Using Risk Analysis to Minimize Adverse Consequences in Non-Standard Designs

Malcolm H. Ray
RoadSafe, LLC
Box 312
12 Main Street
Canton, Maine 04221
Phone: 207 514 5474, e-mail: mac@roadsafelllc.com

Christine E. Carrigan
RoadSafe, LLC
Box 312
12 Main Street
Canton, Maine 04221
Phone: 207 513 6057, e-mail: christine@roadsafelllc.com

Submitted July 23, 2014
Submitted to TRR February 27, 2015

Word count
Text = 4,023
Figures&Tables: 6 @ 250 words each =1,500
Total number of words= 5,523

Paper prepared for consideration for presentation and publication at the 94th Annual Meeting of the Transportation Research Board, January 2015
Using Risk Analysis to Minimize Adverse Consequences in Non-Standard Designs
Malcolm H. Ray and Christine E. Carrigan

ABSTRACT

The concepts, designs, and philosophies presented in AASHTO’s Roadside Design Guide (RDG) “…cannot, and should not, be included in their totality on every single project.” (1) Roadside safety engineers currently lack a quantitative method to balance the philosophies presented in the RDG with situations encountered on existing roads especially where it is not possible to follow the guidelines in the RDG. Generally, the goal of roadside design is to minimize, in so far as practical, the chance of severe or fatal injury crashes on the roadway. Engineers often are left to using “good engineering judgment” to make these choices. This paper presents a risk assessment methodology and demonstrates through example problems how this methodology may be used as a more quantitative approach for measuring the inherent risk of different roadside design alternatives such that engineers can identify “where the greatest safety benefit can be realized.” (1)

Benefit-cost methods have been used in roadside safety for over 35 years to balance improvements to safety with implementation costs. While widely used, this approach presents several challenges. This paper discusses the advantages and challenges in using both the benefit-cost method and the proposed risk method. The two tools can, in fact, be used together to result in better roadside designs and roadside policy.
INTRODUCTION

The opening pages of AASHTO’s Roadside Design Guide (RDG) are very clear that the RDG is intended as a guide. The concepts, designs, and philosophies presented in the RDG “…cannot, and should not, be included in their totality on every single project.” The guidelines presented in the RDG “…are mostly applicable to new construction or major reconstruction projects.” “It will be generally necessary to selectively incorporate roadside safety guidelines on 3R projects only at locations where the greatest safety benefit can be realized.” (1) Engineers often encounter situations on existing roads where it is not possible to follow the guidelines in the RDG. For example, an intersecting roadway may limit the use of a full-length guardrail terminal, an isolated large tree may have aesthetic or historical value that prevents its removal or a deep rock cut close to the roadway may be prohibitively expensive to widen. In situations like these, the engineer must decide if the problem should be treated and how to treat the problem even if the solution is not in full conformance with the RDG.

Generally, the goal of roadside design is to minimize, in so far as practical, the chance of severe or fatal injury crashes on the roadway. While it may not be possible to minimize that risk to the level implied in the RDG, it may often still be worthwhile to minimize the risk as far as practical. On the other hand, there are often situations which do not conform to the RDG guidelines where it is not clear that there will be any practical benefit to changing the existing situation. Engineers often are left to using “good engineering judgment” to make these choices. This paper presents a more quantitative approach for measuring the inherent risk of different roadside design alternatives such that engineers can identify “where the greatest safety benefit can be realized.” (1)

Benefit-cost methods have been used in roadside safety for over 35 years to balance improvements to safety with implementation costs. Benefit-cost methods compare the risk reduction (i.e., reduction in crash costs) to the capital cost increase (i.e., cost of construction, repair and maintenance) for each viable alternative. While widely used, this approach presents several challenges: (1) although risks and costs are both measured in dollars both change over time and by region; (2) risk reductions (i.e., benefits) do not usually accrue to the individuals or organizations that provide the capital cost and sometimes the accrual does not even occur in the same generation; (3) benefit-cost methods compare the average risk reduction over the project life. Analysis of alternatives which have extreme values (i.e, low cost, high volume, high cost, etc.) cannot always be successfully captured using the benefit-cost approach.

A typical roadside safety benefit-cost analysis consists of two parts: (1) a risk assessment to determine the number and severity of crashes and (2) an economic analysis to determine the most effective use of funds. This two part approach will always be a valuable tool to compare reasonably similar alternatives for application in design but sometimes this approach obscures the effect of design decisions on risk. An additional tool is needed to quantify safety improvements when the ideal situation is not achievable, when extreme situations or projects with different design lives must be compared, and for the development of roadside policy when it is not desirable to have the design goal shifting with time or by region.

The risk assessment portion of the benefit-cost process, where risk is the absolute level of safety provided, has largely occurred in the background and decisions are usually based on the economic analysis alone. The risk assessment portion of the analysis has the potential to fill this identified void. Additionally, the risk assessment portion may provide more meaningful results from which to develop national roadside policy which does not vary by time or region. These assessment tools are readily available to the user in the third version of the Roadside Safety
Analysis Program (RSAPv3). This paper discusses the advantages to separately using the risk analysis portion of the encroachment probability model for the development of national policy and assessment of less than ideal design situations.

BACKGROUND

When comparing design alternatives, an average annual crash cost is calculated by summing the expected crash costs for the predicted crashes. These crash costs are then normalized to an average annual basis. Any direct costs, as defined by the user (i.e., initial installation and annual maintenance) are also normalized using the project life and the discount rate to an annualized basis and the benefit-cost ratio (BCR) is calculated. The BCR is defined as follows:

\[
\text{BCR}_{ij} = \frac{CC_i - CC_j}{DC_j - DC_i}
\]

Where:
- \(\text{BCR}_{ij}\) = Incremental BCR of alternative j with respect to Alternative i
- \(CC_i, CC_j\) = Annualized crash cost for Alternatives i and j (i.e., Risk reduction)
- \(DC_i, DC_j\) = Annualized direct (i.e., construction, maintenance and repair) cost for Alternatives i and j

Throughout the last decade, the national index of construction costs indicate construction costs have fallen while the national index of crash costs has continued to grow. Further complicating this phenomenon is new research which supports using crash cost adjustments for each individual state. \(^{(5,2)}\) It has been long recognized that construction costs vary by state and this theory was recently confirmed by a 2002 Washington state study on construction costs. \(^{(6)}\) In short, both crash costs and construction costs vary both in time and space and they often do not move in the same directions.

New York, for example, has a relative construction cost of 3.63; it costs more than three times as much to construction a lane mile of highway in New York than the national average.\(^{(6)}\) Arkansas and California both have approximately average construction costs, while states like Mississippi, Michigan and Montana have below average construction costs. If a national roadside safety guideline was developed using a BCR of 2 and national average construction and crash costs, the policy would result in a project whose actual regionally adjusted BCR would be more than two in Mississippi and much less than two in New York. The guideline would have the unintended effect of recommending non-cost beneficial projects in some States.

While benefit-cost will always be a valuable design tool for choosing among feasible alternatives in the same region for immediate application, the temporal and regional variation of both crash costs and construction costs create a problem when developing national guidelines that are intended for long-term use across all regions of the country. For example, say a roadside design guideline was developed in 2008 that assumed a decision BCR of 2. By 2011 the construction costs would decrease by a factor of 0.82 but the crash cost would have increased by a factor of 1.0 \(^{(5)}\) so the benefit-cost of that same alternative would really be 2.6; even better than the conditions of the original policy. On the other hand, if construction prices begin to increase dramatically in the coming years to an NHCCI of 2.6 and crash cost reach $12 million
the same alternative will have a BCR of 1.5, below the threshold value of 2 used to develop the guideline. Since design alternatives generally have economic lives of 20 to 30 years, it would seem highly likely that the actual BCR will change dramatically over the life of the project due to temporal and regional variations.

**Risk Analysis**

An alternative approach to benefit-cost analysis not often used explicitly in roadside safety but common in many other types of engineering is risk analysis. In risk analysis, the risk of experiencing a particular type of event is quantified using probabilistic models. Risk is a measure of safety that does not change by region or in time. An acceptable level of risk is established over the project life and then the system is engineered to ensure that the risk in-service is below the targeted acceptable risk.

**Establishing Acceptable Risk Target**

Establishing a risk target is a policy decision and could be done nationally or locally. As an example, the State of Maine has 23,450 miles of roadway or about 50,000 edge-miles of road. In 2008, Maine experienced 69 fatal run-off-road (ROR) crashes, 356 fatal and severe (A+K) ROR crashes, and 3,029 injury and fatal (KABC or F+I) ROR crashes. The existing 2008 risks in Maine for these different levels of crash severity are, therefore:

- 0.0014 Fatal crashes/edge-mi/yr (1/725),
- 0.0071 Fatal + Severe crashes/mi/yr (1/140) and
- 0.0616 Injury and Fatal crashes/mi/yr (1/17).

Individual roads will experience a range of different risks; some will be higher and some will be lower than the average State-wide risks shown above. A highway agency could use these measures in order to identify particular roads where the risk is higher than either the average or the acceptable risk. A recently completed project on selecting bridge railings based on site and traffic conditions recommended a target risk of less than a 1/100 severe or fatal crashes in 30 yrs/1,000-ft of bridge rail. This is equivalent to a risk of less than 1/600 severe or fatal crash/edge-mi/yr on roadways.

A transportation agency could establish a target goal that the risk on its two-lane rural roads be less than 1/600 severe and fatal injury crashes/edge-mi/yr. Improvements could then be focused on roadways where the target risk is exceeded. Roadways that already fall below the target risk would not need improvements even if some of the roadway and roadside characteristics do not conform to the RDG. In these cases, the agency may choose to leave the existing situation as-is and spend safety dollars at another location where the target risk is exceeded. For situations where the target risk cannot be obtained due to field conditions, the achievable level of risk can at least be documented and compared against the existing risk on other similar roads. Focusing on the level of risk allows highway agencies to target the roads where the risk is greatest.
Risk Assessment Procedures

Risk assessment procedures are currently used to estimate the reduction in anticipated crash costs (i.e., the benefits) which are then used to perform a standard benefit-cost analysis that includes agency costs like construction, maintenance and repair over the life of the project. Roadside safety analysis programs like Roadside, BCAP and RSAP have always calculated the average expected cost of crashes by simulating tens of thousands of possible encroachments and then multiplying by the expected number of encroachments each year. The average crash costs are calculated as follows:

$$
\bar{C} = \frac{1}{NM} [M \sum_{j=1}^{M} W_j \sum_{i=1}^{N} C_{ij}]
$$

where:

- $\bar{C}$ = The average annual crash cost,
- $C_{ij}$ = The crash cost of encroachment i with vehicle type j,
- $W_j$ = The proportion of the traffic volume accounted for by vehicle type j,
- $N$ = The total number of encroachments simulated and
- $M$ = The total number of different vehicle types in the traffic mix.

Earlier roadside safety benefit-cost programs simply calculated the average annual crash costs “on the fly” without saving the crash cost of each encroachment. The third version of the roadside safety analysis program (RSAPv3) saves these individual crash costs such that the distribution of crash costs over the life of the project can be examined. In other words, the risk assessment module is explicitly available to users.

The severity of crashes are most commonly measured using the police reported KABCO injury scale where a K injury represents a fatal injury, an A represents a severe injury, a B represents a serious injury, a C represents a minor injury and an O represents a property damage only crash (i.e., PDO). Recently Ray and Carrigan defined the equivalent fatal crash cost ratio, EFCCR, for use in RSAPv3. (7) The EFCCR is simply the ratio between the crash cost of a particular crash divided by the cost of a fatal crash. RSAPv3 contains a database of EFCCR values used in RSAPv3 for many common roadside features. These values were developed based on observed crash data. Essentially, the EFCCR values in the RSAPv3 database represent the average severity of a crash with that particular type of object divided by the cost of a fatal crash. Since the EFCCR is a dimensionless ratio it does not vary with time. Figure 1 shows a plot relating the EFCCR values for the KABCO scale crash severities to the increase in cost between each injury level. As shown in Figure 1, each crash severity level is roughly one order of magnitude apart; a fatal crash has a crash cost 10 times greater than a severe injury crash and a severe injury crash has a crash cost 10 times greater than a serious injury crash and so forth.

Crash data from police reports specify a discreet level of injury but, in fact, the actual crash cost for a specific crash can vary widely. RSAPv3 estimates crash costs on a continuous scale so it is necessary to map the continuous crash cost spectrum onto the discreet KABCO levels. Table 1 shows recommended cut-off values for the various typical severity levels. For example, while an EFCCR of 1 represents the average fatal crash severity any crash with an EFCCR greater than 0.173 is considered a fatal crash.
Example Problem: Narrow Median

As an example, suppose a highway agency has a relatively low volume divided highway with an average annual daily traffic (AADT) of 5,000 veh/day with no trucks. The median is only 20-ft wide which, according to the RDG, would generally warrant a median barrier. What is the risk of leaving the median the way it is (i.e., no median barrier) versus installing either a TL-3 w-beam median barrier or a TL-5 concrete median barrier? If there has been no crash history problem at the site should scarce funds be spent simply to have the median conform to the RDG?

Figure 2 shows the cumulative distribution of the crash severity measured using the EFCCR obtained from RSAPv3. The horizontal axis is a measure of the severity of crashes using the EFCCR with higher severity increasing toward the right. The vertical axis is the cumulative probability at each EFCCR severity level. For example, an EFCCR of 0.01 represents a serious injury (i.e., B level) crash. In the unprotected median case, about 45 percent of the crashes have severities that are 0.01 or less on the EFCCR scale. Conversely, about 55 percent of the crashes have severities that are greater than 0.01. The probability of observing a crash with a severity above a given EFCCR level is easily determined using a graph like Figure 2.

If the highway agency had a policy which established the target risk as less than 1/50 (0.02) fatal crashes/edge-mi/yr the engineer could develop a cumulative probability distribution using RSAPv3 like the one shown in Figure 2. To be an acceptable, the alternative crash severity would have to be less than the target crash severity before the cumulative distribution reaches 0.98 (i.e., 1-0.02=0.98). Each alternative curve in Figure 2 that reaches a cumulative probability of 0.98 before reaching the target EFCCR value (i.e., Table 1) has a risk less than the target risk. For this example, the EFCCR value of 0.173 for a fatal crash exceeds the limits of the chart (i.e., it plots to the right of the maximum value) so the unprotected median already meets that risk target even without a median barrier. If, on the other hand, the agency had a policy which established the target risk as less than 1/50 severe and fatal crashes/edge-mile/yr (i.e., EFCCR = 0.013) then a w-beam median barrier would satisfy this criteria as shown in Figure 2. Finally, if the agency considered the target risk less than 1/50 injury and fatal crashes/edge-mi/yr then this goal is not achievable with any median barrier option. If the target is to minimize injury and fatal crashes, Figure 2 indicates that while the TL-5 median barrier does not meet the target, it does provide the lowest level of risk. As shown by this example, the alternative chosen depends on exactly what the target level or risk is.

If the engineer had conducted the analysis using a traditional cost-benefit analysis, the RSAPv3 results would be as shown in Figure 3. The analysis would result in the conclusion that a w-beam median barrier is most cost effective but it would not indicate the actual level of risk associated with that decision.

Example Problem: Utility Pole

Another example is a utility pole located six feet from the edge of the travel lane of a two-lane undivided highway. The pole is on the outside of a horizontal curve with a 400-ft radius. Aside from the isolated pole, the clearzone is obstacle-free and traversable. The traffic volume is 5,000 veh/day with 12% trucks. The pole is located within the clearzone as defined by the RDG so moving or shielding the pole would bring the site into conformance with the guidelines. Does the pole in its present location, however, create so much risk that it should be moved?
Three alternatives that could be considered are to (1) leave the utility pole where it is, (2) move the pole to the inside of the curve or (3) move the pole back to the edge of the clearzone. A conventional benefit-cost analysis using RSAPv3 indicates that moving the utility pole outside the clearzone to a location 30-ft from the edge of the travel lane is the most cost-beneficial solution as shown in Figure 4.

The upper portion of the cumulative probability distribution of the crash severities in terms of EFCCRs is shown for three utility pole alternatives in Figure 5. A risk of 1/600 equates to the 99th percentile of the cumulative probability distribution for this ¼-mile road segment as shown in Figure 5. The 99th percentile in Figure 5 for the pole in its existing location has an EFCCR of just over 0.013 (i.e., 0.016) so the existing situation does not meet the target risk goal of less than 1/600 severe or fatal injury crashes/edge-mi/yr. Moving the pole to the inside of the curve results in a crash severity of 0.011 at the 99th percentile and moving the pole to the outside of the clearzone results in a crash severity of 0.0085; both of which meet the target risk goal of less than 1/600 severe or fatal injury crashes/edge-mi/yr.

**Conclusion**

There are advantages and disadvantages to both the cost-benefit and risk methods of analysis. The benefit-cost method has the advantage that it includes both societal benefits and agency costs such that the benefits are maximized while making the best possible use of agency funds. The disadvantage is that since costs are explicitly included, regional and temporal variations in the cost elements can make the same solution cost-beneficial in one region and not cost beneficial in another. Likewise, the benefit-cost ratio may become disadvantageous at some time in the future if economic conditions change as they invariably will over a design life of 15 to 30 years. Another disadvantage is that the risk is not necessarily uniform so one cost-beneficial solution can have a different inherent risk than another with the same benefit-cost ratio.

On the other hand, risk analysis sets a specific risk objective that is uniform across regions and through time such that the risk of an unacceptable event is always the same. The disadvantage is that the best risk-based solution may not always be cost-beneficial in one region or at some point in time. The primary advantage to a risk-based approach is that construction and maintenance cost do not affect the results so the performance goal will not change over time or from one region to another. This allows the policy decision about the appropriate level of safety that should be provided to the travelling public to be separated from the question of which alternative is the most cost effective at a particular moment in time and at a particular location. A further advantage is that policy decisions for new construction and reconstruction would be identical using a risk-based approach. For example, a decision to install 32-inch concrete median barrier for 20,000 vpd and 10% trucks would be set regardless of whether the barrier will be installed where no barrier currently exists (i.e., new barrier construction costs only) or for replacing an existing barrier (i.e., new barrier construction costs plus demolition and removal of an existing barrier costs). The goal remains the same in both cases.

Benefit-cost analysis has been a valuable tool in roadside safety for nearly 35 years and has been used to both prioritize specific projects as well as develop State and national guidelines for barrier selection and placement. On the other hand, the level of risk implicit in these decisions is usually hidden resulting in different levels of risk based on the time an analysis was performed and the region where the alternative was placed in service.
The two tools can, in fact, be used together. If guidelines are developed based on acceptable risk criteria then benefit-cost methods can be used to determine the most economical way of achieving the desired risk level on a project-by-project basis. Agencies in different regions may choose different roadside safety alternatives based on the economic situation in their locale but the overall level of risk would be uniform throughout the nation.

Acknowledgments

This work was sponsored in part by NCHRP 22-12(03). The authors wish to thank the project panel and the program officer, Mr. Mark Bush for their thoughtful comments and feedback throughout the research effort. The New Jersey and Maine Departments of Transportation provided access to their crash records and research reports for the development of the tables presented herein.

References

List of Figures and Tables
Figure 1. EFCCR Values Relative to Increase in Severity................................................................. 11
Figure 2. Cumulative Probability Distribution of EFCCR for Median Barrier Alternatives........ 12
Figure 3. Median Barrier Example Problem Using Cost-Benefit Approach................................. 13
Figure 4. Utility Pole Example Problem Using Cost-Benefit Approach........................................ 14
Figure 5. Cumulative Probability Distribution of EFCCR for Utility Pole Alternatives............ 15

Table 1. EFCCR Threshold for Each Identified Target Risk................................................................. 16
Figure 1. EFCCR Values Relative to Increase in Severity.
Figure 2. Cumulative Probability Distribution of EFCCR for Median Barrier Alternatives.
Figure 3. Median Barrier Example Problem Using Cost-Benefit Approach.
<table>
<thead>
<tr>
<th>Alternative No.</th>
<th>ALTERNATIVE NAMES</th>
<th>Decision Point Benefit-Cost Ratio:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Do Nothing</td>
<td>1.00</td>
</tr>
<tr>
<td>2</td>
<td>Move to Inside of Curve</td>
<td>51.62</td>
</tr>
<tr>
<td>3</td>
<td>Move Outside of Clear Zone</td>
<td>4.83</td>
</tr>
<tr>
<td>1</td>
<td>Do Nothing</td>
<td>1.00</td>
</tr>
<tr>
<td>2</td>
<td>Move to Inside of Curve</td>
<td>0.00</td>
</tr>
<tr>
<td>3</td>
<td>Move Outside of Clear Zone</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Figure 4. Utility Pole Example Problem Using Cost-Benefit Approach.
Figure 5. Cumulative Probability Distribution of EFCCR for Utility Pole Alternatives.
Table 1. EFCCR Threshold for Each Identified Target Risk.

<table>
<thead>
<tr>
<th></th>
<th>K</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>PDO</th>
</tr>
</thead>
<tbody>
<tr>
<td>EFCCR</td>
<td>1.0</td>
<td>0.07</td>
<td>0.01</td>
<td>0.007</td>
<td>0.0007</td>
</tr>
<tr>
<td>Risk of Fatal (K) Threshold</td>
<td>$\leftarrow K &gt; 0.173$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Risk of K+A Threshold</td>
<td>$\leftarrow A+K &gt; 0.013$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Risk of KABC Threshold</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\leftarrow F+I &gt; 0.001$</td>
</tr>
</tbody>
</table>