repair costs (present dollars)
- \(C_m\) = Annual maintenance cost (present dollars)
- \(C_{OVD}\) = Average occupant injury and vehicle damage cost per accident (present dollars).
- \(A\) severity index assigned to the obstacle helps determine the accident costs
- \(C_s\) = Salvage value of feature being studied
- \(f\) = collision frequency (accidents per year)
- \(T\) = useful life of the obstacle (years)
- \(K_r\) = Factor to account for the project life and the discount rate
- \(K_j\) = Factor to account for the project life

Warranting methods can be divided into three main categories: charts, flow-charts, and guidance tables and figures. The Georgia Department of Transportation gives a number of charts for determining locations that warrant guardrails, such as Figure 2 and Figure 3.

According to Figure 2, locations with slopes less drastic than 3:1 never warrant guardrails. Slopes more drastic than 3:1 may warrant guardrails if the roadside height is sufficiently severe. Georgia (1991) provides different figures for different traffic volumes, attempting to provide guardrails in the busiest locations in order to save the most lives and avoid the most injuries.

While Figure 2 is used for roads with more than 3000 vehicles per day, Figure 3 evaluates roads with slightly less daily traffic. As a result, the shape of the warranting curve is slightly altered. The combination of slope and height must be more drastic on the lower traffic volume road in order for guardrail to be warranted. For example, in Figure 2, at a height of 10 feet and a slope of 2.5:1, a guardrail is warranted. In Figure 3, these conditions would not warrant guardrail. The changing warranting curves attempt to incorporate a cost-effectiveness analysis by allowing higher trafficked roads to more easily warrant guardrails. The California Department of Transportation uses a similar graphic shown in Figure 4.

Figure 4 is similar to the charts used in Georgia (1991). However, there is only one chart provided; thus, the traffic volume aspect addressed by Georgia (1991) is omitted.

Wolford and Sicking (1997) develop simplified charts for determining when guardrails are warranted. The charts are derived from a benefit-cost analysis evaluating the severity of embankment heights of varying magnitude and varying lateral offsets of culverts. Three charts are given. Figure 5 provides warranting guidelines for cable guardrail; Figure 6 gives warranting guidelines for W-beam guardrails; and Figure 7 provides warranting guidelines when culverts are present.
Like the figures provided in Georgia (1991), these warranting charts attempt to bring a cost-effectiveness factor into the decision. Adjusting the warranting conditions according to daily traffic aims to put limited funds toward areas where the most citizens will benefit.
Figure 4. Warranting chart (California DOT 1999)

Figure 5. Cable guardrail need for embankments (Wolford and Sicking 1997)
Figure 6. W-beam guardrail need for embankments (Wolford and Sicking 1997)

Figure 7. W-beam guardrail need for culverts (Wolford and Sicking 1997)
AASHTO (1977) presents flow charts shown in Figure 8.

Figure 8. Flow chart used for warranting guardrail (AASHTO 1977)

Figure 9 is a chart similar to those already discussed.

Tables 2a and 2b are also used with the flowchart shown in Figure 8. These tables provide another means of determining if a guardrail is warranted.

### Table 2a. Guidance Table

<table>
<thead>
<tr>
<th>Non-traversable Hazard Within Clear Zone as Determined by Figure 10</th>
<th>Traffic Barrier Required?</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td>Rough rock cuts</td>
<td>X</td>
</tr>
<tr>
<td>Large boulders</td>
<td>X</td>
</tr>
<tr>
<td>Streams or permanent bodies of water less than 2 feet in depth</td>
<td>X</td>
</tr>
<tr>
<td>Streams or permanent bodies of water more than 2 feet in depth</td>
<td></td>
</tr>
<tr>
<td>Shoulder drop-off with slope steeper than 1:1</td>
<td></td>
</tr>
<tr>
<td>a. Height greater than 2 ft.</td>
<td>X</td>
</tr>
<tr>
<td>b. Height less than 2 ft.</td>
<td></td>
</tr>
</tbody>
</table>
Figure 9. Warranting guideline (AASHTO 1977)

Table 2b. Guidance Table

<table>
<thead>
<tr>
<th>Fixed Objects Within Clear Zone as Determined By Figure 10</th>
<th>Traffic Barrier Required?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sign, traffic signal, and luminaire supports</td>
<td></td>
</tr>
<tr>
<td>a. Breakaway or yielding design with linear impulse:</td>
<td></td>
</tr>
<tr>
<td>1. less than 1,100 lb-sec</td>
<td>X</td>
</tr>
<tr>
<td>2. Greater than 1,100 lb-sec</td>
<td>X</td>
</tr>
<tr>
<td>b. Concrete base extending 6 in. or more above ground</td>
<td>X</td>
</tr>
<tr>
<td>Fixed sign bridge supports</td>
<td>X</td>
</tr>
<tr>
<td>Bridge piers and abutments at underpasses</td>
<td>X</td>
</tr>
<tr>
<td>Retaining walls and culverts</td>
<td>X</td>
</tr>
<tr>
<td>Trees with diameter greater than 6 in.</td>
<td>X</td>
</tr>
<tr>
<td>Wood poles or posts with area greater than 50 in²</td>
<td>X</td>
</tr>
</tbody>
</table>
Figure 10 helps determine if objects are in the clear zone.

![Figure 10. Additional warranting guidelines (AASHTO 1977)](image)

An alternative chart given by AASHTO (1977), shown in Figure 11, provides step-by-step questions to determine if a guardrail upgrade project is warranted in a given location.

Step-by-step methodologies such as those in Figures 10 and 11 can be helpful in evaluating a location while avoiding numerous complex calculations.

Informal Contact with State Transportation Agencies

A number of state departments of transportation were contacted in order to understand how highway agencies compare locations needing guardrail installations or upgrades. In general, the agencies do not formally prioritize guardrail improvements. The agencies generally use warranting methods and fund warranted projects as allowed by their budgets.

The following questions were addressed to some U.S. state departments of transportation for the purpose of understanding how states across the country allocate their funds earmarked for safety improvements, including guardrails.

Figure 11. Flow chart used for evaluating currently installed guardrail

- 1. Is barrier warranted? NO → Remove barrier
- 2. Can hazard be reduced or eliminated so that barrier is no longer needed? YES → Eliminate or reduce hazard and remove barrier
- 3. Does barrier meet strength and safety standards? NO → Take corrective action
- 4. Does the lateral placement of the barrier meet suggested criteria? NO → Take corrective action
- 5. Is rail height proper distance above ground? NO → Take corrective action
- 6. Are posts firmly embedded? YES → Restore embedment
- 7. Are rails firmly attached to posts? NO → Tighten attachments
End of check

- NO
- YES

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1. Who in your agency, or elsewhere, has authority in the areas of funding allocation for guardrails, management of guardrail inventories, and screening of wide geographic areas for guardrail needs?

2. What recommendations do you have for a transportation agency that is faced with many needs for new installations and upgrades of guardrail but limited funding? (Please share your experiences in prioritizing your locations.)

3. Does your agency keep an inventory/database of all guardrail installations? (If so, then share your experiences in maintaining the inventory.)

4. What databases, reports, methodologies, etc., that are supportive of cost-benefit-risk analyses does your agency use for managing its inventory and needs for guardrail?

5. What standards does your agency employ to determine if guardrail is warranted (i.e., any criteria above and beyond the Roadside Design Guide)?

6. What are the factors you consider for replacement/upgrade of guardrail (e.g., obsolescence, height, new standards)?

The small number of states that do apply a process reflects the limited number of viable methodologies found in the literature. Responses to Question 1 indicate the complexity of decisions regarding allocation of guardrail funds. The changing of personnel involved in the decision makes consistency a challenge. Maintenance divisions of the agency most often manage allocation, but other involved divisions include roadway design, policy and budget, design and traffic engineers, highway safety engineers, state traffic engineers, and highway operations. New York State is divided by 11 regions, each of which is responsible for designing, constructing, and operating its own roads. Allocation of funds is managed within each region, so prioritization can be accomplished only on a regional level, and coordinating efforts across regions is difficult.

Responses to Question 2 indicate that Kentucky is one of few states that use a methodology that proactively prioritizes locations needing guardrail improvements. The Kentucky DOT builds on Pigman and Agent (1989, Section 2.5). The state of Washington uses a benefit-cost ratio to compare individual locations. Rhode Island recommends upgrading/installing guardrail in conjunction with other scheduled projects. Indiana first evaluates areas with high accident rates and subsequently includes average daily traffic statistics.

Question 3 responses indicate about a quarter of the interviewed states maintain a database of existing guardrails. The databases track such items as the amount of guardrail installed; the guardrail type, end treatment, location, and length; and information on completed projects. Some states indicate that they are in the process of developing databases. A detailed inventory, possibly integrated with a geographic information system (GIS), is beneficial to an agency evaluating roadway locations or sections for guardrail need. Information on each location is catalogued and readily accessible, giving decision makers all of the information they need when comparing locations.
The responses to Question 4 indicate most states apply the AASHTO Roadside Design Guide to individual sites, if any methodology is used at all. The guidance of the National Cooperative Highway Research Plan (NCHRP) 350 is also used in some cases.

Question 5 responses indicate the states emphasize that the judgment and expertise of a resident engineer should be integral to the process. Georgia, among a few other states, has developed a warranting standard.

Question 6 responses indicate most states evaluate physical characteristics such as obsolescence, height, absence of block-outs, substandard end treatments, insufficient length of need, rail condition, and crash-worthiness. Some states upgrade guardrails only when another project is scheduled concurrently in the location. Accident history, presence of a 3R/4R project, compliance with NCHRP 350 requirements, and Federal Highway Administration mandates are other factors planners evaluate.

In VDOT, personnel familiar with the areas in question decide whether or not to install guardrail. A cursory evaluation of the location is performed, and if funding is available, a guardrail is installed if justified in the evaluator’s eyes. Locations usually come under scrutiny as a result of identification by VDOT or through citizen complaints (VDOT 1999).

The New York State Department of Transportation (1999) also performs no prioritization of locations. Instead, each location is evaluated to determine if the clear zone is sufficient. When this is not the case, a guardrail is installed, provided funding is available. Guardrails are also installed whenever potential hazards cannot be made crash-worthy.

The Ohio DOT (1999) uses a warranting system to determine when a guardrail is justified. No prioritization of locations needing guardrail installations is performed.

The California DOT (1999) uses crash history, potential, geometrics, average daily traffic, and slope to determine when a guardrail should be installed. No prioritization technique is used.

In Minnesota, the DOT (1999) uses the AASHTO guide and evaluations by personnel to determine when guardrails are warranted. No prioritization of locations is done.

The clear zone requirements of the Wyoming DOT (1999) match those of the AASHTO guide. No prioritization of locations is done.

The Alaska Department of Transportation (1999) developed an automated spreadsheet for performing a cost-effectiveness analysis. The system requires data for “Traffic Input” such as the average daily traffic, a traffic growth factor, grade, number of lanes, lane width, and highway type. There is also a section for “Roadside Model Input,” which requires data on the slope rate, the offset of the slope/obstacle, and the slope/obstacle width and length. The system asks for a severity index for the hazard and a variety of cost factors and returns an accident prediction output and a project cost output. The cost output is broken down into the present worth and the annual costs.
METHODS OF ANALYSIS

The approach for the development of a decision aid for guardrail resource allocation is in three parts: (1) a database of protected and unprotected hazards is proposed; (2) a corridor-by-corridor screening is performed; and (3) a site-by-site evaluation of guardrail needs is performed.

Database of Protected and Unprotected Hazards

The development and maintenance of a database of guardrail and guardrail needs are addressed. There is yet no record or reporting format for the hazardous sites along the more than 60,000 miles of Virginia’s secondary roadway system. Nor is there a process for recording locations that are protected or unprotected by guardrail or other treatments, including what type and standard of protection is afforded to the sites. A standard recording format of hazardous sites is developed in order to capture in a database such characteristics as the location severity and the type and standard of existing guardrails. In addition, data such as daily traffic records and complaint records are associated with the respective sites. By compiling related information on hazardous sites in one database, calculations and comparisons of the sites in both an individual corridor and between different corridors can be performed readily. The database supports subsequent guardrail management approaches described here as depicted in Figure 12.

Figure 12. Excerpt from the database of protected and unprotected run-off-road hazard sites, characterizing locations, lengths, severities, traffic rates, existing and proposed guardrails, costs of remedy, accident history, complaints, among other factors
Corridor-by-Corridor Screening

Over 60,000 miles of Virginia’s secondary (and primary) roads are in need of screening for guardrail improvements. Figure 13 shows different attributes considered in identifying locations. It is infeasible to consider all of these possible locations together in a single funding cycle; the data collection alone would be unmanageable. Therefore, it is necessary to screen potential locations in aggregate groups that can later be analyzed in detail.

![Attributes Considered](image)

**Figure 13.** Attributes considered for corridor-to-corridor screening of guardrail needs

Thus, the method first entails a comparison of road corridors in broad geographic regions (e.g., counties or residencies). The data collection for comparing corridors across regions is manageable. Corridors are compared on the basis of guardrail coverage (e.g., percentage of covered hazards in a sample), guardrail condition, topography, accident history, or other relevant factors. For example, some districts of VDOT maintain a regional database with the number and condition of guardrails.

For corridor accident history, it is important to sort accidents into related and non-related incidents. Related events, which are fixed-object and run-off-road accidents, are those accidents that perhaps could have been prevented or alleviated through the use of guardrails. The type of accident designation in police reports varies in different law enforcement agencies, so it is important to define what kinds of accidents are potentially related to guardrail coverage.

An important factor in comparing corridors is the average daily traffic (ADT). The higher the ADT, the more the importance of a corridor. ADT is a measure of exposure; higher ADT leads to a greater number of guardrail-relevant accidents. With every vehicle that travels past a particular location, there is opportunity for an accident. A pilot study was conducted using data obtained from VDOT’s accident databases (HTRIS) of 17 roadway corridors in the Richmond District. Figure 14 compares 17 corridors based upon their daily vehicle miles traveled (DVMT) and their accident rates over a span of 1 year. DVMT is useful for comparing corridors as it reflects (more so than ADT) the exposure to hazards. Figure 14 shows that corridors 610 and 621 have the highest accident rates and may be excellent candidates for guardrail studies. Also, Figure 14 shows that corridors 601 and 634 have the highest amount of property damage per DVMT, making them excellent candidates for guardrail studies, as well.

Use of accident data to choose guardrail sites is precarious, yet by aggregating the accidents at all sites across a corridor, reliable indicators of corridor-wide need can be developed. The uncertainty of the extreme event of an accident in any one location is diminished. The
longer the corridor or the greater the ADT, the more reliable are the conclusions from accident history about the corridor need.

![Figure 14. Number of related accidents and amount of property damage per corridor daily vehicle mile traveled (DVMT): Used for corridor-to-corridor screening](image)

The effects as well as the number of accidents may be taken into account. Effects include the damage to persons and property associated with an accident. In Figure 14, corridors 601, 610, and 634 stand out as having high amounts of property damage associated with accidents and may heighten the concern of safety planners. The numbers of injuries and fatalities are two factors that can be considered in corridor screening. Comparisons can be made between corridors with low rates of highly severe accidents and corridors with high rates of less severe accidents.

Figure 14 provides insight as to which corridors should receive further attention. This figure is not used independently, in that insights from this figure can be supplemented with insight from another, helping the safety planner to focus on an area where further study should be applied. Following the high-level screening, an in-depth comparison of site needs follows.

**Site-by-Site Evaluation**

A detailed analysis is used to aid planners to select at a set of sites for allocation of funds. Benefit-cost analysis is a method for distributing limited resources as it maximizes or minimizes some objective function (the B/C ratio) while adhering to defined constraints. The approach
presented here is to consider the benefits alternately in different perspectives. Figure 15 presents different objectives that are used to aid the planner in site prioritization.

![Figure 15. Attributes considered in prioritizing individual locations](image)

In prioritizing locations needing guardrail installation or upgrade, there is a variety of useful mathematical objective functions and constraints. A planner may attempt to maximize the total length of hazardous sites protected for the largest number of people possible while staying within a monetary budget constraint. The following are examples of plausible objectives and constraints:

- **Miles protected.** A planner may wish to maximize the total length (centerline mileage) of hazardous sites protected.

- **Severity protected.** A planner may wish to maximize the hazardous sites protected based on their total severity. The severity rating of a hazard is dependent upon such factors as the roadside slope in the area, the average speed, the size of the hazard, etc. The assignment of a severity rating is performed by the surveying engineer. In the interest of consistency among raters, it is suggested that engineers train one another through case studies and attempts to reach consensus that the qualitative narrative description of the severity rating is representative of a particular site. The Roadside Design Guide (1996) is an example of the assignment of numerical severity ratings for hazards.

- **Vehicle miles protected.** The vehicle miles protected is the product of the length of the hazard and the average daily traffic at the site. It is important because the most cost-effective solutions protect the most traffic.

- **Severity miles protected.** The severity miles protected is the product of the severity index and the length of the off-road hazard.

- **Severity vehicle miles protected.** This is the product of the severity index and the daily vehicle miles (product of ADT and site length) protected at the site.

- **Cost.** Planners work with a limited budget, and thus cost is modeled as a constraint.

However, it also possible to model cost as an objective to be minimized.

A benefit-cost ratio is calculated for each site, with the benefit being one of the described objectives. The benefit-cost ratio is used to order the sites from most to least need. The planner
can select sites in such order until the budget constraint is reached. The objectives and constraints listed here are not necessarily the best measures to apply to the problem of prioritizing locations. A planner can easily substitute his or her own set of objectives and constraints. The alternate use of various objectives facilitates discussion and debate among the engineers, planners, and their constituencies.

RESULTS AND DISCUSSION

An on-site visit with VDOT personnel to secondary roads in the Richmond District was supplemented by ADT data obtained from VDOT’s HTRIS. The roads were selected from New Kent County by the district traffic engineer for their winding topography and proximity to the district office. The sample is not intended to be representative of the district as a whole. A sample of 10 locations for evaluation is selected to demonstrate the benefit-cost ratio formulation. Figure 16 shows the sample sites. The sample sites are located along a corridor that could have been identified using the aids described. Table 3 shows the data provided for the sites, and Table 4 shows the site severity scale 1 to 10. Table 4 was developed in consultation with field engineers who recommended that from Tables 3 and 4, the vehicle miles protected, the severity miles protected, and the severity vehicle miles protected are calculated for each location. These factors are shown in Table 5.

Tables 3, 4, and 5 are used in the program of benefit-cost ratio formulations. First, a project cost is estimated for each location. The cost typically depends only on the length of guardrail needed (a typical cost estimate is $10 per foot), the number and type of end treatments necessary (each end treatment is approximately $2,000), and whether or not the location needs an installation or an upgrade (upgrades are slightly more costly because the current guardrail on site must be removed). Table 4 was developed in the current effort to simplify a cumbersome severity assessment of Pigman and Agent (1991). Field engineers reported that application of the numerous tables and charts of Pigman and Agent (1991) was time consuming and inefficient and that Table 4 is an efficient and accurate substitute. Table 6 gives the costs assigned to each sample location.
Figure 16. Sample of sites along a corridor needing guardrail improvements

Table 3. Data for Each Hazard Site under Evaluation

<table>
<thead>
<tr>
<th>Location</th>
<th>Length of Need (miles)</th>
<th>Severity of Obstacle, Slope, Curvature, etc.</th>
<th>ADT (vehicles per day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>0.038</td>
<td>4</td>
<td>258</td>
</tr>
<tr>
<td>L2</td>
<td>0.061</td>
<td>9</td>
<td>258</td>
</tr>
<tr>
<td>L3</td>
<td>0.028</td>
<td>8</td>
<td>782</td>
</tr>
<tr>
<td>L4</td>
<td>0.038</td>
<td>1</td>
<td>485</td>
</tr>
<tr>
<td>L5</td>
<td>0.057</td>
<td>2</td>
<td>485</td>
</tr>
<tr>
<td>L6</td>
<td>0.095</td>
<td>3</td>
<td>485</td>
</tr>
<tr>
<td>L7</td>
<td>0.047</td>
<td>6</td>
<td>485</td>
</tr>
<tr>
<td>L8</td>
<td>0.322</td>
<td>9</td>
<td>1118</td>
</tr>
<tr>
<td>L9</td>
<td>0.011</td>
<td>8</td>
<td>1118</td>
</tr>
<tr>
<td>L10</td>
<td>0.320</td>
<td>10</td>
<td>531</td>
</tr>
</tbody>
</table>
Table 4. Severity Scale Used to Characterize Severity of an Unprotected Hazard at Candidate Site

<table>
<thead>
<tr>
<th>Severity</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 to 10</td>
<td>Permanent water hazards consisting of more than 2 ft of depth, slopes ratio much greater than 2:1 (indicating a high chance of vehicle rollover), fixed objects that present a clear danger to occupants of vehicles (such as the blunt “spear” ends of substandard guardrails), or areas of incidence include high potential for loss of life or property.</td>
</tr>
<tr>
<td>6 to 8</td>
<td>Water hazards that could potentially reach heights of over 2 ft during periods of flooding, slope ratio higher than 2:1, potential dangerous fixed objects (such as improperly mounted guardrails or a substantial number of trees with diameters greater than 4 in).</td>
</tr>
<tr>
<td>4 to 6</td>
<td>Slope ratio about 2:1 (marginal possibility for vehicle rollover), a small number of trees with diameters greater than 4 in).</td>
</tr>
<tr>
<td>2 to 4</td>
<td>Slope ratio less than 2:1, few fixed objects (such as trees with diameter greater than 4 in).</td>
</tr>
<tr>
<td>0 to 2</td>
<td>Area has a slope that is not likely to have vehicle rollovers occur, guardrails placed here will likely pose more of a hazard than do existing conditions, recovery zone adequate.</td>
</tr>
</tbody>
</table>

Table 5. Derived Factors for Each Hazard Site under Evaluation

<table>
<thead>
<tr>
<th>Location</th>
<th>Vehicle Miles Protected</th>
<th>Severity Miles Protected</th>
<th>Severity Vehicle Miles Protected</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>9.8</td>
<td>0.15</td>
<td>39.1</td>
</tr>
<tr>
<td>L2</td>
<td>15.9</td>
<td>0.55</td>
<td>142.9</td>
</tr>
<tr>
<td>L3</td>
<td>22.2</td>
<td>0.23</td>
<td>177.7</td>
</tr>
<tr>
<td>L4</td>
<td>18.4</td>
<td>0.04</td>
<td>18.4</td>
</tr>
<tr>
<td>L5</td>
<td>27.6</td>
<td>0.11</td>
<td>55.1</td>
</tr>
<tr>
<td>L6</td>
<td>45.9</td>
<td>0.28</td>
<td>137.8</td>
</tr>
<tr>
<td>L7</td>
<td>23.0</td>
<td>0.28</td>
<td>137.8</td>
</tr>
<tr>
<td>L8</td>
<td>360.2</td>
<td>2.90</td>
<td>3241.6</td>
</tr>
<tr>
<td>L9</td>
<td>12.7</td>
<td>0.09</td>
<td>101.6</td>
</tr>
<tr>
<td>L10</td>
<td>170.0</td>
<td>3.20</td>
<td>1699.6</td>
</tr>
</tbody>
</table>

For the 10 projects under consideration, a budget of $55,000 is assumed for the set of benefit-cost formulations where cost is a constraint, as shown in Figure 17. Each objective function is maximized in turn in Solutions 1 to 5. Table 7 gives the results when applying Microsoft Excel’s solver to maximize the factors from Figure 17. In Table 7, the numbers represent the order in which the benefit-cost ratios should be funded to maximize the overall benefit, with 1 being the most recommended and 10 being the least recommended. Table 8 shows the results of applying Microsoft Excel for the various objective functions (benefits) maximized in turn subject to the above budget constraint. Note, for example, that funding
locations 2, 6, 8, and 10 maximize the miles protected while remaining within the budget constraint. Table 8 gives the solutions for a sample of the additional maximization criteria discussed.

Table 6. Cost of Guardrail Project at Each Site

<table>
<thead>
<tr>
<th>Location</th>
<th>Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>$6,000</td>
</tr>
<tr>
<td>L2</td>
<td>$6,900</td>
</tr>
<tr>
<td>L3</td>
<td>$6,000</td>
</tr>
<tr>
<td>L4</td>
<td>$6,000</td>
</tr>
<tr>
<td>L5</td>
<td>$7,000</td>
</tr>
<tr>
<td>L6</td>
<td>$8,475</td>
</tr>
<tr>
<td>L7</td>
<td>$6,225</td>
</tr>
<tr>
<td>L8</td>
<td>$19,284</td>
</tr>
<tr>
<td>L9</td>
<td>$6,000</td>
</tr>
<tr>
<td>L10</td>
<td>$19,185</td>
</tr>
</tbody>
</table>

A transportation planner is now faced with deciding what solution, or combination of solutions, to implement. Tables 7 and 8 show the several solutions that maximize one objective function or another. A planner must evaluate how the solutions compare with respect to the benefits under consideration and decide on one (or a combination) to implement. In such an iterative process, the planner discovers what benefit, or set of benefits, is most important. One comparison method is to evaluate graphically the tradeoffs the solutions provide. Table 9 summarizes the cumulative benefits for each of the optimizing solutions.
Table 7. Benefit-Cost Priorities (1-10) for Sites L1 through L10

<table>
<thead>
<tr>
<th>Site Location</th>
<th>Solution 1</th>
<th>Solution 2</th>
<th>Solution 3</th>
<th>Solution 4</th>
<th>Solution 5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Miles Protected</td>
<td>Severity Protected</td>
<td>Vehicle Miles Protected</td>
<td>Severity Miles Protected</td>
<td>Severity Vehicle Miles Protected</td>
</tr>
<tr>
<td>L1</td>
<td>7</td>
<td>5</td>
<td>10</td>
<td>7</td>
<td>9</td>
</tr>
<tr>
<td>L2</td>
<td>4</td>
<td>3</td>
<td>8</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>L3</td>
<td>9</td>
<td>1</td>
<td>5</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>L4</td>
<td>8</td>
<td>10</td>
<td>7</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>L5</td>
<td>5</td>
<td>9</td>
<td>4</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>L6</td>
<td>3</td>
<td>8</td>
<td>3</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>L7</td>
<td>6</td>
<td>4</td>
<td>6</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>L8</td>
<td>1</td>
<td>7</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>L9</td>
<td>10</td>
<td>2</td>
<td>9</td>
<td>9</td>
<td>6</td>
</tr>
<tr>
<td>L10</td>
<td>2</td>
<td>6</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 8. Benefit-Cost Funding Decisions with Budget Constraint of $55,000

<table>
<thead>
<tr>
<th>Site Location</th>
<th>Solution 1</th>
<th>Solution 2</th>
<th>Solution 3</th>
<th>Solution 4</th>
<th>Solution 5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Miles Protected</td>
<td>Severity Protected</td>
<td>Vehicle Miles Protected</td>
<td>Severity Miles Protected</td>
<td>Severity Vehicle Miles Protected</td>
</tr>
<tr>
<td>L1</td>
<td>Funded</td>
<td>Funded</td>
<td>Funded</td>
<td>Funded</td>
<td>Funded</td>
</tr>
<tr>
<td>L2</td>
<td>Funded</td>
<td>Funded</td>
<td>Funded</td>
<td>Funded</td>
<td>Funded</td>
</tr>
<tr>
<td>L3</td>
<td>Funded</td>
<td>Funded</td>
<td>Funded</td>
<td>Funded</td>
<td>Funded</td>
</tr>
<tr>
<td>L4</td>
<td>Funded</td>
<td>Funded</td>
<td>Funded</td>
<td>Funded</td>
<td>Funded</td>
</tr>
<tr>
<td>L5</td>
<td>Funded</td>
<td>Funded</td>
<td>Funded</td>
<td>Funded</td>
<td>Funded</td>
</tr>
<tr>
<td>L6</td>
<td>Funded</td>
<td>Funded</td>
<td>Funded</td>
<td>Funded</td>
<td>Funded</td>
</tr>
<tr>
<td>L7</td>
<td>Funded</td>
<td>Funded</td>
<td>Funded</td>
<td>Funded</td>
<td>Funded</td>
</tr>
<tr>
<td>L8</td>
<td>Funded</td>
<td>Funded</td>
<td>Funded</td>
<td>Funded</td>
<td>Funded</td>
</tr>
<tr>
<td>L9</td>
<td>Funded</td>
<td>Funded</td>
<td>Funded</td>
<td>Funded</td>
<td>Funded</td>
</tr>
<tr>
<td>L10</td>
<td>Funded</td>
<td>Funded</td>
<td>Funded</td>
<td>Funded</td>
<td>Funded</td>
</tr>
</tbody>
</table>

Table 9. Cumulative Factors for Each Solution S1 through S5

<table>
<thead>
<tr>
<th>Solution</th>
<th>Miles Protected</th>
<th>Severity Protected</th>
<th>Vehicle Miles Protected</th>
<th>Severity Miles Protected</th>
<th>Severity Vehicle Miles Protected</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>0.80</td>
<td>31</td>
<td>592</td>
<td>6.94</td>
<td>5,222</td>
<td>$53,844</td>
</tr>
<tr>
<td>S2</td>
<td>0.51</td>
<td>45</td>
<td>254</td>
<td>4.51</td>
<td>2,299</td>
<td>$50,310</td>
</tr>
<tr>
<td>S3</td>
<td>0.79</td>
<td>24</td>
<td>604</td>
<td>6.50</td>
<td>5,134</td>
<td>$53,944</td>
</tr>
<tr>
<td>S4</td>
<td>0.75</td>
<td>34</td>
<td>569</td>
<td>6.94</td>
<td>5,222</td>
<td>$51,594</td>
</tr>
<tr>
<td>S5</td>
<td>0.72</td>
<td>33</td>
<td>575</td>
<td>6.61</td>
<td>5,257</td>
<td>$50,694</td>
</tr>
</tbody>
</table>

Figure 18 highlights the severity protected and daily vehicle miles protected by each optimizing solution, with the size of the bubble representing the cost of the solution. Figure 18 shows that the costs of all of the solutions are roughly equal (the cost of $55,000 is a binding constraint to all solutions). If a planner is most concerned with protecting severity, then Solution
2, non-dominated by any other solutions for severity protected, would be the frontrunner. If a planner is primarily interested in protecting DVMT, then Solution 3, non-dominated by any other solutions for DVMT protected, might be preferred. If a combination of protecting DVMT and severity is sought, then Solutions 4, 5, and 1 (all closely similar the same in protecting DVMT and severity) could be preferred, as they protect only slightly less DVMT than the dominant DVMT solution, 3, but protect more cumulative severity. Figure 19 shows graphics of each optimizing solution. The vertical position of the project icons reflects severity, the horizontal position reflects the exposure (vehicle miles traveled exposed to the hazard), and the icon area reflects the relative costs of guardrail projects.

Figure 18. Graphical comparison of portfolios of funded projects—Each icon is a portfolio of installation/upgrade sites

A planner may be interested to find a set of sites that is included in most of the optimizing solutions. For example, in Tables 7 and 8, Location 10 is recommended for implementation regardless of the factor maximized. Furthermore, Location 8 is recommended by all but one of the formulations. These locations provide benefits in multiple dimensions of those considered, and a decision maker may, therefore, be encouraged to choose them to receive funding.

A useful method to compare the solution sets is to calculate a median rank (along with highest and lowest rankings) for each location as shown in Figure 20. Notice in Figure 20 that Location 8 had a median ranking (across ranking methods) of one (first place) but that it received a ranking of 7 in at least one of the methods. An implication of Figure 20 is significant: methods that are preferred by individual localities, for example, because of mountainous versus flat terrains, will yield different priorities for the funding of guardrails. However, locations that are more often ranked highly may provide a consensus of methods and, thus, suggest to a decision maker that the locations are a win-win allocation from multiple perspectives. Baker (2000) demonstrates integer programming to generate solutions that reflect compromises among the various optimization criteria.
Figure 19. Portfolios of solutions: (a) hazard length, (b) severity, (c) vehicle miles, (d) severity miles, (e) severity vehicle miles; each icon is an individual hazard (the icon area reflects the relative cost of guardrail installation or upgrade; shaded icons are funded within the budget constraint)
CONCLUSIONS

Two phases of analysis in support of resource allocation to roadway guardrails were developed and demonstrated. The first is a screening phase based on a high-level comparison of corridors. The screening phase compares corridors through the accident history statistics, traffic, and other factors and highlights corridors for further study for guardrail needs. The second phase makes site-by-site comparisons of the screened sites applying benefit-cost ratios to allocate the limited funds of a highway agency for guardrail projects. The two phases, together with the specified supporting database, comprise an aid to decision making, supporting discussion among planners, engineers, and the public about what benefits are important to be considered for resource allocation for guardrail needs.

RECOMMENDATIONS

The recommendations of the effort are as follows.

1. VDOT should consider the deployment of the developed database of protected and unprotected hazards, including the associated data collection.

2. VDOT should consider the deployment of the developed corridor screening tool, including the associated data collection.
3. VDOT should consider the deployment of the developed site evaluation tool and the associated data collection.

4. Workshops for resident engineers should be convened to facilitate the adoption of the developed tools.

5. The application of the tool should be considered for the primary road system (upgrading and new locations), the secondary system (new locations), and the interstate system (new locations).

6. With the new capability provided by the specified database, VDOT should consider whether to decouple the funding of new installations from the funding of upgrades to existing guardrails; the database specified in the current effort is the first to distinguish new installations from upgrades in a catalog of guardrail needs.

7. VDOT should consider supporting the maintenance of a website on its intranet for resources (including the developed softwares) relevant to guardrail installation and upgrade.

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