

2010-04-11

DEVELOPMENT OF A PERFORMANCE-
BASED HIGHWAY DESIGN PROCESS:
Incorporating Safety Consideration into Highway
Design

Christine Elizabeth Conron
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**DEVELOPMENT OF A PERFORMANCE-BASED HIGHWAY DESIGN
PROCESS:**

Incorporating Safety Considerations into Highway Design

by

Christine Elizabeth Conron

A Dissertation

Submitted to the Faculty

of the

WORCESTER POLYTECHNIC INSTITUTE

in partial fulfillment of the requirements for the

Degree of Doctor of Philosophy

in

Civil Engineering

May 2010

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Abstract

For nearly 100 years the design of highways has incorporated safety through the application of criteria to each individual design element. Design elements are items like the horizontal curve, vertical curves, the cross-section, clear zone and roadside slopes. As a result, safety is only indirectly addressed since the design elements are developed in isolation without a good understanding on the impact of one element on another. To make matters worse, design elements communicate messages to the driver about the appropriate speed for the highway. Long straight tangent sections encourage drivers to drive faster whereas curved highway segments communicate a lower operating speed. This can lead to inconsistent message to the driver when design elements are not coordinated with each other. A new method is proposed that accounts for the interaction between design elements in such a way that the designer can estimate the frequency and societal cost of motor vehicle crashes. With this estimate of cost, the designer can base design decisions on what would minimize the societal cost of both the infrastructure improvement and safety. This method will allow designers to formulate highway designs that achieve a specific level of safety and communicate consistent information to drivers. This research provides a valuable planning and design tool for practitioners and policy makers alike. It represents an important shift in the highway design paradigm.

I dedicate this dissertation to Jack and Joe. You provided the motivation I needed to start my graduate degrees and inspiration to go all the way. Thank you boys.

Acknowledgments

Thank you to all of the people who helped make this dissertation possible.

First, I wish to thank my advisor, Dr. Malcolm Ray for his guidance, encouragement, and support. His genuine interest in highway safety has been a great inspiration to me.

The members of my dissertation committee, Dr. Roberto Pietroforte, Dr. Guillermo Salazar, and Dr. Joseph Petruccelli, have kindly given their time and expertise to enhance my work. I thank them for their contributions. Additionally, I would like to thank Dr. Shaw-Pin Miaou for his helpful insights and suggestions.

I must acknowledge as well the many friends and colleagues who discussed my research and provided their opinions and wisdom and have supported me over the many years of our friendship. They have consistently helped me keep perspective on what is important in life and work.

I'm grateful to my family and John who have provided support and helped me maintain the delicate balance between work, school, and family.

This research was funded in part by NCHRP Project 22-27. Participants in this research project, including several software vendors and researchers, gave their time freely in the development of this research, for which I am truly indebted.

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CHAPTER 1

INTRODUCTION

Risk or the potential for crashes is not often directly considered during the planning and design phases of a project, but the designers often rely on established design standards as a means for producing a “safe” design. These established design standards, including: *A Policy on Geometric Design of Highways and Streets*¹, also known as the Green Book, published by the American Association of State Highway and Transportation Officials (AASHTO) and the *Roadside Design Guide*² (RDG), also published by AASHTO, provide the designer with a set of warranting criteria to design a roadway. These warrants are simple to follow and require little knowledge of the project area. For example, the Green Book suggests in Exhibit 3-26 that for a design speed of thirty miles per hour (30 mph or 50 km/h) that a minimum horizontal curve radius of 3,350 feet (1,110 meters) be used if superelevation is not used.³ This warranting criterion, however, gives no consideration to the vertical alignment, the clear zone, the number of lanes, the side slopes or the expected traffic this section of road will experience. Each design element is considered independent of the other elements of the road which impact the overall performance of the road.

The current design practice allows for flexibility in application of design principals, is long-established and rooted in the design community. The practice itself, however, lacks a formal methodology resulting in varying degrees of application of engineering principals by region and individual. The flexibility that currently exists in Highway Engineering must remain, but an improved understanding of the consequences (i.e., construction cost, capacity, highway safety, etc.) of the flexibility is needed. This improved understanding can be accomplished through establishing a highway design process which is performance-based rather than prescriptive (e.g., warrants). Any changes to the current design process, however, must account for the long and rich history of highway design and the massive existing body of knowledge and research on highway characteristics.

In addition to the many established design standards used by highway planners and designers, there are many statistical models which have been developed to predict where crashes may occur along the road and the roadside. These mathematical models often consider the vertical and or horizontal alignment of the highway, the placement of roadside objects, the speed of the traffic, and many other factors in relation to each other. The use of these models during planning and design in conjunction with established design standards will bring the issue of maximizing highway safety to the forefront of the highway design process. An informed discussion of the cost of changes to an alignment can be assessed over the design life of a highway with the economic impacts of safety also a factor in the analysis. These models, however, are complex and scattered throughout various literatures and are not easily accessible to the engineer or planner who works on highway designs every day. Additionally, they are not easy to integrate into the typical highway design process which uses computer software to generate detailed designs.

The United States Government has recognized the need to reduce highway related injuries for many years. The first highway safety legislation appeared in 1966. This formal recognition has continued through today, as outlined here:

- The *Highway Safety Act of 1966*: This legislation provided financial assistance to the States to accelerate highway safety program development and reduce highway crashes. This Act required States to develop and maintain a safety program.
- The *Highway Safety Act of 1973*: This legislation established five program areas: highway-rail crossings, high hazard locations, pavement marking demonstration programs, elimination of roadside obstacles, and the Federal-aid safer roads demonstration.
- The *Surface Transportation Assistance Act of 1978*: This legislation consolidated the five program areas enacted in 1973 into two programs, the Highway-Rail Grade Crossings and Hazard Elimination Programs.
- The *Intermodal Surface Transportation Efficiency Act of 1991*: This legislation was responsible for funding the two programs enacted under the 1978 legislations.
- The *Transportation Equity Act for the 21st Century*: This legislation added a provision that a State must consider bicycle safety.⁴

Much of this legislation, including the most recent, also was a means to provide funding for the operation of the United States highway system. Many different factors contribute to the cost of operating a transportation system such as the network of roads that comprise the United States highway system. Costs are realized from the planning of the network through the design, construction and maintenance of the network. Many of these costs are obvious to the observer and include the designer's fee, the construction costs, and the costs to maintain the infrastructure.

Motor vehicles crashes cost society more than \$230 billion annually.⁵ During an average day, American roads experience approximately 117 fatalities. Thirty percent of these fatalities are people under the age of twenty-five. In total, this amounts to a societal cost of \$630 million lost per day.

Some costs are less obvious and are a result of decisions made during the early stages of designing a new roadway or upgrading an existing roadway. For example a decision to route an existing stream through a culvert and provide a headwall protected by a guardrail may appear to be the most cost effective decision to the designer concerned with minimizing construction costs, however, when the potential for vehicles striking the guardrail during the project life is considered, the possible societal loss through the cost of the crashes and increased maintenance costs throughout the design life of that section of road can result in costs not considered by the original designer. If the safety costs of decisions are included when considering alternatives, the choice of a guardrail and head-wall may not be as economically attractive as moving the culvert intake farther from the road such that a guardrail is no longer necessary.

It is the objective of this research to develop a performance-based highway design process which capitalizes on the existing body of knowledge, available CAD tools and analytical tools, and develop new support tools to demonstrate the proposed design process. The proposed performance-based process is demonstrated using highway safety measured in dollars, as the measurable outcome. The process can be extended to include other highway engineering outcomes such as vehicle capacity.

CHAPTER 2

LITERATURE REVIEW

Achieving and maintaining a competitive edge over other regions or nations has been linked to the size and quality of the available transportation network, however, any transportation network has risks associated with it. These risks include the frequent crashes on the various modes of transportation. Highway crashes result in the death of approximately 43,000 people per year in the United States alone.⁶ Balancing the benefits to society of transportation network improvements with risks such as crashes has not been explicitly considered extensively to date. The reduction or increase in construction costs, however, are often juggled and judged by individual engineers with little guidance regarding safety provided through design standards, resulting in each potential improvement or design alternative being evaluated differently. The American Association of State Highway and Transportation Officials (AASHTO) publishes a variety of highway design guidelines to assist highway designers in the development and assessment of highway designs. These guidelines include *A Policy on Geometric Design of Highway and Streets*⁷ (Green Book) and the *Roadside Design Guide*⁸ (RDG). Additional guidelines and policies also used include the *Manual of Uniform Traffic Control Devices*⁹ (MUTCD) published by the Federal Highway Administration (FHWA) and the *Highway Capacity Manual*¹⁰ (HCM2000) published by the Transportation Research Board (TRB).

AASHTO is in the process of balloting a new publication, due for general release sometime in 2010, called the *Highway Safety Manual* (HSM). The HSM provides highway designers with a tool to quantify and compare the expected relative crash risk of various highway design alternatives. Each of these design policies and guidelines are discussed in more detailed in the “Existing Design Process” chapter. The following review examines other aspects of highway engineering, including benefit-cost analysis, highway crashes and crash modeling, and software available to assist highway engineers.

Benefit-Cost Analysis for Highways

When conducting a benefit-cost analysis, it is important to calculate a benefit-cost ratio (B/C) for each feasible alternative with benefits in the numerator and project costs in the denominator. The resulting B/C for each alternative should be listed in descending order to allow for a comparison of the ratios, not just benefits or project costs. Project benefits are defined “...as an increase in well-being or a decrease in the use of real resources.”¹¹ Therefore, benefits include a reduction in crashes. Project costs include the design, construction, and maintenance costs associated with the improvement. While each element of a project’s benefit can be quantified using different units, each benefit is converted to a common monetary unit of measure for comparison with project costs. The B/C ratio, therefore, is unitless.

Through the creation and publishing of the User Benefit Analysis for Highways Manual¹² (the Red Book), AASHTO recognized the need to provide analytical tools for evaluating highway improvement alternatives. The “Red Book” compares different improvement alternatives through an analysis of the costs for the alternative and the expected benefits to the user. User benefits are determined by travel time costs, operating costs, and crash costs. The focus of this method of alternative evaluation is user benefit. The basic premise is that when user costs such as travel time or accident costs are high, a user will avoid the corridor, whereas when the user costs are low, the corridor will be used more. Non-user benefits such as environmental impacts, urban growth, economic influences, etc. are not included in this method.

The Roadside Design Guide (RDG)¹³ has also adopted a Benefit-Cost approach to evaluating roadside design alternatives. For each alternative, an average annual crash cost is calculated by summing the expected crash costs for the predicted crashes using the method outlined in Appendix A of the RDG and discussed below. These crash costs are then normalized to an annual basis. Any direct costs, as defined by the user (i.e., initial installation and maintenance) are also normalized using the project life and the discount rate.

After the total crash costs and the direct costs are calculated for each improvement alternative, the concept of incremental benefit/cost (*B/C*) is used to determine the cost-effectiveness of the design. The *B/C* ratio used is as follows:

$$B/C \text{ Ratio}_{2-1} = \frac{CC_1 - CC_2}{DC_2 - DC_1}$$

Where:

B/C Ratio 2-1 = Incremental *B/C* ratio of alternative 2 to Alternative 1

*CC*₁, *CC*₂, = Annualized crash cost for Alternatives 1 and 2

*DC*₁, *DC*₂, = Annualized direct cost for Alternatives 1 and 2

Understanding the cost of crashes and possible reduction of those costs (i.e., benefits) and the project costs (e.g., design, construction, and maintenance) is important when calculating the *B/C* for each improvement alternative and conducting a *B/C* analysis to determine which alternative is the preferred alternative.

Project Costs

Conducting a *B/C* analysis requires a reasonable understanding of all the project costs. Project costs are easily recognized as the design, construction and maintenance costs of an improvement alternative, however, they also include environmental mitigation and right-of-way (ROW) costs associated with the preferred alternative. Impacts to the environment, available ROW and their associated costs are routinely evaluated when considering improvement alternatives as these costs can be considerable for projects with

alignment or cross-section changes. Construction costs, however, are generally the largest project related cost considered by the programming agencies and are used as the benchmark for other costs during the planning stage of a project.

A recent report prepared and submitted in 2003 by the United States General Accounting Office (GAO) to the United State Senate Committee on Government Affairs Subcommittee on Financial Management looked to compare states in terms of highway construction costs using data collected by the Federal Highway Administration (FHWA). This review found "...significant issues regarding the quality of the data that FHWA collects and report."¹⁴ The review determined the comparison could not be made with the data FHWA collects. FHWA is evaluating the data collected and the collection process for its ability to meet future needs.¹⁵

The Washington Department of Transportation (WSDOT) preformed a survey of highway agencies within the United States in 2002 to better understand all project related costs and to gauge how WSDOT costs relate to other States. Figure 2-1 is a summary of the study's findings for Construction costs per lane mile of construction.

WSDOT found the average construction cost is \$2.3 Million per lane mile of highway. This figure excludes "...right of way, pre-construction environmental compliance, and construction environmental compliance and mitigation."¹⁶ These exclusions are quite variable by project and region, let alone State. A range of ROW costs and costs related to environmental mitigation are summarized in Table 2-1 as a percentage of Construction costs.

Design costs, or the costs related to preparing a project for construction, are generally accepted to be approximately ten percent of the construction costs of the project. The WSDOT study defined this task as preliminary engineering (PE) and found the costs range from four to 20 percent for PE with an average of 10 percent. When a consultant is hired to prepare a project for construction, the same consultant or another consultant is often hired to perform construction administration and oversight of the construction project. These duties include responding to Requests for Information (RFIs), attending pre-construction meetings, and in some cases inspection of construction activities. These activities often supplement a robust staff of construction inspection personnel within the State highway departments and are referred to as construction engineering (CE). Some larger, more complicated projects have contracts exclusively for CE, while smaller reconstruction projects have limited budgets for CE. The WSDOT study found that CE is 11 percent of the total Construction Costs by State.¹⁷

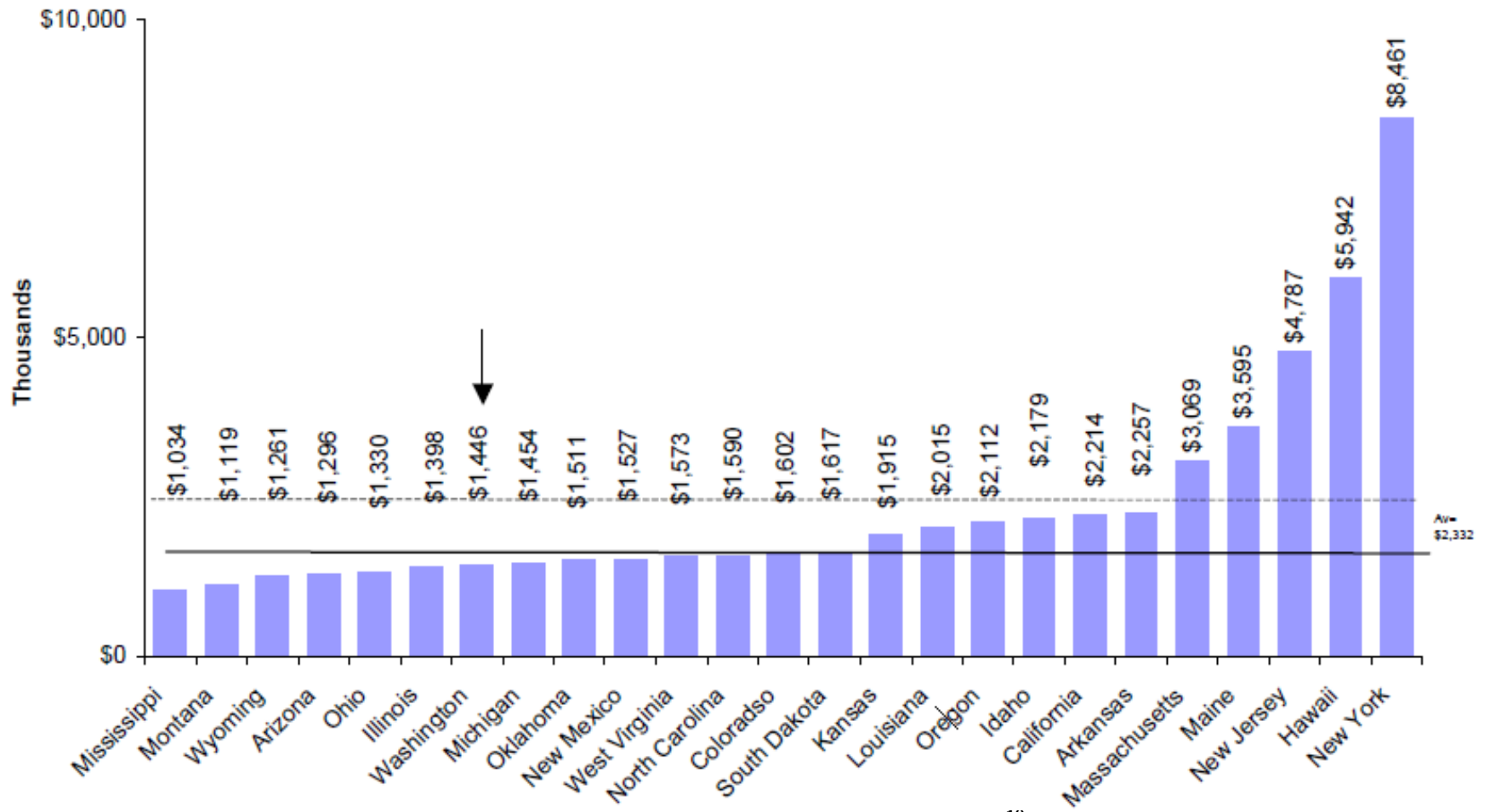


Figure 2-1. Lane Mile Cost Comparison by State.¹⁸

Table 2-1. Summary of Project Related Costs.¹⁹

State Name	Construction Cost	Right Of Way Variability	Environmental Documentation Variability	Environmental Mitigation Variability	State Prevailing Wage Law	PE %	CE %	Mob. %
Mississippi	\$1,033,576	11 - 20%	0 - 10%	0 - 10%	No	No Data	5%	5%
Montana	\$1,118,827	0 - 10%	0 - 10%	0 - 10%	Yes	<10%	10%	8%
Wyoming	\$1,261,046	11 - 20%	0 - 10%	0 - 10%	Yes	10%	12%	8%
Arizona	\$1,295,908	>30%	11 - 20%	11 - 20%	No	8%	15%	10%
Ohio	\$1,330,176	11 - 20%	0 - 10%	0 - 10%	Yes	10%	8%	3%
Washington	\$1,445,662	0 - 10%	0 - 10%	11 - 20%	Yes	15%	15%	10%
Illinois	\$1,398,314	0 - 10%	0 - 10%	0 - 10%	Yes	10%	12%	3%
Michigan	\$1,454,462	>30%	11 - 20%	11 - 20%	Yes	8%	0 - 15%	5%
New Mexico	\$1,526,631	> 30%	0 - 10%	0 - 10%	Yes	8 - 10%	15 - 20%	10%
Oklahoma	\$1,510,910	11 - 20%	0 - 10%	0 - 10%	No	5%	9%	3%
South Dakota	\$1,616,581	0 - 10%	0 - 10%	0 - 10%	Yes	4%	10%	10%
North Carolina	\$1,590,182	> 30%	0 - 10%	0 - 10%	Yes	10%	10%	5%
West Virginia	\$1,572,946	11 - 20%	0 - 10%	0 - 10%	Yes	15%	18%	1%
Kansas	\$1,914,917	11 - 20%	0 - 10%	0 - 10%	No	7%	10%	6%
Louisiana	\$2,015,042	ROW costly item in urban areas	0 - 10%	0 - 10%	No	15%	4%	5%
Oregon	\$2,112,486	11 - 20%	0 - 10%	0 - 10%	Yes	12%	No Data	10%
Idaho	\$2,178,689	> 30%	0 - 10%	0 - 10%	No	10%	10%	10%
California	\$2,213,519	0 - 10%	0 - 10%	0 - 10%	Yes	20%	15%	10%
Arkansas	\$2,257,449	11 - 20%	0 - 10%	0 - 10%	Yes	10%	10%	10%
Massachusetts	\$3,069,336	Varies Widely	0 - 10%	0 - 10%	Yes	10%	10%	0%
Maine	\$3,594,823	0 - 10%	0 - 10%	0 - 10%	No	9%	10%	8%
New Jersey	\$4,787,288	11 - 20%	0 - 10%	0 - 10%	Yes	15%	10%	10%
Hawaii	\$5,942,278	11 - 20%	11 - 20%	0 - 10%	Yes	10%	15%	10%
New York	\$8,461,288	No Data	No Data	No Data	Yes	5%	10%	4%
Colorado	\$1,602,251	No Data	0-10%	11-20%	No	11%	11%	5%
Total Const. Cost	\$58,304,586							
Average Const. Cost	\$2,332,183							

Cost of Crashes

Measuring the costs of crashes may seem challenging. In fact, there are many different indexes that have been developed which measure just that. The “Red Book” measures accidents costs as those that directly impact the user, including:

- “Injury, morbidity, and mortality of the user;
- Injury, morbidity and mortality of those other than the user who must be compensated;
- Damage to the property of the user;
- Damage to the property of others.”²⁰

FHWA uses the willingness-to-pay concept, which has been documented by economists who observed that people “...express how much well-being they get out of something by demonstrating *willingness-to-pay* for it.”²¹ Willingness-to-pay, however, is a misnomer and the figures actually represent how much a person actually pays. When considering crash costs, this concept would translate to “... how much people actually pay to reduce safety risks.”²² A study updated by FHWA in 1994 relates this concept to the KABCO scale commonly used by Police to describe the severity of a crash. Each letter of the scale equals a different severity (e.g., K for a fatal injury and O for a property damage only crash) and results in a different willingness-to-pay. Table 2-2 summarizes the findings of the 1994 update. The authors state that “these costs should be updated annually using the GDP implicit price deflator.”²³

Table 2-2. Comprehensive Costs (1994 Dollars) Police-Reported Crashes.²⁴

SEVERITY	DESCRIPTOR	COST PER INJURY
K	Fatal	\$ 2,600,000
A	Incapacitating	\$ 180,000
B	Evident	\$ 36,000
C	Possible	\$ 19,000
PDO	Property Damage Only	\$ 2,000

A recent study conducted by the American Automobile Association (AAA), *Crashes vs. Congestions – What’s the Cost to Society?*,²⁵ found that in 2005, crashes in cities cost every person (i.e., society), not just the people involved in the crash, an average of \$1,051 per person in 2005.²⁶ This estimate includes such costs as “property damage; lost earnings; lost household production (i.e., non-market activities occurring in the home); medical costs; emergency services; travel delay; vocational rehabilitation; workplace costs; administrative; legal; and pain and lost quality of life. The economy and the environment also are impacted but those costs are not quantified in the study.”²⁷

The National Highway Traffic Safety Administration (NHTSA) conducted research in 2000 and determined the economic cost of motor vehicle crashes in the United States was \$230.6 billion, "...which represents the present value of lifetime costs for 41,821 fatalities, 5.3 million non-fatal injuries, and 28 million damaged vehicles, in both police-reported and unreported crashes."²⁸ The contributions of various factors to this assessment are summarized in Figures 2-2 and 2-3. These costs do not include the consequences of these events and "... should not, therefore, be used alone to produce cost-benefit ratios."²⁹

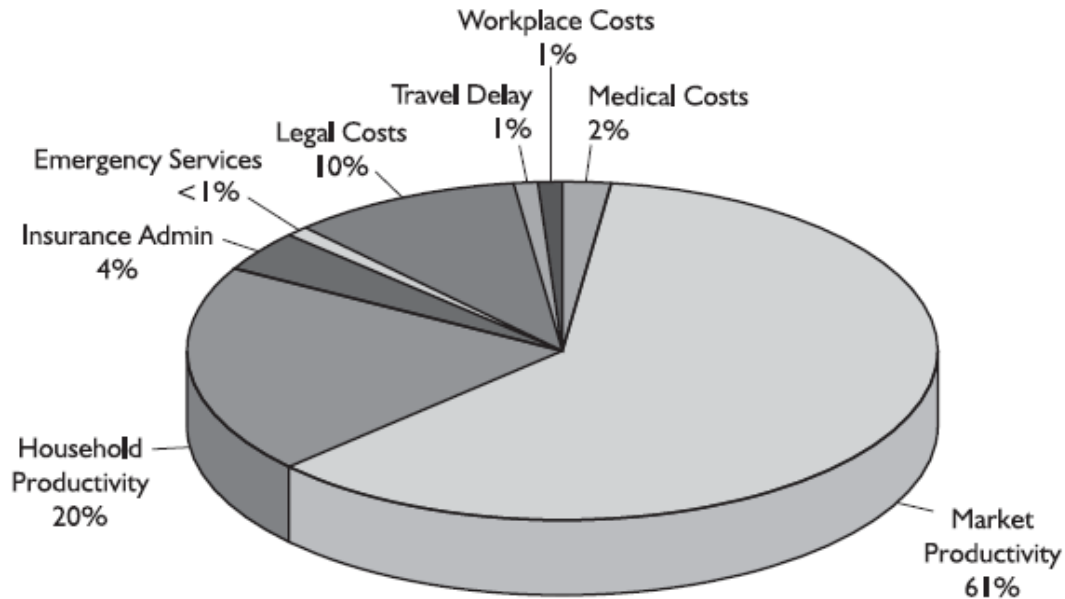


Figure 2-2. Components of Total Costs, Fatalities.³⁰

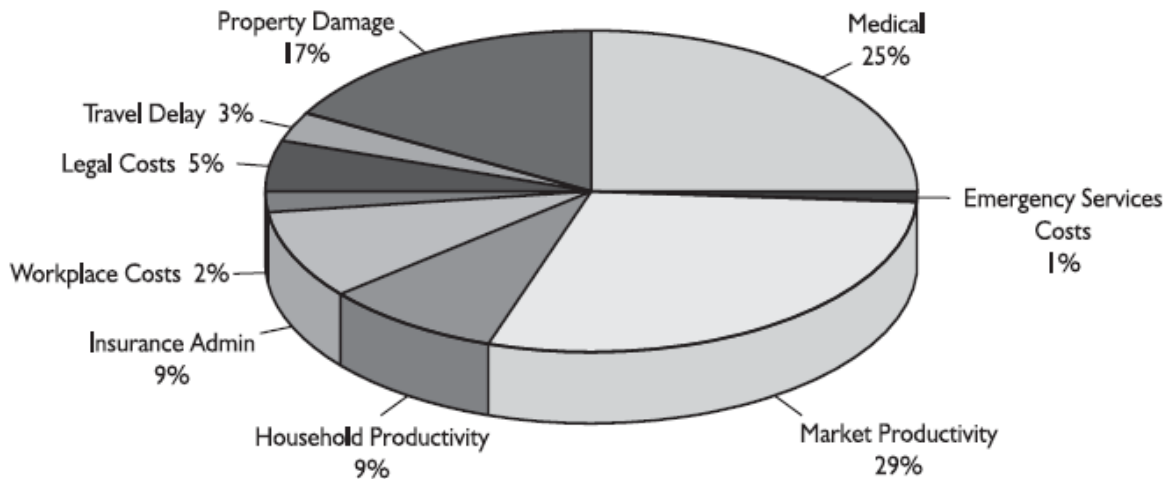


Figure 2-3. Components of Total Costs, Non-Fatal Injuries.³¹

The costs are presented in Table 2-3, using the Abbreviated Injury Scale (AIS). The AIS is used to classify the severity of injuries, as follows: AIS 1 = Minor; AIS 2 = Moderate; AIS 3 = Serious; AIS 4 = Severe; AIS 5 = Critical; and AIS 6 = Fatal. The injury rating may not be the same throughout the body, therefore, the more serious injury dictates the scale ranking.

Table 2-3. Economic Costs (2000 Dollars) of Reported and Un-reported Crashes.³²

Severity	Cost per Injury
PDO	\$2,532
MAIS0	\$1,962
MAIS1	\$10,562
MAIS2	\$66,820
MAIS3	\$186,097
MAIS4	\$348,133
MAIS5	\$1,096,161
Fatal	\$977,208

In summary, crash costs can be estimated many different ways, which results in many different dollar amounts. Each index has an appropriate use. When considering benefits to society, it's accepted that the FHWA willingness-to-pay concept is most appropriate and should be used in combination with an appropriate crash modeling technique which can capture crash severity, as discussed in the following section.

Crash Modeling

Historically, two methods have been used to model crashes. These methods include the crash-based method and the encroachment method. Both methods typically use a regression model with either a crash rate or crash frequency as the dependent variable and highway characteristics such as traffic volume, geometrics, roadside design, etc. as the explanatory variables.

Crash rates and crash frequency are two ways of comparing crashes at multiple locations. Crash rates are a common way of comparing different locations with different traffic volumes. The crash rate represents the risk of becoming involved in a crash each time a vehicle traverses the highway segment. Crash frequency is the number of crashes per time period, for example crashes per year. Crash rate is the crash frequency divided by the exposure in the same period, for example, crashes per 100 million vehicles miles traveled.

$$\text{crash rate} = \frac{\text{crash frequency in a time period}}{\text{exposure in the same period}}$$

When crash statistics are compared for large geographical regions, it has been traditionally viewed as cumbersome to use crash rates due to the data collection necessary, therefore, crash frequency expressed as a percentage is often used. Recently, with the publication of the Highway Safety Manual, crash frequency has gained favor for specific segments and intersection

studies because “the use of crash rate incorrectly assumes a linear relationship between crash frequency and the measure of exposure.”³³

Crash- based method

Road inventories and crash data are collected and maintained by state Departments of Transportation (DOTs), Departments of Public Safety, and the National Highway Traffic and Safety Administration (NHTSA). The crash-based approach uses these data in regression models to model relationships between crashes and the geometric features of a highway, the roadside, traffic, etc. These models are generally formulated to predict crashes with the highway geometry, the roadside, traffic, etc. as input variables.

Using these data to model the probability of a crash has advantages and disadvantages. The biggest advantage is the size of the data set, but real crash data is generally under reported for minor crashes, often lacks detail, and is often gathered by the people involved in the crash, which can impact the reporting characteristics.

Encroachment method

Encroachment modeling has a long history in roadside design. This approach has the potential to be expended across the entire road. This approach models a series of events from when the vehicle “encroaches” to the collision. This approach has been used extensively in cost-benefit analysis because additional modeling can be done to obtain the severity of the crash and the expected societal cost associated with the crash. The concept is based on a series of conditional probabilities which include 1) the probability of encroachment; 2) given an encroachment, the probability of a crash; 3) given a crash, the severity of the crash; and 4) given a severity, the societal cost of the crash.

Using this method, one must first model the probability of an encroachment which requires data on vehicle encroachment. Several failed attempts have been made at data collections through direct and indirect observation methods, which have results in the continued use of two data sets collected in the 1960’s³⁴ and in the 1980’s³⁵.

In the late 50’s and early 60’s Hutchinson and Kennedy conducted a direct observation study of encroachments on medians in Illinois to “determine the significance and nature of vehicle encroachments on certain types of medians under selected field conditions...” to better understand the function of medians.³⁶ Highway segments included Edens, Calumet, and Kingery expressways in Chicago, Illinois during winter months. Data was also collected from the newly opened Federal Aid Interstate Route 74 between Urbana and Danville, Illinois from October 4, 1960 (day it opened) to April 6, 1961 and along US Route 66. Encroachment locations and extent of encroachment were identified through observation of the snow covered medians and supplemental data was gathered from available police accident reports and construction plans. In total, detailed data was collected for approximately 207 miles of road, primarily US 66 and FAI 74.

All of these highways, including FAI 74, were partial access control roads with intersections at grade. Traffic volumes varied from 3,700 to 6,200 vpd. Hutchinson notes that “traffic volumes

have fluctuated rather sharply on all three expressways due to the opening of portions of the Illinois Toll Highway and other expressways in the Chicago area.”³⁷ Hutchinson concluded that the frequency of encroachments can be related to traffic volume below practical capacity as follows:

$$F = (705)10^{-0.0000466V}$$

Where:

F= frequency, encroachments per 100 million vehicles miles of travel

V= average daily traffic volume below practical capacity

Furthermore, as traffic reaches capacity, the rate of encroachment becomes constant.³⁸

Another attempt at collection of encroachment data was undertaken in 1978 in five Canadian provinces. This dataset has been dubbed the Cooper data.³⁹ Data collection took place from July to October in 1978 on 59 road sections, each between 60 and 100 km in length. These road sections were diverse in terms of the posted speed limit, traffic volumes, paved shoulder width, etc. Approximately 20 percent of the segments were high speed divided highways and the remainder were two-lane undivided highways with speed limits of about 80 km/hr (i.e., 50 mph). The traffic volumes ranged from 6,000 to 45,000 vpd for the divided highways and from about 1,000 to 13,000 vpd for the undivided highways. Encroachments that occurred in the median area were not collected. For each encroachment which was identified, these features were measured: 1) maximum extent of lateral encroachment; 2) the longitudinal encroachment length; and 3) the encroachment angle. Cooper analyzed the data and developed the relationship presented in figure 2-4.

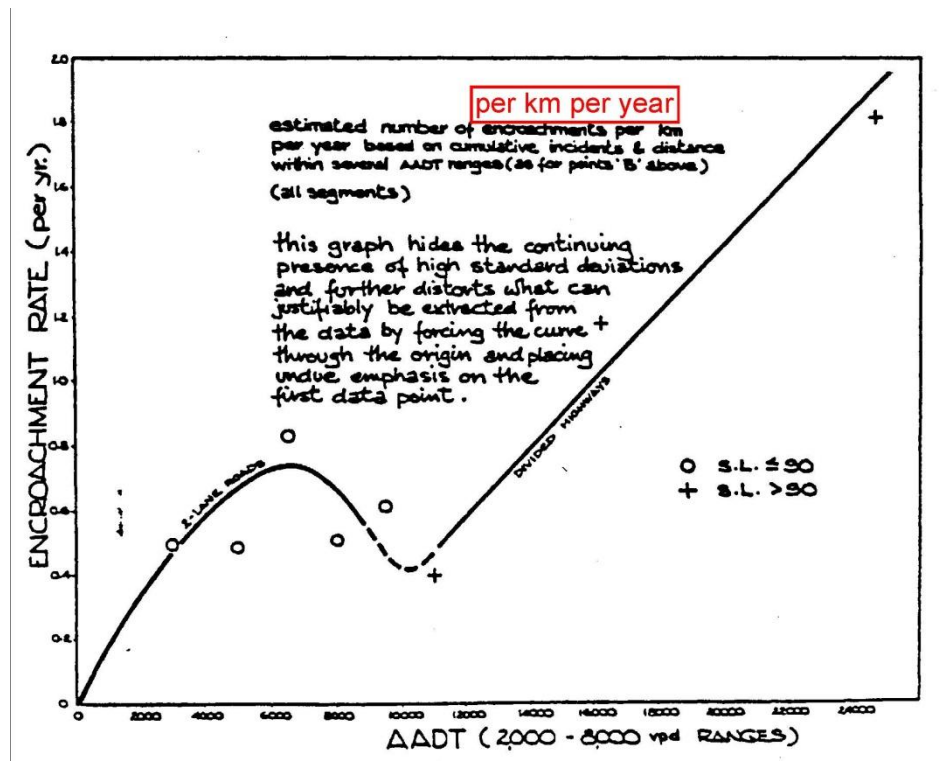


Figure 2-4. Cooper Base Encroachment Rate.⁴⁰

McGinnis conducted a comparative review of both data sets in his paper, “Reexamination of Roadside Encroachment Data”⁴¹ where he reviewed the collection procedures, roadway characteristics and traffic conditions in an effort to determine why the independent research reaches different conclusions about encroachment length. McGinnis concluded, after making adjustments to the Cooper data set to account for variations in data collection techniques and the Hutchinson data to only consider data collected for high speed roads (70 mph), the data sets have similar findings regarding encroachment length. McGinnis further notes that current information is needed.⁴²

Combining Encroachment and Crash-Based Modeling

Miaou investigated the possibility of combining both approaches in, “Estimating Roadside Encroachment Rates with the Combined Strengths of Accident and Encroachment-Based Approaches.”⁴³ Miaou used the existing accident-based prediction models without collecting additional the data. He reviewed the relationships between a roadside encroachments and run-off-road crashes for rural two-lane roads using the Poisson and Negative Binomial (NB) regression models. “The goal of these accident-based models is not only to estimate the expected number of accidents and its association with key covariates, but also to estimate the statistical uncertainty associated with the estimates.”⁴⁴

A Poisson distribution is a “discrete distribution that is often referred to as the distribution of rare events... typically used to describe the probability of occurrence of an event over time, space, or length.”⁴⁵ It takes the form shown here:

$$P(X = x) = P(x; \lambda) = \frac{\lambda^x e^{-\lambda}}{x!}; \text{ for } x = 0, 1, 2, 3, \dots$$

Where:

x = occurrences per interval

λ = mean of occurrences per interval

NB distribution is a “discrete distribution characterized by the count of observation that remains unchanged in a binomial process,”⁴⁶ represented as follows:

$$P(Y_k = n) = C(n - 1, k - 1)p^k(1 - p)^{n-k}; \text{ for } n = k, k + 1, K + 2, \dots,$$

Where:

k = successes

p = probability of success

C(a,b) = number of combinations of b objects taken from a objects

A Binomial Distribution is “the number of successes in n trials, when the probability of success (and failure) remains constant from trial to trial and the trails are independent,”⁴⁷ shown here:

$$P(T = x, n; p) = \frac{n!}{(n - x)! x!} p^x (1 - p)^{n-x}$$

Where:

x = “successes” out of n trials

p = probability of success

Using the Poisson and NB regression models, Miaou developed a function which relates the expected encroachments to highway characteristics, using crash data and the encroachment-based approach.⁴⁸ This function is as follows:

$$E = \left(\frac{365 * ADT}{1,000,000} \right) \exp \left[\frac{\beta_{st} - 0.04 * ADT}{1,000} + L_{nf} + H_{azf} + 0.12HC + 0.05VG \right]$$

Where:

E = expected number of roadside encroachments per mile per year

ADT = average annual daily traffic between 1,000 to 12,000 vpd

β_{st} = State constant with a default value of -0.42. For those areas (or States) where rural two-lane road data are available, it is recommended that β_{st} be estimated as the natural log of the run-off-road accident rate for road segments with ADT < 2,000 vpd, that are relatively straight (e.g., horizontal curvature < 3 degrees) and level (e.g., vertical grade < 3%).

L_{nf} = 0, 0.20, and 0.44 respectively for lane widths of 12', 11', and 10'.

H_{azf} = 0.4 to 0.5 (0.45 is the default value)

HC = horizontal curvature in degrees per 100' arc from 0 to 30 degrees

VG = vertical grade in percent from 0 to 10 percent.

SOFTWARE REVIEW

As previously discussed there are a number of different types of software available to support highway planning and design analysis and documentation. Documentation is generally accomplished through the preparation of plans, specifications, and estimates with the plans prepared in a CAD program. An internet search for the definition of CAD returned several definitions which are all similar in nature. *DefineThat* suggests that CAD is a general “term referring to applications and the method to design things using your computer.”⁴⁹ *Wikipedia* suggests that a “CAD system is a combination of hardware and software that enables engineers and architects to design everything from furniture to airplanes. In addition to the software, CAD systems require a high-quality graphics monitor; a mouse, light pen, or digitizing tablet for drawing; and a special printer or plotter for printing design specifications.”⁵⁰

For the purpose of this research, CAD is considered a drafting tool used to represent one’s design. Typical CAD software does not offer advanced design capabilities, but only a means to communicate a design. Highway design software is also available that takes advantage of the drafting capabilities of programs like AutoCAD and MicroStation. AutoDesk offers AutoCAD Civil 3D and Bentley offers InRoads and GEOPAK for highway designers. All three of these applications are CAD-based and built to work in conjunction with the CAD drafting tools.

General Highway Design and Documentation

The introduction of Computer Aided Drafting (CAD) tools in the 1980’s moved the drafting task from a table to a computer and from manual to electronic. CAD programs like AutoCAD and MicroStation automated drafting in the 1980’s. The recent advent of parametric modeling tools has caused an equally monumental transformation in the way Civil Engineers are designing and documenting projects. New software applications like Civil3D and InRoads are automating much of the civil engineering highway design process leaving the engineer to make design decisions at an increasingly higher level.

While the transportation engineering sub-discipline of civil engineering has traditionally experienced success through integrating design practitioners, the parametric modeling tools available for design and documentation will change workflows as they are adopted. For years, researchers have imagined possible contract documentation workflows which have the possibility of reducing errors on documents which reference the same item. The introduction of object-oriented parametric modeling software which dynamically links the horizontal and vertical alignments with the cross-section of the roadway and earthwork quantities requires the designer to enter design data for any object only once, thus reducing the likelihood of error. Departments of Transportation (DOTs) and transportation consulting firms alike have begun adopting these tools. In addition to the reduction of multiple inputs of the same design information, there is an increase in the amount of design data stored within the CAD file which is accessible to a variety of sub-disciplines involved in any large, complex design activity. For example, in highway design, the surveyor, highway engineer, drainage engineer and structural engineer all have access to and can modify the same information in the model. This helps to eliminate inconsistencies between the different parts of the design leading to better coordination and error reduction throughout the design team. Additional benefits may prove to be quicker, less costly updates and changes to the design files. The development of model-centric projects

will prompt the development of more software which is capable of reading these design data stored within the model.

AutoCAD Civil 3D by Autodesk

Civil 3D is a suite of software tools which includes AutoCAD, Autodesk Map 3D (Map 3D), highway design tools, and survey tools. Civil 3D creates a model which dynamically links model objects such as the horizontal, vertical, and cross-sectional elements of linear designs or the grading groups and drainage structures for site development projects. While designing, the engineer is creating drawing “objects.” For example, a horizontal alignment would be one object. The engineer would reference the horizontal alignment object and link it to the vertical alignment object for the same road. This would continue for the cross-sectional design data, eventually creating an entire “corridor” where information consisting of several objects are linked together. If one object is shifted, or a curve within the corridor object is changed, all of the objects within the corridor affected by the change are updated. A corridor’s design information (i.e., horizontal alignment, vertical alignment cross-sectional data, etc.) can be accessed from external programs so that all the different engineers responsible for the various design tasks can use the correct information. The corridor properties can be queried or changed from an external source. For example, a program could be written to read the horizontal curves of a corridor to check for compliance with a 30 mph design speed. If a curve does not meet the design speed, the external program could send back a file updating the corridor to the minimum horizontal curve for a 30 mph design speed. When the drainage engineer obtains the information to design the roadway ditches, the new information will be available so the drainage design will be based on the correct information.

Map 3D, a geospatial database software tool designed to create and manage large data sets, allows the user to combine and query multiple data sources. (Autodesk, 2008) It supports over 3000 coordinate systems. Map3D reads and writes data in these formats: DWG, DGN, SHP, and MID/MIF. Map 3D reads Spatial Data Files, many raster formats, and many database formats.⁵¹ The Civil 3D software suite, capitalizing on its Map 3D platform can import and export available data from many state Geographic Information Systems (GIS) and Google Earth.

Highway Design Suites by Bentley

Bentley offers GEOPAK built on the Microstation platform and InRoads which is cross-platform program compatible with both Microstation and AutoCAD. Both tools document the highway design as the designer is designing. Highway design calculations are preformed during the drafting tasks and the resulting information is stored within the design file.

The GEOPAK design suite integrates software tools for planners, surveyors, highway designer, and bridge designers. GEOPAK currently has the ability to perform a construction quantity export to the AASHTO Transport software and can import comma separated files (.CSV) and MS Access database formats.

The InRoads suite provides five separate modules for the designer to choose from (i.e. InRoads, InRoads Bridge, InRoads Survey, InRoads Site, and InRoads Storm & Sanitary). This software is more focused on the individual aspects of highway engineering and evaluation of design alternatives.⁵²

Data Exchange

While these tools offer exciting opportunities to those who have a license to use them, interoperability between the various software platforms should also be considered. Both Autodesk and Bentley offer extended options to save the user output in non-native formats. An industry standard language for interoperability between various CAD based programs has also developed in the form of Land XML data exchange format. Bentley and Autodesk have signed an agreement to support and further the development of Land XML and share Application Program Interface (API) through the Open Data Alliance (ODA).⁵³

Land XML is an industry standard language for interoperability between over 70 CAD-based programs that allows users to exchange information between a variety of software applications.⁵⁴ LandXML represents data at several levels of abstraction. The FHWA's IHSDM effort, for example, uses Land XML to ensure interoperability between it and InRoads and Civil3D.

LandXML saves project data in a generic, text-based file format with a .xml extension as shown in Figure 2-5. These files can be used to transfer data to other CAD-based software packages similar to a DXF™ file, which is a generic file format for vector-based drawing information.

Recognized project data includes:

- Horizontal alignments,
- Profiles,
- Cross sections,
- Points, and
- Surfaces.

An example of an export file is provided in figure 2-6.

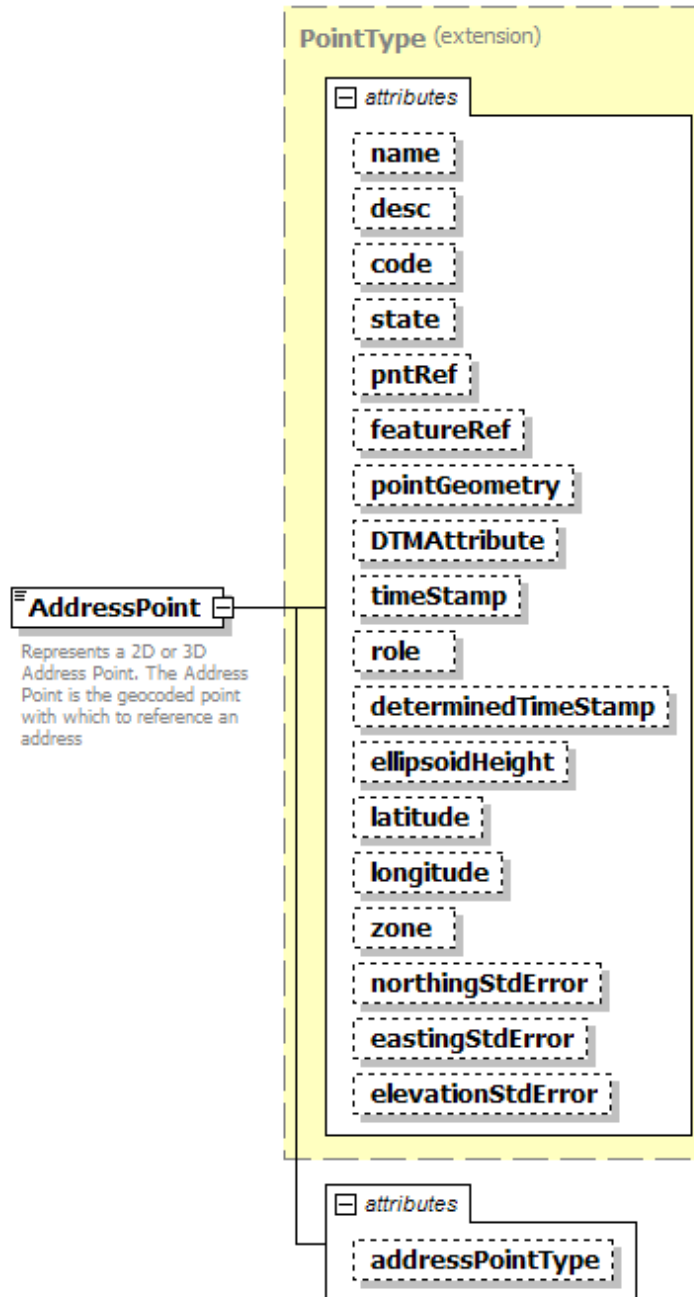


Figure 2.5. LandXML Data Diagram.⁵⁵

```

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```

Figure 2-6. Example LandXML Data Export.

Safety Analysis Software

Software tools are also available to help with assessing highway safety. Some of these tools are appropriate for planning level or network analysis while others lend themselves to review of design alternatives and some to specific design elements. A discussion of various safety support software and the necessary input data follows.

Roadside Safety Analysis Program (RSAP)

The Roadside Safety Analysis Program (RSAP) provides a review of roadside designs based on the probability of encroachment (i.e., the likelihood that a vehicle will leave the travelled way). It incorporates a cost-effectiveness review of alternative roadside designs. “The basic concept is that public funds should be invested only in projects where the expected benefits would exceed

the expected direct costs of the project.”⁵⁶ The reduction in crash costs are considered benefits and direct costs are the highway agency costs.

RSAP uses these four modules to assess the cost-effectiveness of a design:

- Encroachment Module,
- Crash Prediction Module,
- Severity Prediction Module, and
- Benefit/Cost Analysis Module.

The encroachment probability model, shown below, is built on a series of conditional probabilities. First, given an encroachment, the crash prediction module then assesses if the encroachment would result in a crash, $P(C/E)$. If a crash is predicted, the severity prediction module estimates the severity of the crash, $P(I/C)$. The severity estimate of each crash is calculated using crash cost figures so the output is in units of dollars. The user may enter regional figures or use those contained within the program, including the AASHTO *Roadside Design Guide* costs and the FHWA comprehensive cost figures.

The encroachment probability model is as follows:

$$E(\text{Crash Cost}) = ADT * P(\text{Enc.}) * P(\text{Crash}/\text{Enc.}) * P(\text{Injury}/\text{Crash}) * C(\text{Injury})$$

Where:

$E(\text{Crash Cost})$ = Expected crash cost

ADT = Average Daily Traffic

$P(\text{Enc.})$ = Probability of encroachment (encroachment rate)

$P(\text{Crash}/\text{Enc.})$ = Probability of crash given encroachment

$P(\text{Injury}/\text{Crash})$ = Probability of injury given crash

$C(\text{Injury})$ = Cost of injury

Appendix A of the 1988 Roadside Design Guide (RDG)⁵⁷ included a computer program called ROADSIDE, which was a software implementation of the risk-based cost-effectiveness procedures proposed by Glennon in 1974⁵⁸ and incorporated in the 1977 Barrier Guide. [BarrierGuide77] Additional research and budding computer technology lead to the development of RSAP, which was completed in 2003. RSAP was documented in NCHRP Report 492 by Mak and Sicking.⁵⁹ The RSAP procedure was included in the 2002 RDG, and has been included in subsequent editions ever since.⁶⁰

Crash Prediction Module of the Interactive Highway Safety Design Module (IHSDM CPM)

IHSDM is a suite of software tools which includes five modules:

- *Policy Review Module*: checks design elements against design policies for compliance.
- *Crash Prediction Module*: estimates the frequency and severity of crashes based on the geometric design and traffic characteristics. This module was created as the direct software implementation of Part C of the Highway Safety Manual (HSM).
- *Design Consistency Module*: identifies potential speed inconsistencies.

- *Intersection Review Module*: systematically evaluates the geometric design of an intersection to identify potential safety concerns.
- *Traffic Analysis Module*: “Uses the TWOPAS traffic simulation module to estimate traffic quality of service measures for an existing or proposed design under current or projected future traffic flows...”⁶¹

The CPM uses models from the HSM, based on accident modification factors (AMF). The two-lane rural road base model is as follows:

$$N_{br}=(ADT)(L)(365)(10^6)e^{-0.4865}$$

where:

N_{br} =Predicted number of total roadway segment crashes per year under base conditions,
 L = Segment length and
 ADT = Average Daily Traffic

This model assumes the following:

- 3.7 meters [12 foot] lanes,
- 1.75 meters [6 foot] shoulders,
- Roadside hazard rating of 3,
- Five driveways per mile,
- No horizontal curvature,
- No vertical curvature and
- Zero percent grade.

If the model requires modification because the base conditions do not match the features of the design, then AMFs can be employed using this equation:

$$N_{fs}=N_{br}C_r(AMF_{1r}, AMF_{2r}, \dots, AMF_{nr})$$

where:

N_{fs} =Predicted number of total roadway segment crashes per year after application of AMFs,
 $AMF_{1r}, AMF_{2r}, \dots, AMF_{nr}$ = Accident modification factors of design features, and
 C_r = Calibration factor for roadway segments developed for use for a particular geographical area.

The HSM suggests additional refinement of the safety prediction using the Empirical Bayes method if the data is available. This refinement should be conducted using this equation:

$$E_p=w(N_{rs})+(1-w)N_o$$

where:

E_p = Expected total crash frequency based on a weighted average of N_{rs} ,
 w = Weight to be determined by an equation in a future chapter of the HSM and
 N_o = Number of crashes observed during a specified period of time.

In summary, the *CPM* is one of five software tools available within the IHSDM. The *IHSDM CPM* is used in conjunction with the HSM for predicting crashes within a highway segment. This software runs independent of CAD-based programs, but is able to accept input from a LandXML file.

Roadside Hazard Rating Accident Modification Factor (RHR AMF)

The HSM uses the roadside definition from the RDG, including the “area between the outside shoulder edge and the right-of-way limits. The area between roadways of a divided highway may also be considered roadside.”⁶² Unfortunately, this definition is not completely observed throughout the HSM. For example, when defining a segment, one does not consider the present of lack of a median as a new segment, but the Roadside Hazard Rating (RHR), discussed below, is used to determine segment boundaries as they relate to the roadside. The effect of medians on crash frequency is only considered as a modifier to the base conditions. In fact, many different AMFs are included for considering medians, but these are not considered Roadside AMFs by the HSM.

The HSM uses the RHR AMF to account for the “effect of roadside design.”⁶³ This AMF relies on the visual and subjective RHR scale developed by Zegeer *et al.*⁶⁴ The base model uses an RHR equal to three. If the user feels the RHR equal to three does not represent the roadside environment, adjustments can be made using an AMF. One RHR AMF applies to both sides of the road, not the median, and is calculated as follows⁶⁵:

$$AMF_{10r} = \frac{e^{(-0.6869+0.0668 *RHR)}}{e^{(-0.4865)}}$$

where:

AMF_{10r}=Accident Modification Factor for the effect of roadside design;

RHR= Roadside Hazard Rating

RHR is a qualitative index that is subjective and visual. The visual comparison relies mainly on sideslope and clear zone impressions based on comparison of the study segment to standardized reference photographs. The RHR has a scale of 1 to 7 with 1 representing very good and 7 representing very poor roadside conditions, respectively. Zegeer’s original photographic examples and definitions for the RHR scale are available in Appendix A of Chapter 13 of the HSM, however, the IHSDM CPM software does not provide the same pictures for evaluating the user’s RHR choices, but does provide a help menu with this text ⁶⁶:

Rating = 1

- Wide clear zones greater than or equal to 9 m (30 ft) from the pavement edgeline.
- Sideslope flatter than 1:4.
- Recoverable.

Rating = 2

- Clear zone between 6 and 7.5 m (20 and 25 ft) from pavement edgeline.
- Sideslope about 1:4.

- Recoverable.

Rating = 3

- Clear zone about 3 m (10 ft) from pavement edgeline.
- Sideslope about 1:3 or 1:4.
- Rough roadside surface.
- Marginally recoverable.

Rating = 4

- Clear zone between 1.5 and 3 m (5 to 10 ft) from pavement edgeline.
- Sideslope about 1:3 or 1:4.
- May have guardrail (1.5 to 2 m from pavement edgeline).
- May have exposed trees, poles, or other objects (about 3 m or 10 ft from pavement edgeline).
- Marginally forgiving, but increased chance of a reportable roadside collision.

Rating = 5

- Clear zone between 1.5 and 3 m (5 to 10 ft) from pavement edgeline.
- Sideslope about 1:3.
- May have guardrail (0 to 1.5 m from pavement edgeline).
- May have rigid obstacles or embankment within 2 to 3 m (6.5 to 10 ft) of pavement edgeline.
- Virtually non-recoverable.

Rating = 6

- Clear zone less than or equal to 1.5 m (5 ft).
- Sideslope about 1:2.
- No guardrail.
- Exposed rigid obstacles within 0 to 2 m (0 to 6.5 ft) of the pavement edgeline.
- Non-recoverable.

Rating = 7

- Clear zone less than or equal to 1.5 m (5 ft).
- Sideslope 1:2 or steeper.
- Cliff or vertical rock cut.
- No guardrail.
- Non-recoverable with high likelihood of severe injuries from roadside collision.

Using the text or the original photos, a single RHR is chosen to represent both sides of the road for an entire segment. Variations in the roadside are not captured over the segment using this method, nor can alternatives be accurately evaluated or compared. For example, if removal of the utility pole shown in the photo of RHR equal to four in Figure 2-7 is under consideration, the RHR would likely still equal four, even after the unprotected hazard at the start of the guardrail has been removed.

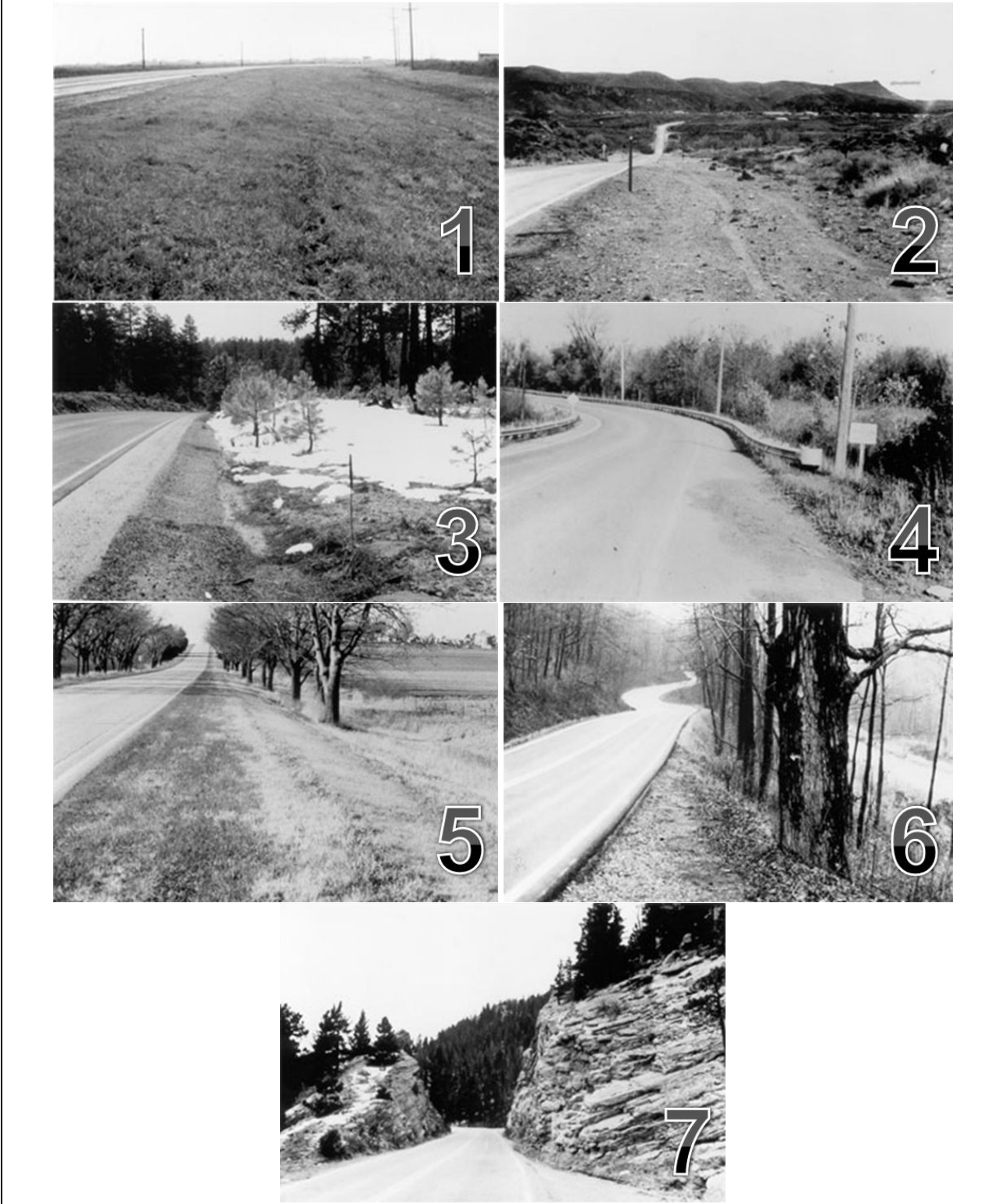


Figure 2-7. Photographic Representation of Roadside Hazard Ratings (RHR).⁶⁷

- Segment location (in a form that is linkable to crash locations) ,
- Segment length (mi) ,
- Area type (rural/urban),
- Number of through traffic lanes (by direction of travel) ,
- Median type (divided/undivided),
- Access control (freeway/nonfreeway),
- Two-way vs. one-way operation and
- Traffic volume (AADT).

Intersection Characteristics Data

- Intersection number,
- Intersection location (in a form that is linkable to crash locations),
- Area type (rural/urban),
- Number of intersection legs,
- Type on intersection traffic control,
- Major-road traffic volume (AADT) and
- Minor-road traffic volume (AADT).

Ramp Characteristics Data

- Ramp number,
- Ramp location (in a form that is linkable to crash locations),
- Area type (rural/urban),
- Ramp length (mi),
- Ramp type (on-ramp/off-ramp/freeway-to-freeway ramp),
- Ramp configuration (diamond/loop/directional/etc.) and
- Ramp traffic volume (AADT).

Crash Data

- Crash location,
- Date,
- Collision type,
- Severity,
- Relationship to junction and
- Maneuvers by involved vehicles (straight ahead/left turn/right turn/etc.).

In summary, *SafetyAnalyst* provides six software tools for evaluating and programming safety improvements at the system-wide level. This stand-alone software is used to identify crash patterns and determine high frequency locations for potential safety improvement projects. Using GIS data inputs, wide scale planning can be done to prioritize improvement projects to allow for the projects with the largest safety benefits to be prioritized accordingly.

Other Safety Software

Arizona Local Government Safety Project Analysis Model (LGSP)73

The Arizona LGSP facilitates identification and safety project selection by local jurisdictions and planning organizations. This tool generates a list of the most hazardous locations based on user-

defined parameters (e.g., alcohol involvement, location reference, distance, weighting method, etc.) based on a database of crashes and highway information.

SafeNET⁷⁴

SafeNET is safety management tool developed by the UK Department for Transport. It includes crash prediction models for intersections and roadways. This stand-alone tool is used to predict crashes in the transportation network. Additionally, SafeNET is used with a traffic assignment model “CONTRAM.” This enables the software to account for safety and congestion simultaneously.

PLANSAFE⁷⁵

This planning level safety prediction model is a stand-alone software package developed under NCHRP 8-44. It is used to predict the frequency of crashes per analysis zone. Crashes of various types are modeled as functions of various predictors (e.g., mileage of the functional classifications of highways, vehicle miles traveled, socio-economic and demographic factors, and population characteristics.) This model was developed using data from Pima and Maricopa Counties in Arizona and the state of Michigan and take the standard form of log linear regression models. These models are shown in Table 7. Comparison of the planned alternatives is conducted by the designer or planner in a program such as Microsoft excel. Due to the nature of these models, their application to reconstruction projects appears limited. These models rely on changes in the number of intersections or mileage if the functional classification and socio-economic factors are unchanged. Other possible model predictors of safety include development and population changes. These predictors will also remain unchanged for a reconstruction project.

Table 2-4: PLANSAFE Regression Models.⁷⁶

MODEL FORMS
<p>Total Accident Frequency Model</p> $\text{Log}(\text{Accident_Frequency} + 1)$ $= 5.020 + 0.474 \times 10^{-1}(\text{POP_PAC}) + 0.196 \times 10^{-3}(\text{POP16_64})$ $+ 0.151 \times 10^{-2}(\text{TOT_MILE})$
<p>Property Damage Only Accident Frequency Model</p> $\text{Log}(\text{PDO_accident_frequency} + 1)$ $= 4.762 + 0.515(\text{PH_URB}) + 0.566 \times 10^{-1}(\text{POP_PAC}) + 0.392 \times 10^{-3}(\text{VMT})$
<p>Fatal Accident Frequency Model</p> $\text{Log}(\text{Fatal_accident_frequency} + 1)$ $= 0.652 - 0.924 \times 10^{-1}(\text{INT_PMI}) + 1.762(\text{PNF_0111}) + 1.389(\text{PNF_0512})$ $+ 0.263 \times 10^{-3}(\text{POP00_15}) + 0.319(\text{PPOPMIN})$
<p>Incapacitating and Fatal Accident Frequency Model</p> $\text{Log}(\text{Incapacitating_and_Fatal_accident_frequency} + 1)$ $= 2.257 - 0.659 \times 10^{-1}(\text{INT_PMI}) + 3.328(\text{PNF_0111}) + 3.674(\text{PNF_0512})$ $+ 0.512 \times 10^{-3}(\text{POP00_15})$
<p>Nighttime Accident Frequency Model</p> $\text{Log}(\text{Nighttime_accident_frequency} + 1)$ $= 4.092 - 19.167(\text{MI_PACRE}) + 3.524(\text{PNF_0111}) + 1.414(\text{PNF_0214})$ $+ 3.588(\text{PNF_0512}) + 0.861(\text{PPOPMIN}) + 0.238 \times 10^{-3}(\text{WORKERS})$
<p>Pedestrians Accident Frequency Model</p> $\text{Log}(\text{frequency_of_accidents_involving_pedestrians} + 1)$ $= 1.443 - 0.706 \times 10^{-3}(\text{HH_INC}) + 0.129(\text{POP_PAC}) + 0.884 \times 10^{-4}(\text{POPTOT})$ $- 0.902(\text{PWTPRV})$
<p>Injury Accident Frequency Model</p> $\text{Log}(\text{frequency_of_injury_accidents} + 1)$ $= 3.108 + 0.153(\text{HU_PACRE}) + 0.768(\text{PPOPURB}) + 0.443 \times 10^{-3}(\text{VMT})$
<p>Accidents Involving Bicycles Frequency Model</p> $\text{Log}(\text{frequency_of_Accidents_involving_bicyclists} + 1)$ $= 0.655 \times 10^{-1} + 0.252 \times 10^{-3}(\text{HU}) + 0.162 \times 10^{-2}(\text{TOT_MILE}) + 0.292 \times 10^{-5}(\text{VMT})$ $+ 1.539(\text{WORK_PAC})$

The SafetyAdvisor⁷⁷

This stand-alone software tool was developed for performing a safety assessment of highway designs using the encroachment-based modeling approach. This program calculates a safety scale based on the characteristics of the highway, supplied by the user. The safety scale is displayed in the view along with a graphical representation of the roadway. The safety scale is developed following a prediction of crashes based on several crash predictor models. These models include:

Encroachment Model

$$P(E) = \prod_{k=1}^1 a_k b_k^{c_k}$$

where:

a_k , b_k , & c_k are characteristics of the roadway or constants.

Collision Model

$$P(C) = 0.1520 (1.0435^V) (0.9036^Y)$$

where:

$P(C)$ = Probability of collision,

V = mean travel speed of the roadway and

Y = lateral offset of the roadway hazard.

Severity Model

$$P(A + K)_i = P(E)_i P(C|E)_i P(A + K|C)_i$$

where:

The probability of experiencing a fatality or injury for a particular hazard i is estimated by adding injury and fatal crashes (A+K).

These models can all be easily updated based on new research. It is labor intensive, however, to input roadway characteristics into this program. Ray acknowledges that an interface with CAD programs would reduce the required input time and increase the amount of data available to the safety analysis.⁷⁸

Software Platform and Programming Issues

A computer program is a series of instructions that enables the computer to solve a problem. These instructions can be programmed in many different languages. Visual Basic and C# are both popular languages for Windows and Web applications. C and C++ emphasize flexibility and fast running times. Java is a flexible language which can run on many different computer systems.⁷⁹ RSAP was originally coded with the computational engine in Fortran and the graphical user interface in C++. Fortran is an old computer programming language largely used in the sciences and engineering because it was structured specifically for performing high-level extensive calculations. More modern programming languages like C have largely replaced Fortran as “number crunching” programming languages and few software developers today develop new code using Fortran.

While Fortran was a good choice for performing numerical calculations, it always has been unsuitable for developing the type of graphical user interface that most users expect in modern engineering software. The original developers of RSAP recognized this and used C++, the object-oriented version of C, to develop the user interface. Today’s user interfaces, however, are even more sophisticated than those used when RSAP was originally coded. Modern civil engineering design suites like InRoads and Civil3D are developed and maintained in even more modern object-oriented codes like visual basic (VB).

VB is a programming environment and language. The programmer can create, through a windows interface, a new program’s user interface which allows the programmer to piece together a form from a toolbox and then add code to support the form. The coding language is similar to the original BASIC programming language.⁸⁰

VB is known for its strong ability to integrate different programs and languages. RSAP2010 could be coded with the computational engine in Microsoft Excel and the graphical user interface in VB. Excel has widespread use among engineers and scientists, is structured for multiple worksheets, is powerful in performing high-level extensive calculations, and introduces the ability to easily update statistical models as new research develops. The use of Excel for the computational engine would make integration with the users who do not have the application much simpler and would also make the program easier to maintain in the long run. VB could also be used to facilitate the exchange of highway geometric data from CAD software.

Options for RSAP to interface with CAD-based highway design software include a separate, direct interface specifically coded for each program (i.e., Civil 3D, InRoads, Geopak, etc.), which can be loaded through the CAD software and interacted with directly while in the CAD software. This option would require separate versions of RSAP for each CAD-based highway design software suite. AutoDesk, the developer of Civil3D, provides third party developers access to the core software using application programmers interfaces (API) and the API works with visual basic (VB). Third-party developers are companies, universities and programmers that develop software products that interact with the core highway design software suites, for example AutoDesk’s Civil3D. Access to the API is generally restricted to third party developers approved by the developer of the software suite and this development team has been granted access. Bentley does not grant developers this same level of access to APIs, however both

Autodesk and Bentley, as previous discussed, have signed an agreement to support and further the development of Land XML.⁸¹

Land XML is an industry standard language for interoperability, as discussed above.⁸² The FHWA's IHSDM effort, for example, uses Land XML to received geometric data about the highway from CAD-based highway design suites. A new version of RSAP can be coded to parse a LandXML input for the highway geometrics and prompt the user for specifics about roadside features (i.e., TL-4 or TL-5 barrier, Cable or Concrete, etc.). A new version of RSAP can also be coded to interface directly with AutoCAD Civil 3D.

RSAP2010 could be developed with the ability to receive geometric data from a CAD-based highway design software suite (e.g., Civil3D or InRoads) electronic file for risk analysis. Additionally, the user could maintain the option of manually entering the alignment data if they do not have or want to use CAD software. The option exists for coding the RSAP computations with or without an MS Excel template.

The ability to easily update a program is paramount in this era of ever changing computational power and developing research. Additionally, the ability for a user to customize RSAP to meet their local or regional needs is vital. Having default data hard-coded in the software makes these updates and local customization difficult to accomplish. Template files coded in a familiar program like Excel allows for easy updates and user customization. When new research becomes available, a template file can be updated and posted online with instructions for users to replace the existing template with the updated template. If users wish to customize default data for local conditions, instructions can be provided for replacing the template with the customized template. The results of the analysis could be saved in a MS Excel file. In the event the user chooses to share the results with another party, the user would have the option of sending the second party an Excel file. This option of documenting the analysis results was incorporated in the recently completed NCHRP project for computing pavement designs, the Mechanistic-Empirical Pavement Design Guide (MEPDG).

Summary

Highway crashes occur at an alarming rate and cost society billions of dollars. Estimating the frequency and severity of crashes can be very challenging since a good deal of data is required. Some of this data has been challenging to obtain, such as highway geometric data, but the use of CAD-based highway documentation software makes this data more readily available during the design stages of a project. The existing crash modeling and highway safety evaluation software does not effectively interface with these CAD-based programs. Progress of computers and design support software has made the possibility of automating project specific data entry into crash modeling software a realistic possibility, which could change the way highways are designed and evaluated. The following chapters discuss the existing highway design practice and areas where integration of new techniques would improve highway safety and reduce highway fatalities.

CHAPTER 3

CURRENT DESIGN PRACTICE

The current highway design practice is based on a series of design manuals which rely on a progression of decisions about the intended use of the facility. Therefore, the volume of traffic it will serve, the speed the traffic *should* be able to travel and the expected level of service are process inputs. Based on these initial assumptions, the designer makes another set of design decisions regarding the number of lanes and the amount of sight distance to be provided, which are supported by published policies and manuals such as *A Policy on Geometric Design of Highway and Streets*⁸³ (Green Book) and the *Roadside Design Guide*⁸⁴ (RDG), published by AASHTO; the *Manual of Uniform Traffic Control Devices*⁸⁵ (MUTCD), published by the Federal Highway Administration (FHWA); and the *Highway Capacity Manual*⁸⁶ (HCM2000), published by the Transportation Research Board (TRB). Each State generally supplements these publications with its own Highway Design Manual. AASHTO is expected to release a new publication in 2009, the *Highway Safety Manual*⁸⁷ (HSM), which is intended as a guide to assess the safety implications of design decisions. Designers also rely on a variety of software tools to support their design tasks. For example, the HCM2000 is supported by the Highway Capacity Software (HCS2000); the RDG offers the Roadside Safety Analysis Program (RSAP) to support cost-effectiveness decisions; the HSM will provide software support through the Interactive Highway Safety Design Model Crash Prediction Module (IHSDM CPM) to predict crash frequency for highway and intersection segments; and software companies offer many graphics-based tools which supplement established CAD software for performing analysis of specific components of the design such as storm sewer design, turning movement design, guide sign design, etc.

The warrants and guidelines used during a typical highway design are long-established and rooted in the design community as the basis for every design. The existing highway design process, however, is not a formal one nor is it documented in literature. The following paragraph is the only mention of any guidance or design process type language available in the Green Book:

*The first step in the design process is to define the function that the facility is to serve. The level of service needed to fulfill this function for the anticipated volume and composition of traffic provides a rational and cost-effective basis for the selection of design speed and geometric criteria within the ranges of values available to the designer. The use of functional classification as a design type should appropriately integrate the highway planning and design process.*⁸⁸

There is a surprising lack of guidance about the process one would follow to complete a design using the policy set forth in the “Green Book.” There are, of course, many factors influencing any design, but every design follows the same general steps. These steps should be outlined in the nationwide policy on geometric design of highways.

The existing process is typically handed down from generation to generation of highway designers with knowledge accumulated from field and design experience. Application of the existing warrants and established guidelines varies by State and within States. In some States where tort liability is a large concern, decisions to upgrade or not upgrade geometric features of a facility may be made on the basis of whether or not all of the warrants can be fulfilled. In other

situations, decisions of geometrics might be made based on concerns about available right-of-way and the ability to relocate certain types of owners, environmental regulations, or impacts to such things as public park lands or historic landmarks. There is a good deal of flexibility in the existing design process which allows the designer to accommodate many obstacles during design, but accommodating all of these obstacles comes at a cost and that cost is safety. These decisions are made with little understanding of how they impact the overall safety of the corridor under design.

The warrants presented in the Green Book were originally developed with little empirical evidence, but rather they were established based on physical properties and “engineering judgment.” These original warrants and guidelines have remained in place with only minor changes to input variables based on the evolution of the vehicular fleet over time.

The warrants presented in the RDG are based on empirical data and have evolved over time as new data presents itself. The draft version of the HSM is also based on empirical evidence and promises to evolve as changes occur in driver behavior, highway geometrics, and vehicle fleet. Designs completed today are often done by consultant firms hired by municipal and state agencies. As a result, streamlining the design and documentation process has become increasingly important as a means to reduce costs and increase profit. The major CAD software providers have recognized this trend and have been producing increasingly more advanced combinations of highway design/documentation tools. These tools are discussed in more detail in the Software section of the Literature Review. These software tools have become an integral part of the highway design process for many design firms, as engineers can now simultaneously design and document the highway design. The current process, using the guidelines discussed above and the software tools available, generally follows these steps outlined here and discussed in more detail below:

- Step 1: Determine if the existing number of lanes is sufficient or additional lanes are necessary to accommodate future traffic volumes.
- Step 2: Determine the functional classification of the road and the corresponding design criteria.
- Step 3: Simultaneously design and draft the horizontal alignment electronically in a CAD program overlaid on the electronic field survey data, using the established horizontal alignment criteria.
- Step 4: Simultaneously design and draft the proposed ground profile using the previously established vertical alignment criteria.
- Step 5: Draft a typical cross-section using the proposed number of lanes and produce cross-sections of the corridor.
- Step 6: Edit these cross-sections, horizontal and vertical alignments as needed to minimize impacts such as right-of-way (ROW) and environmentally sensitive areas.
- Step 7: Produce a Construction Cost Estimate and submit preliminary plans and estimate for review, sometimes called the 80% review
- Step 8: Address reviewing agency concerns with the geometric design. Produce a pavement stripping and signing plan, construction specifications, more detailed construction plans and cost estimate. Submit Final plan set for review, often called the 100% review.
- Step 9: Address reviewing agency concerns with construction documents and produce final Plans, Specifications, and Estimate (PS&E).

- Step 10: Project is Bid and Constructed. Areas of safety concern are often identified after the project is constructed and opened to traffic.

Pre-design preparation: Collect necessary field data.

Before commencing design activities, field data is ordered to a level of accuracy and precision specified by the local design standards. This data generally included a field survey and traffic counts.

Traditionally highway surveys have involved measuring and computing horizontal and vertical angles, elevations, and distances using a variety of data-gathering equipment. Using this field gathered data, through a series of calculations and manipulations, a base map with contour lines and existing highway alignments can be created. Recently, more sophisticated survey data collection techniques have been developed which include either measuring of distances and elevations from a remote location (i.e., airplanes, satellites, etc.) or using electronic field data collectors, which automate some of the post-processing of field data and aid in the production of a CAD file for design. The accuracy and precision, as well as the amount of data gathered, govern which data collection method is used.⁸⁹

Google Earth⁹⁰ is one of several public domain sources for information gathered through remote sensors. Google Earth compiles this information from other sources and notes the original source at the bottom of the screen. The compilation of information contains geographically referenced images and terrain information of varying degrees of precision and accuracy, as established by the original data gatherer.⁹¹

The scope of the project generally dictates the number and type of traffic counts necessary for a highway design. Generally, if an intersection is located within the limits of a corridor improvement project, turning movement counts and pedestrian counts are taken and automatic traffic recorder (ATR) counts are ordered on all approaches of the intersection. A corridor improvement project absent of intersections only requires one ATR, unless there is a major traffic generator (i.e., large box store, shopping mall, etc.) within the project limits, in which case it should be treated as an intersection. Turning movement and pedestrian counts are conducted by people to determine the number of vehicles and people moving in each direction at an intersection during 15-minute periods for a minimum of two consecutive hours which are representative of the peak-period of traffic. An ATR is a tube placed across the road which measures the number of vehicles that cross the tube, generally over a minimum of 24-hours. Different configurations of the tube/tubes make it possible to determine how many vehicles are traveling in each direction, the classes of vehicles, how many of each class, and the speed of the vehicles.

Step 1: Determine if the existing number of lanes is sufficient or additional lanes are necessary to accommodate future traffic volumes.

The Traffic Characteristics section of the Green Book states that “all information should be considered jointly. Financing, quality of foundations, availability of materials, cost of right-of-way, and other factors all have important bearing on the design; however, traffic volumes indicate the need for the improvement...”⁹² This statement clearly reflects AASHTO’s opinion

about highway capacity being the driving factor in justifying highway improvements, rather than other considerations such as highway safety or user benefits. Traffic volumes are the driving factor in determining highway capacity and level of service (LOS). Highway capacity and LOS are discussed and defined in detail in the Highway Capacity Manual⁹³ (HCM2000) published by the NCHRP. In addition to the number of highway lanes, the number of lanes approaching and leaving intersections along the corridor and the treatment of intersections is also a concern at this stage of the project.

The Green Book defines several traffic volume terms for discussion and design purposes. These terms include:

- *Average Daily Traffic (ADT)*: "...the total volume during a given time period (in whole days), greater than one day and less than one year, divided by the number of days in that time period."⁹⁴ *Average Annual Daily Traffic (AADT)* is another common term to describe traffic volumes and some confusion existing among many practitioners about the difference. Often these terms are used interchangeably. AADT is the average of a 24 hour count collected every day for a minimum of a year. Most traffic data is an ADT, except for data gathered through a continuous counting station.
- *Peak-Hour Traffic*: More commonly referred to as the *Design Hour Volume (DHV)*, "...It is recommended that the hourly traffic volume that should generally be used in design is the 30th highest hourly volume of the year."⁹⁵ Common practice is, however, to conduct traffic counts for a two day period and design for the highest volume. Generally, an abundant amount of traffic volume information is not available. Some communities do maintain more complete records and traffic models and, therefore, have more precise data for estimating design hour volume.
- *Directional Distribution (D)*: The directional distribution of traffic is expressed as a percent and the number is given for the higher direction only. For example if 55 percent of the vehicles are traveling northbound during the peak hour, then D equals 55 northbound.
- *Composition of Traffic*: Recognizing that "...vehicles of different sizes and weights have different operating characteristics..." should be considered in design. Trucks, of course, have a much different acceleration, sight distance, and intersection with highway and roadside elements than passenger vehicles. The *percentage of trucks (T)* is generally gathered for design purposes. This percentage would include "...all buses, single-unit trucks, combination trucks, and recreational vehicles."⁹⁶

The projection of traffic volumes to a future year generally equates to an increase in traffic volumes. The decision of which future year is appropriate could depend on many influencing factors including how accurately one can project the future needs of the highway corridor if it is not already developed, the possible addition of new intersections or other roadways servicing the same origin and destination and perhaps most significantly, economics. "...If the added cost of a 50-year design over a design with a 25-year life expectancy is appreciable, it may be imprudent to make a further investment providing capacity that will not be needed for at least 25 years."⁹⁷ The savings that are realized may be used elsewhere. A period of 20 years is widely used as a basis for a design project, however, for reconstruction or rehabilitation projects, a 5 to 10 year period generally is used because of uncertainties and funding constraints.

Upon determining the traffic characteristics of the corridor and intersections/interchanges under consideration, the HCM is consulted and a capacity analysis is performed to determine an acceptable number of lanes and appropriate intersection/interchange configuration. This long, tedious analysis is often performed using the HCS2000 software.

Step 2: Determine the functional classification, design speed, and the corresponding design criteria.

The functional classification of highways was developed for planning purposes. This type of classification groups highways by the character of services they provide, or their “function.” Generally, roads can be broken down into three categories, arterials, collectors, and local roads with arterials at the top of the hierarchy. Ideally, a local road should provide access to a collector and a collector to an arterial thereby assembling traffic at slower speeds with more access points (local road) and gradually progressing toward higher speeds with less access points intended for longer trips (arterials). The same general principles can be applied in urban, suburban and rural areas, however, the dense pollution and land use in urban areas makes this hierarchy system difficult to identify. Figure 3-1 provides a schematic of the relationship between functional classification, mobility and land access.⁹⁸

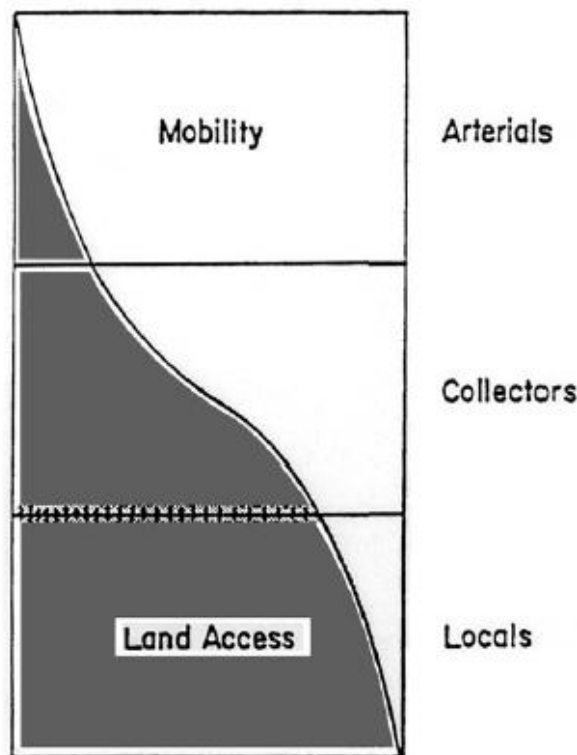


Figure 3-1. Relationship of Mobility to Functional Classification.⁹⁹

Urban areas and rural areas have different design criteria, as the land use the density of the population can vary dramatically. “Urban areas are those places within boundaries set by the

responsible State and local officials having a population of 5,000 or more.”¹⁰⁰ Rural areas are all other areas.

The Green Book uses functional classification as a means to distinguish between various design criteria tables. Criteria for local roads are provided in Chapter five, Local Road, where criteria for Rural and Urban Arterials are provided in Chapter seven. One notable exception to this is Freeways. Freeways carry a functional classification of principal arterial, but have very specific design criteria, therefore have their own chapter (Chapter 8).

Speed

After determining the functional classification of the road under design, but before progressing to the individual design criteria chapters, a design speed must be established, as it is needed for selection of design criteria. When discussing “speed,” it’s important to know the several ways highway engineers consider the term, including Operating Speed, Running Speed, and Design Speed. The Green Book defines each as follows:

- “*Operating speed* is the speed at which drivers are observed operating their vehicles during free-flow conditions.” The speed limit for a road is often set using the 85th percentile value of this speed. In other words, the speed limit can be determined by calculating the speed that 85 percent of the vehicles are traveling at or below.
- *Running speed* is “the speed at which an individual vehicle travels over a highway section...” calculated by dividing the length of a highway section by the time required for the vehicle to travel through the section. This value can vary considerably during a given day, week, or year, therefore reference should be made to whether the value is a peak-hour, and which season if applicable. This measure is often used for evaluating a facilities level-of-service (LOS).
- “*Design speed* is a selected speed used to determine the various geometric design features of the roadway.”¹⁰¹

Regarding design speed, the Green Book suggests that “...every effort should be made to use as high a design speed as practical to attain a desired degree of safety, mobility, and efficiently...” This suggests that highway facilities should be over-designed with little reason to justify these steps, other than the presumption that designing for a higher speed will produce a safer design. Then the Green Book suggests that the design speed “...should be consistent with the speeds that drivers are likely to expect on a given highway facility.” “Drivers do not adjust their speeds to the importance of the highway, but to their perception of the physical limitations of the highway and its traffic.” The text goes on to say “the selected design speed should fit the travel desires and habits of nearly all drivers expected to use a particular facility.”¹⁰² These statements seem contradictory and unachievable. Overdesigning a facility to provide safety in the absence of empirical evidence which suggests safety is in fact delivered can lead to wasteful spending and misdirection of public funds. There is room for a systematic approach to reviewing the design alternatives, not based on design speed as a basis of safety, but based on empirical evidence.

The text goes on to give some broad guidance on selecting a design speed for each functional classification. Figure 3-2 is an example of the Table provided for determining the design speed for a Local Road. Throughout this text, there is a surprising lack of cited research studies or empirical data to back the claims about driver behavior related to speed and how this should be

handled in design. Design speed is the basis for all design related decisions in the Green Book and should be better documented.

Type of terrain	Metric						US Customary					
	Design speed (km/h) for specified design volume (veh/day)						Design speed (mph) for specified design volume (veh/day)					
	50 under 50	250 to 250	400 to 400	1500 to 1500	2000 to 2000	and over	50 under 50	250 to 250	400 to 400	1500 to 1500	2000 to 2000	and over
Level	50	50	60	80	80	80	30	30	40	50	50	50
Rolling	30	50	50	60	60	60	20	30	30	40	40	40
Mountainous	30	30	30	50	50	50	20	20	20	30	30	30

Figure 3-2. Minimum Design Speed for Local Rural Roads.¹⁰³

Design Criteria

The highway designer designs for a specific “design vehicle.” The Green Book uses four general classes of design vehicles including passenger cars, buses, trucks and recreational vehicles. All four of these general categories have vehicles which vary in size and shape within the category. Not noted in the “Green Book,” but of growing concern is the population of motorcyclists, which have different design considerations altogether. In addition to vehicles, the highway designer must also consider pedestrians and bicyclists when designing improvements. In the case of a parking lot design, a passenger car is considered adequate with provisions for handicap access, where in the case of an intersection a larger vehicle’s turning path should be accommodated to maintain efficient and safe traffic flow. Using the traffic counts which were conducted early in the project, the traffic distribution can be determined and the designer and funding agency will balance the costs of accommodating the larger vehicles with the societal benefits. This balancing of benefits and costs are generally accomplished through discussions between the designer and the party responsible for the facility (e.g., Highway Department) but there is no formal methodology.

Highway Users

One must also consider the driver in addition to the vehicle, but this is not explicitly done nor are there any measures to do so, in highway design beyond designing to a highway design speed. There is a good deal of difference between the time needed and the way each individual perceives, processes, and reacts to information. This time varies by the amount of information necessary to process and the age of the driver. “Primacy relates the relative importance of safety of competing information.” Actions that help avoid crashes, such as maintaining control have higher primacy than actions that help navigate your trip. The Green Book concludes that “the design should focus the drivers’ attention on the safety-critical design elements and high-priority information sources...by providing clear sight lines...”¹⁰⁴ but does not provide specific criteria beyond improving sight distance to design for older or over taxed drivers. Other options might include minimizing roadside advertisements, unnecessary street signs, or other possible distractions.

Horizontal Alignment

“Sight distance is the length of roadway ahead that is visible to the driver.”¹⁰⁵ The current design practice is to design highway elements by sight distance such that “the available sight distance on a roadway [is] sufficiently long to enable a vehicle traveling at or near the design speed to stop before reaching a stationary object in its path.” The Green Book goes on to say “although greater lengths of visible roadway are desirable, the sight distance at every point along a roadway should be at least that needed for a below-average driver or vehicle to stop.”¹⁰⁶ By following these standards, therefore, its accepted practice to over designed to allow average drivers to comfortably drive at speeds higher than the design speed, which is already higher than the travel speed.

Stopping Sight Distance (SSD) is the sum of (1) the distance traveled by the vehicle after the driver perceives a need to stop and (2) the distance traveled while the driver is breaking. SSD can be expressed as follows:

$$SSD = \text{Break Reaction Time} + \text{Breaking Distance}$$

Break reaction time has been the subject of many studies over time and with results ranging from half a second to over three seconds. The Green Book surmises that 90 percent of the population, including older drivers could successfully react in 2.5 seconds. The rate of deceleration is also a concern. While drivers may be able to quickly decelerate and stop, maintaining control of the vehicle at all times, including inclement weather is important. After some study, a deceleration rate of 3.4m/s² [11.2ft/s²] was determined to be a comfortable rate for most drivers according to the Green Book. Using these values and the equations presented in Figure 3-3, the SSD can be calculated. The equations presented in Figure 3-3 are absent of the effect of vertical grade of stopping. Typically, a road has some vertical grade to maintain flow of drainage. In some regions, the grades must be steep to match existing ground conditions and minimize earth removal/filling. In the event vertical grade is present, the effects are accounted for using the equations presented in Figure 3-4.

Metric	US Customary
$d = 0.278Vt + 0.039\frac{V^2}{a}$	$d = 1.47Vt + 1.075\frac{V^2}{a}$ (3-2)
where: t = brake reaction time, 2.5 s; V = design speed, km/h; a = deceleration rate, m/s ²	where: t = brake reaction time, 2.5 s; V = design speed, mph; a = deceleration rate, ft/s ²

Figure 3-3. Stopping Sight Distance Equations absent of Vertical Grade.¹⁰⁷

Metric	US Customary
$d = \frac{V^2}{254 \left(\left(\frac{a}{9.81} \right) \pm G \right)}$	$d = \frac{V^2}{30 \left(\left(\frac{a}{32.2} \right) \pm G \right)} \quad (3-3)$

Figure 3-4. Stopping Sight Distance Equations including Vertical Grade.¹⁰⁸

Using basic mechanics to model a vehicle as a point mass, the basic horizontal curve formula is derived as shown in Figure 3-5.

Metric	US Customary
$\frac{0.01e + f}{1 - 0.01ef} = \frac{v^2}{gR} = \frac{0.0079V^2}{R} = \frac{V^2}{127R}$	$\frac{0.01e + f}{1 - 0.01ef} = \frac{v^2}{gR} = \frac{0.067V^2}{R} = \frac{V^2}{15R} \quad (3-8)$
<p>where:</p> <ul style="list-style-type: none"> e = rate of roadway superelevation, percent; f = side friction (demand) factor; v = vehicle speed, m/s; g = gravitational constant, 9.81 m/s²; V = vehicle speed, km/h; R = radius of curve measured to a vehicle's center of gravity, m 	<p>where:</p> <ul style="list-style-type: none"> e = rate of roadway superelevation, percent; f = side friction (demand) factor; v = vehicle speed, ft/s; g = gravitational constant, 32.2 ft/s²; V = vehicle speed, mph; R = radius of curve measured to a vehicle's center of gravity, ft

Figure 3-5. Basic Horizontal Curve Formula.¹⁰⁹

The rate of roadway superelevation (e) is used to counteract the centrifugal forces a vehicle experiences while traveling around a curve. It is expressed as a percent and typically ranges from 2%-12%. Superelevation is limited by several factors. In urban areas, a high rates of superelevation may make meeting existing conditions difficult. Climates which experience freeze-thaw conditions, typically limit superelevation to 8% to minimize the possibility of a stopped vehicle sliding across the pavement on ice. The side friction of the pavement also counteracts the centrifugal forces acting on the vehicle. A number of research studies have been conducted to determine appropriate side friction values, but ultimately, it depends on the pavement material and age as well as the vehicle tires contacting the pavement. A minimum radius of curvature equation is recommended in Figure 3-6 with design values shown in Figure 3-7.

Metric	US Customary
$R_{\min} = \frac{V^2}{127(0.01e_{\max} + f_{\max})}$	$R_{\min} = \frac{V^2}{15(0.01e_{\max} + f_{\max})} \quad (3-10)$

Figure 3-6. Minimum Radius of Horizontal Curve.¹¹⁰

METRIC						US Customary					
Design Speed (km/h)	Maximum e (%)	Maximum f	Total (e/100 + f)	Calculated Radius (m)	Rounded Radius (m)	Design Speed (mph)	Maximum e (%)	Maximum f	Total (e/100 + f)	Calculated Radius (ft)	Rounded Radius (ft)
15	4.0	0.40	0.44	4.0	4	10	4.0	0.38	0.42	15.9	16
20	4.0	0.35	0.39	8.1	8	15	4.0	0.32	0.36	41.7	42
30	4.0	0.28	0.32	22.1	22	20	4.0	0.27	0.31	86.0	86
40	4.0	0.23	0.27	46.7	47	25	4.0	0.23	0.27	154.3	154
50	4.0	0.19	0.23	85.6	86	30	4.0	0.20	0.24	250.0	250
60	4.0	0.17	0.21	135.0	135	35	4.0	0.18	0.22	371.2	371
70	4.0	0.15	0.19	203.1	203	40	4.0	0.16	0.20	533.3	533
80	4.0	0.14	0.18	280.0	280	45	4.0	0.15	0.19	710.5	711
90	4.0	0.13	0.17	375.2	375	50	4.0	0.14	0.18	925.9	926
100	4.0	0.12	0.16	492.1	492	55	4.0	0.13	0.17	1186.3	1190
						60	4.0	0.12	0.16	1500.0	1500
15	6.0	0.40	0.46	3.9	4	10	6.0	0.38	0.44	15.2	15
20	6.0	0.35	0.41	7.7	8	15	6.0	0.32	0.38	39.5	39
30	6.0	0.28	0.34	20.8	21	20	6.0	0.27	0.33	80.8	81
40	6.0	0.23	0.29	43.4	43	25	6.0	0.23	0.29	143.7	144
50	6.0	0.19	0.25	78.7	79	30	6.0	0.20	0.26	230.8	231
60	6.0	0.17	0.23	123.2	123	35	6.0	0.18	0.24	340.3	340
70	6.0	0.15	0.21	183.7	184	40	6.0	0.16	0.22	484.8	485
80	6.0	0.14	0.20	252.0	252	45	6.0	0.15	0.21	642.9	643
90	6.0	0.13	0.19	335.7	336	50	6.0	0.14	0.20	833.3	833
100	6.0	0.12	0.18	437.4	437	55	6.0	0.13	0.19	1061.4	1060
110	6.0	0.11	0.17	560.4	560	60	6.0	0.12	0.18	1333.3	1330
120	6.0	0.09	0.15	755.9	756	65	6.0	0.11	0.17	1656.9	1660
130	6.0	0.08	0.14	950.5	951	70	6.0	0.10	0.16	2041.7	2040
						75	6.0	0.09	0.15	2500.0	2500
						80	6.0	0.08	0.14	3047.6	3050
15	8.0	0.40	0.48	3.7	4	10	8.0	0.38	0.46	14.5	14
20	8.0	0.35	0.43	7.3	7	15	8.0	0.32	0.40	37.5	38
30	8.0	0.28	0.36	19.7	20	20	8.0	0.27	0.35	76.2	76
40	8.0	0.23	0.31	40.6	41	25	8.0	0.23	0.31	134.4	134
50	8.0	0.19	0.27	72.9	73	30	8.0	0.20	0.28	214.3	214
60	8.0	0.17	0.25	113.4	113	35	8.0	0.18	0.26	314.1	314
70	8.0	0.15	0.23	167.8	168	40	8.0	0.16	0.24	444.4	444
80	8.0	0.14	0.22	229.1	229	45	8.0	0.15	0.23	587.0	587
90	8.0	0.13	0.21	303.7	304	50	8.0	0.14	0.22	757.6	758
100	8.0	0.12	0.20	393.7	394	55	8.0	0.13	0.21	960.3	960
110	8.0	0.11	0.19	501.5	501	60	8.0	0.12	0.20	1200.0	1200
120	8.0	0.09	0.17	667.0	667	65	8.0	0.11	0.19	1482.5	1480
130	8.0	0.08	0.16	831.7	832	70	8.0	0.10	0.18	1814.8	1810
						75	8.0	0.09	0.17	2205.9	2210
						80	8.0	0.08	0.16	2666.7	2670
15	10.0	0.40	0.50	3.5	4	10	10.0	0.38	0.48	13.9	14
20	10.0	0.35	0.45	7.0	7	15	10.0	0.32	0.42	35.7	36
30	10.0	0.28	0.38	18.6	19	20	10.0	0.27	0.37	72.1	72
40	10.0	0.23	0.33	38.2	38	25	10.0	0.23	0.33	126.3	126
50	10.0	0.19	0.29	67.9	68	30	10.0	0.20	0.30	200.0	200
60	10.0	0.17	0.27	105.0	105	35	10.0	0.18	0.28	291.7	292
70	10.0	0.15	0.25	154.3	154	40	10.0	0.16	0.26	410.3	410
80	10.0	0.14	0.24	210.0	210	45	10.0	0.15	0.25	540.0	540
90	10.0	0.13	0.23	277.3	277	50	10.0	0.14	0.24	694.4	694
100	10.0	0.12	0.22	357.9	358	55	10.0	0.13	0.23	876.8	877
110	10.0	0.11	0.21	453.7	454	60	10.0	0.12	0.22	1090.9	1090

Figure 3-7. Design Values for Minimum Radius of Horizontal Curve.¹¹¹

Vertical Alignment

Designing according to Green Book methods, sight distances govern both horizontal and vertical design in level terrain, however, as the terrain becomes more rolling or mountainous, there is an increasing need to excavate side slopes to improve sight distance around corners.

Chapters five through eight of the Green Book provide design guidelines, specific to the various functional classifications of highways including: Local Roads (Chapter Five), Collector Roads and Streets (Chapter Six), Rural and Urban Arterials (Chapter Seven), and Freeways (Chapter Eight). Each chapter has guidance for rural and urban design, an appropriate design speed range, exhibits which relate speed to vertical grade and curvature to provide minimum sight distance, and a discussion of highway elements specific to the respective functional classification. Examples of the exhibits for vertical design elements are shown in Figures 3-8 and 3-9.

Metric				US Customary			
Initial speed (km/h)	Design stopping sight distance (m)	Rate of vertical curvature, K^a (m/%)		Initial speed (mph)	Design stopping sight distance (ft)	Rate of vertical curvature, K^a (ft/%)	
		Crest	Sag			Crest	Sag
20	20	1	3	15	80	3	10
30	35	2	6	20	115	7	17
40	50	4	9	25	155	12	26
50	65	7	13	30	200	19	37
60	85	11	18	35	250	29	49
70	105	17	23	40	305	44	64
80	130	26	30	45	360	61	79
90	160	39	38	50	425	84	96
100	185	52	45	55	495	114	115
				60	570	151	136

Figure 3-8. Design Controls for Stopping Sight Distance for Vertical Curves. ¹¹²

Type of terrain	Metric									US Customary								
	Maximum grade (%) for specified design speed (km/h)									Maximum grade (%) for specified design speed (mph)								
	20	30	40	50	60	70	80	90	100	15	20	25	30	40	45	50	55	60
Level	9	8	7	7	7	7	6	6	5	9	8	7	7	7	7	6	6	5
Rolling	12	11	11	10	10	9	8	7	6	12	11	11	10	10	9	8	7	6
Mountainous	17	16	15	14	13	12	10	10	—	17	16	15	14	13	12	10	10	—

Figure 3-9. Maximum Grade for Local Rural Roads. ¹¹³

Rate of vertical curvature, K , is the length of the curve per percent algebraic difference in the intersecting grades (e.g., $K=L/A$).

Design Criteria for Intersections and Interchanges

Chapters nine and ten of the Green Book cover only the geometric design of the elements specific to intersections and interchanges that is the intersection of the curves and tangents, to provide appropriate “intersection” sight distance. An intersection or interchange is where two or more streets meet. Some intersections are signalized, some are unsignalized. Unsignalized intersection may have a traffic circle, rotary, modern roundabout or signs for traffic control, where a signalized intersection used traffic signals to restrict movements. A grade separated interchange separates the conflicting movements and introduces the vehicles back into the traffic flow through a controlled point of access. This controlled point could be signalized or unsignalized intersection or a ramp merging onto a highway. For information on the capacity and level-of-service (LOS) analysis, the reader is referred to the Highway Capacity Manual (HCM)¹¹⁴, published by the National Cooperative Highway Research Program.

Step 3: Simultaneously design and draft the horizontal alignment electronically in a CAD program overlaid on the electronic field survey data, using the established horizontal alignment criteria.

As discussed above, software companies have adapted to the changing needs of engineering firms and streamlined the design and documentation task. Upon determining the design criteria (e.g., minimum horizontal curvature, k value for crest and sag curves, etc.), the designer can begin developing the design in a CAD based program such as AutoCAD Civil 3D (Civil 3D), Bentley InRoads or GeoPak. Designers no longer must produce hand drawn representations of the design with accompanying hand calculations and provide them to a draftsman for project documentation, but now can use CAD-based tools which perform the calculations internally, allowing the designer to design, draft and document simultaneously. This ability to simultaneously design, draft and document the improvements marks a monumental shift in highway design practice. There are still many design firms grappling with this shift, but those who have adopted this practice have reaped benefits which include a reduction in man hours and reduction in potential coordination errors across plan sets.

With a program such as Civil 3D, the designer references the existing ground survey, and locates a proposed construction centerline comprised of tangents and curves which meet the design criteria already established. All improvements constructed will reference this centerline.

Step 4: Simultaneously design and draft the proposed ground profile using the previously established vertical alignment criteria.

After establishing the centerline, the existing ground profile is established by “sampling” the existing ground surface data collected as part of the field survey. The existing ground profile is plotted to the screen and the proposed ground profile is established using the criteria which have already been determined. The proposed ground profile generally follows existing ground as closely as possible in order to minimize cuts and fills.

Step 5: Draft a typical cross-section using the proposed number of lanes and produce cross-sections of the corridor.

After establishing the horizontal and vertical alignments and conducting a capacity analysis to determine the appropriate number of lanes, a typical cross-section for the corridor can be established. This typical cross-section is generally considered to be a “first attempt” as it is needed to assess the impacts of the improvements. To complete this first attempt, the Green Book is consulted again for roadway width (Figure 3-10).

Metric					US Customary				
Minimum width of traveled way (m) for specified design volume (veh/day)					Minimum width of traveled way (ft) for specified design volume (veh/day)				
Design speed (km/h)	1500				Design speed (mph)	1500			
	under 400	400 to 1500	to 2000	over 2000		under 400	400 to 1500	to 2000	over 2000
20	5.4	6.0 ^a	6.0	6.6	15	18	20 ^a	20	22
30	5.4	6.0 ^a	6.6	7.2 ^c	20	18	20 ^a	22	24 ^c
40	5.4	6.0 ^a	6.6	7.2 ^c	25	18	20 ^a	22	24 ^c
50	5.4	6.0 ^a	6.6	7.2 ^c	30	18	20 ^a	22	24 ^c
60	5.4	6.0 ^a	6.6	7.2 ^c	40	18	20 ^a	22	24 ^c
70	6.0	6.6	6.6	7.2 ^c	45	20	22	22	24 ^c
80	6.0	6.6	6.6	7.2 ^c	50	20	22	22	24 ^c
90	6.6	6.6	7.2 ^c	7.2 ^c	55	22	22	24 ^c	24 ^c
100	6.6	6.6	7.2 ^c	7.2 ^c	60	22	22	24 ^c	24 ^c
Width of graded shoulder on each side of the road (m)					Width of graded shoulder on each side of the road (ft)				
All speeds	0.6	1.5 ^{a,b}	1.8	2.4	All speeds	2	5 ^{a,b}	6	8

^a For roads in mountainous terrain with design volume of 400 to 600 veh/day, use 5.4-m [18-ft] traveled way width and 0.6-m [2-ft] shoulder width.

^b May be adjusted to achieve a minimum roadway width of 9 m [30 ft] for design speeds greater than 60 km/h [40 mph].

^c Where the width of the traveled way is shown as 7.2 m [24 ft], the width may remain at 6.6 m [22 ft] on reconstructed highways where alignment and safety records are satisfactory.

See [text](#) for roadside barrier and offtracking considerations.

Figure 3-10. Minimum Width of Traveled Way ¹¹⁵

Guidance on the cross slope of the highway cross section is provided in chapter four. This guidance relates to the curve/speed relationships developed from the breaking distance equations in Chapter three and whether the highway is divided or not divided. The cross slope is generally two percent with the crown (peak) in the middle of the roadway to facilitate drainage. If the roadway is divided, the peak can remain in the middle of the roadway, or separate crowns can be

established on both alignments of the highway. The rate of cross slope varies with sharper curves. This varying of the cross slope is referred to as superelevating the roadway and it is done to counteract the centrifugal forces of the vehicle going around a curve at a given speed. Specific design guidelines for superelevating a highway is provided, for each functional classification of highway, in their respective chapters. There is a noticeable lack of general discussion of the safety implication of transition to a superelevated section.

Guidance is also provided on the selection of the lane widths of a roadway. The influence lane width has on safety and comfort of driving is mentioned, but no means to evaluate the designer's decision is provided. Typically, lane widths of 2.7 to 3.6 m [9 to 12 ft] are suggested. Notably, this section discussed the benefits and costs associated with constructing a wider lane. "The extra cost of providing a 3.6m [12 ft] lane width, over the cost of providing a 3.0m [10ft] lane width if offset to some extent by a reduction in cost of shoulder maintenance and a reduction in surface maintenance due to lessened wheel concentration s at the pavement edges."¹¹⁶ This discussion does not specifically address, however, the expected increase in safety due to the increase in pavement width. Wider lanes are noted as an effective countermeasure in the Highway Safety Manual.¹¹⁷

A discussion on the use of paved and stabilized shoulders is contained in this chapter. This Green Book discussed that shoulders are provided for stopping, evasive maneuvers, a sense of openness, improved sight distance, improved highway capacity, maintenance operations, structural support of the pavement, space for pedestrians and bicyclists, and parked vehicles. Shoulders range in width from 0.3m [1ft] to 3.0m [10ft]. Again, there is little discussion on the expected safety implications of one type of shoulder versus another.

The horizontal clearance to obstructions or "clear zone" is briefly discussed. Curbs are discussed in the context of providing delineation and drainage control. Sideslopes are discussed with roadway stability and recovery area in mind and a general discussion on longitudinal barriers is introduced. The designer is referred to the *Roadside Design Guide* (RDG)¹¹⁸ for detailed guidance on each of these individual elements of the roadside.

The Green Book has a surprising lack of discussion the economic or safety impacts of each potential design decision which is presented to the designer. While all of these options are presented as ranges and one function they may serve is provided (i.e., curbs control water, shoulders improve capacity, etc.) long-term, difficult to quantify impacts these choices may have on safety are missing.

The RDG provides guidance for the treatment of the roadside. This guidance includes appropriate sideslopes which can remain unprotected and adequate clear zones to minimize roadside crashes. This guidance is based on a combination of empirical evidence and engineering judgment. If the minimum roadside design thresholds cannot be met, warrants are provided for the installation of roadside barriers and barrier end treatments.

Step 6: Edit these cross-sections, horizontal and vertical alignments as needed to minimize impacts such as right-of-way (ROW) and environmentally sensitive areas.

The objective of the Green Book and every highway designer is to provide a safe, efficient, coordinated design. The Green Book states “the alignment is comprised of a variety of elements joined together to create a facility that serves the traffic in a safe and efficient manner, consistent with the facility’s intended function. Each element should complement others to produce a consistent, safe, and efficient design.”¹¹⁹ However, the only tool designers have at their disposal to evaluate a highway design are the warrants based on establishing clear sight lines. With this in mind, a highway designer will take the corridor model produced in the previous steps and modify it within the ranges established in an effort to minimize impacts. The designer may be trying to minimize impacts to abutting properties (right-of-way), environmentally sensitive areas, roadside trees, public or private utilities, etc. Making these changes, within the established design ranges, to avoid impacts may increase the risk of crashes. Predicting the crash risk is not a part of highway design warrants established in the Green Book, however, the RDG does provide a Cost/Benefit analysis procedure for roadside design.

In consultation with the RDG, the designer has the ability to minimize impacts without altering the horizontal or vertical alignment through changes to the roadside slope, installation of roadside barriers, reduction of the clear zone, or the installation of a more rigid roadside barrier. These design decisions can all be evaluated using the cost/benefit procedures outlined in the RDG and the Roadside Safety Analysis Program (RSAP) software distributed with the RDG. As discussed in the Survey Results Chapter, very few designers use RSAP at the individual project level because of complexity of data entry and the sheer amount of data that must be entered to adequately evaluate design alternatives. The survey also indicated that linking RSAP with current CAD-based programs, which are integral tools for design, could improve user-friendliness and reduce data entry time.

Step 7: Produce a Construction Cost Estimate and submit preliminary plans and estimate for review, sometimes called the 80% review

After completing the preliminary design, a preliminary construction cost estimate is produced. This estimate is created using only the “big ticket” items such as pavement, excavation, and traffic signal quantities. A large contingency factor, usually approximately 25 percent is added to the estimate and the plans and estimate are submitted to the funding agency for review. The plans are generally reviewed to compliance with geometric design standards including the Green Book and the State Design Manual. Plans are also submitted to the effected utility companies and governing environmental agencies for review of impacts. A meeting is generally held with the utility companies to coordinate any necessary design changes and construction time tables prior to moving the design forward. Depending on the scope and size of the project, the governing environmental agencies will determine if additional documentation or environmental filings are necessary to mitigate impacts to environmentally sensitive areas.

The construction cost estimate is reviewed and the project programmed accordingly on the statewide Transportation Improvement Program (TIP) for construction funding. Long term or

life-cycle costs of the project are generally not considered through any formal means. The importance of economic analysis in highway design is covered through a two-sentence section on page 896 of the Green Book. Reference is made to the AASHTO *User Benefit Analysis for Highways*, discussed in the literature review.

Step 8: Address reviewing agency concerns with geometric design. Produce a pavement stripping and signing plan, construction specifications, more detailed construction plans and cost estimate. Submit Final plan set for review, often called the 100% review.

After addressing any comments received from the funding agency, the governing environmental review agency and the impacted utility companies, a public hearing is scheduled to provide an opportunity for citizens to review and comment on the planned improvement project. After addressing any additional comments, a detailed design and construction documents are prepared and submitted for review. Details are added to the working drawings such as proposed stripping and signing as discussed in the Manual of Uniform Traffic Control Devices (MUTCD),¹²⁰ proposed treatment for impacted areas are detailed and the accompanying construction items list and specifications are coordinated to make the construction documents. The complete set of construction documents are submitted for review to the funding agency only. At this point, the construction documents are reviewed for oversights or lack of coordination in the documents which could lead to cost overruns in construction.

Step 9: Address reviewing agency concerns with construction documents and produce final Plans, Specifications, and Estimate (PS&E).

The reviewed construction documents are returned to the consultant and comments are addressed. A final set of drawings are plotted along with the final plans and construction cost estimate.

Step 10: Project is Bid and Constructed. Areas of Safety Concern are often identified after the project is constructed and opened to traffic.

The project is bid by the funding agency and awarded to the lowest bidder. The roadway improvements are constructed. After construction is completed, the road is considered “open” to traffic, although the road usually remains open during construction. It is at this time that safety concerns are generally identified. Areas where there may have been an opportunity to avoid the potential for crashes become evident when the traffic is flowing free of construction activities for some period of time.

Designing a safe highway is covered on pages 101 through 106 in the 896 page Green Book. After an introduction stating that Congress has mandated that highway safety is the responsibility of the Federal, State and Municipal agencies responsible for the roads, the Green Book text acknowledges that “crashes seldom result from a single cause-usually several influences affect the situation at any given time...”¹²¹ Crashes are in fact generally a result of interaction between the driver, the vehicle, and the highway. Highway designers only can mediate the highway characteristics which contribute to crashes and try to limit the demand on the driver.

For this reason, highways are generally marked with uniform signs and stripping plans to reduce the demand on the drivers. For example, yellow lines are always to the driver-side of the vehicle and white lines always to the passenger-side. Guide signs are green, construction signs are orange, stop signs and yield signs are red, etc. When you drive on an interstate highway, you expect the ramp to exit to the right, you expect wide shoulders, and a reasonable amount of advanced signing. When you travel on a local road, you probably expect little advanced signing and hope to be able to find a street wide enough to park your car.

In addition to these obvious design consistencies, opportunities exist to coordinate design elements such as the start of a horizontal curve and the start of a vertical curve, such that the start of one curve does not visually impair the driver from recognizing the start of the other curve and the driver only has to make one decision, instead of two.

However, the Green Book focuses on access control as the “most significant factor contributing to safety.... Full access control reduces the number, frequency, and variety of events to which drivers must respond.”¹²² The Green Book bases this conclusion on a study conducted in 1945 by Taragin, “Effect of Length of Grade on Speed of Motor Vehicles.”¹²³ “This study showed that crash, injury, and fatality rates on Interstate highways are between 30 to 76 percent of comparable rates of conventional highways that existed before the Interstate highways were opened to traffic. No other single design element can claim comparable reductions.”¹²⁴ In fact, no single design element can claim sole responsibility for the reduction of crash rates with the opening of the interstate system. As discussed above, interstates are now and have always been designed to a separate set of standards. Longer, flatter curves; wider medians, shoulders, lanes, and clear zones; larger signs and different stripping; and more controlled treatment of intersections (e.g., interchanges). A conclusion that access control is the only reason for the reduction in crash rates is an error and in contradiction to other statements within this same chapter and book.

Fortunately, the Green Book does not prescribe full access control for all streets, recognizing that “highways without control of access are essential as land service facilities...”¹²⁵ In fact, speed is also recognized “as a contributing factor in crashes, but its role must be related to actual conditions at a crash site to be understood.”¹²⁶ Little concrete guidance is given to designers about how to treat speed as a factor in designing a safer road. Examining a crash site implies the crash has already taken place, therefore, the designer was not able to take action to produce a design which may have limited the potential risk of that crash. In fact, the design principles of the Green Book are to design roads which allow the driver to go as fast as the driver feels comfortable driving, as discussed above. This provision for designing fast roads seems to conflict with the acknowledgment that speed contributes to crashes, once again providing the designer with little guidance on the interaction of design elements and the influence this interaction has on providing a safe driving environment.

The Highway Safety discussion continues with the introduction of geometric features of the highway. Reference is made to a study Schwender *et al.* conducted in 1957 which determined the risk of a crash is highest on roads having combinations of sharp curves and steep grades.¹²⁷ This chapter of the Green Book concludes that “level rural roads without intersections or significant numbers of private driveways are the safest highways within their general class.”¹²⁸

Two paragraphs later, however, “on extremely long tangents, drivers have a tendency to completely relax...”¹²⁹ leaving the designer to wonder which extreme should they provide for or is the middle the best case scenario? The age of some of the safety related research certainly brings their conclusions into question as well.

The Green Book provides the user with a few dated research studies and broad conclusions without any guidance on how to design a safer road, yet recognizes that congress has mandated attention to safety in the design of highways. Better guidance, strong criteria and coordinated standards are needed to provide the motoring public with the safe roads they deserve.

Highway Safety Manual (HSM)

The first version of the Highway Safety Manual (HSM) is currently being balloted by AASHTO and is scheduled for general released in 2009. The HSM is the result of decades of research, supplemented with new data and research of the crash-data based approach to highway safety. It targets practitioners, providing Accident Modification Factors (AMF) based on crash prediction models, to provide practitioners with an understanding of the relative change in crash frequency any design decision can have. It is unclear at this time how different states will implement this manual into their individual design practices. The standalone procedure for determining crash frequency is described below using a two-lane rural road as an example. The HSM separates roads and intersections into two categories. Roads are further separated into rural and urban categories.

First, the predicted number of total roadway segments crashes per year under base conditions is calculated. The two-lane rural base road model is as follows:

$$N_{br}=(ADT)(L)(365)(10^6)e^{-0.4865}$$

where:

N_{br} =predicted number of total roadway segment crashes per year under base conditions,

L = segment length and

ADT = Average Daily Traffic

This model assumes the following:

- 12 foot lanes,
- 6 foot shoulders,
- Roadside hazard rating of 3,
- Five driveways per mile,
- No horizontal curvature,
- No vertical curvature and
- Zero percent grade.

If the model requires modification because the base conditions do not match the geometric features of the design, then AMFs can be employed:

$$N_{fs} = N_{br} C_r (AMF_{1r}, AMF_{2r}, \dots, AMF_{nr})$$

where:

N_{fs} = predicted number of total roadway segment crashes per year after application of AMFs,
 $AMF_{1r}, AMF_{2r}, \dots, AMF_{nr}$ = accident modification factors of design features, and
 C_r = calibration factor for roadway segments developed for use for a particular geographical area.

Driveway Density AMF

One example of the AMFs used is the driveway density AMF. This AMF is calculated as follows:

$$AMF = \frac{0.2 + [0.05 - 0.05 \ln(AADT)] / DD}{0.2 + [0.05 - 0.05 \ln(AADT)] / 5}$$

where:

AADT = Annual Average Daily Traffic in vehicles per day and
 DD = Driveway Density per mile for both sides of the road combined.

Roadside Design AMF

The HSM uses one AMF to account for the “effect of roadside design.”¹³⁰ This AMF relies on the visual and subjective Roadside Hazard Rating scale developed by Zegeer *et al.*¹³¹ The RHR scale is described in detail in the Literature Review section. The base RHR is equal to three. If the user feels the RHR equal to three does not represent the roadside environment, adjustments can be made using an AMF. One RHR AMF applies to both sides of the road and is calculated as follows¹³²:

$$AMF_{10r} = \frac{e^{(-0.6869 + 0.0668 * RHR)}}{e^{(-0.4865)}}$$

where:

AMF_{10r} = Accident Modification Factor for the effect of roadside design;
 RHR = Roadside Hazard Rating

Other AMFs

There are a number of AMFs available in the HSM for roadway elements, alignment elements, roadside design, and other features.

Crash Effects of Roadway Elements

- Modify Lane Width,
- Add Lanes by Narrowing Existing Lanes and Shoulders,
- Remove through lanes,

- Add or widen paved shoulder,
- Modify shoulder type,
- Provide a raised median and
- Change the width of an existing median .

Crash Effects of Alignment Elements

- Horizontal Curve Radius, Length and Spiral Transitions,
- Improve Superelevation of Horizontal Curves and
- Change Vertical Grade.

Crash Effects of Roadside Elements

- Reduce Roadside Hazard Rating,
- Flatten Sideslopes ,
- Increase the Distance to Roadside Features,
- Change Roadside Barrier along Embankment to Less Rigid Type,
- Install Median Barrier and
- Install Crash Cushions at Fixed Roadside Features.

Other AMFs

- Roadway Signs,
- Rumble Strips,
- Pavement Markings,
- Post-mounted Delineators,
- Raised Pavement Markers,
- Traffic Calming Treatments,
- On-street Parking,
- Highway Lighting,
- Access Management and
- Weather Issues.

Each of these AMFs provides a relative amount of crash reduction through a multiplier applied to the predicted crash frequency. Therefore, a designer will now have a quantitative means to determine how difference design decisions will impact the crash frequency along an improvement alternative.

Additional Refinement

The HSM suggests additional refinement of the safety prediction using the Empirical Bayes method if the data are available, to more closely represent existing conditions prior to modifying for proposed alternatives. This refinement should be conducted using this equation:

$$E_p = w(N_{rs}) + (1-w)N_o$$

where:

E_p = expected total crash frequency based on a weighted average of N_{rs} ,

w = weight to be determined by an equation in a future chapter of the HSM and

N_o = number of crashes observed during a specified period of time.

Summary

The warrants and guidelines used during a typical highway design are long-established and rooted in the design community as the basis for every design, yet these warrants were originally developed absent of empirical evidence, but rather they were established based on physical properties and “engineering judgment.” Minor updates have been made over time as the vehicle fleet morphed. The current design practice has evolved to meet legal concerns and business needs throughout the nation, but the overall process has not been revisited or reviewed. The introduction of the HSM provides new information to designers. The time has come for the review of existing practice and establishment of a formal, flexible process in light of new safety publications and evolving practice.

CHAPTER 4

RESULTS OF SURVEY OF PRACTICE

A survey was conducted to survey users with to identify and catalog problems and perceived shortcomings of RSAP. The survey was distributed via e-mail to about 2,100 roadside safety researchers, highway design consultants, DOT engineers, and users of highway design software. The distribution list was compiled from the ITE database, ATSSA training course participants, members of TRB AFB20 and AASHTO-ARTBA-AGC TF13 and from a list of people who have purchased the Roadside Design Guide from AASHTO. A complete copy of the questionnaire can be found in Appendix A.

The survey was assembled using the on-line tool [surveymonkey.com](http://www.surveymonkey.com) (i.e., www.surveymonkey.com). The survey had several purposes including:

1. To identify the user community of the existing RSAP program.
2. To determine the degree to which RSAP is used in the design profession.
3. To identify know RSAP software “bugs” and limitations that can limit its use and also present users with results that are difficult to interpret.
4. To solicit the types of software highway designers are using for their particular highway design projects.

Approximately 136 people started the survey and 122 people completed it after starting resulting in a six percent response rate and a completion rate of 84 percent. The survey asked a variety of questions about the type of work the respondent does, the software tools they use, their use of RSAP, specific questions about RSAP and solicited beta testers for the updated RSAP.

The following sections include a discussion of each question and an assessment of the responses. Also included is information about the respondents.

Question 1: Please provide the following optional information about yourself.

Respondents that completed the survey were asked to provide contact information. Approximately 85 percent of the respondents provided this information.

Question 2: What type of work do you do?

Most of the respondents consider themselves roadside and/or highway designers, as shown in Figure 1. The respondents who describe themselves as doing “other” work are engaged in activities like the manufacturing or distribution roadside devices, performing structural or traffic design services, constructing highway improvements and/or participating in engineering education. Respondents could check all categories which define the work they do, therefore, somebody who engages in highway design production and research would have checked both categories and been counted twice. One interesting observation is that most respondents engage in some type of design work with sixty percent identifying themselves as working as roadside designers and more than fifty percent working as highway designers. Policy work, roadside safety research and highway design research were indentified in about 20 percent of the responses as shown in Figure 4-1.

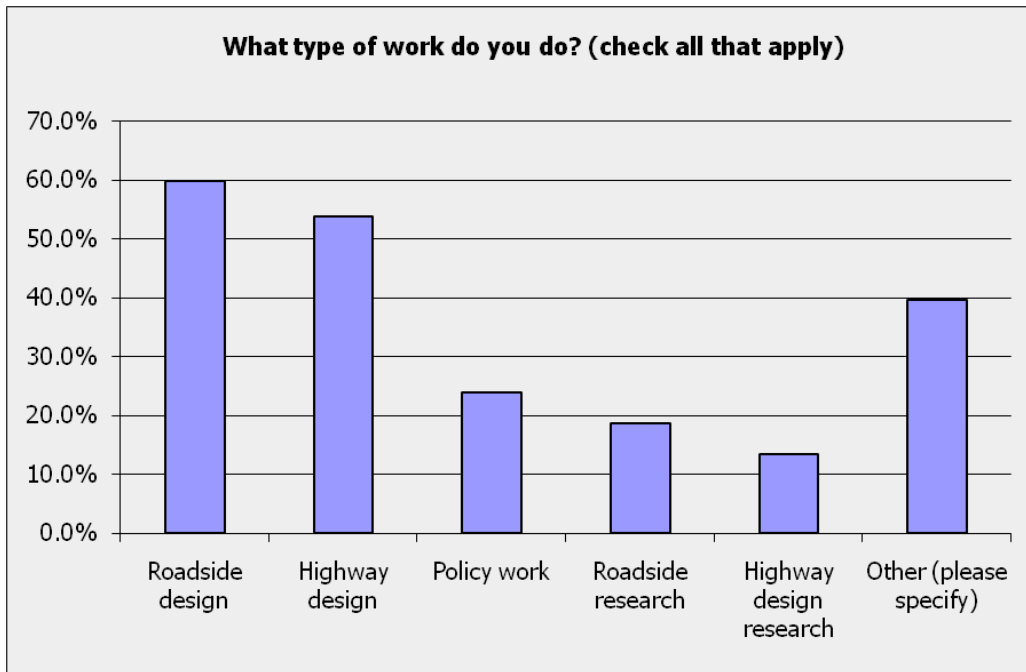


Figure 4-1. Distribution of Respondents' Work Categories.

Question 3: Which highway design software tools does your company/organization use for design and plan production?

All but fourteen percent of the respondents use some form of CAD-based software tools for documentation and plan production as shown in Figure 4-2. Given the wide range of survey distribution, this is a staggering number. Respondents also noted the use of several other Bentley and Autodesk products or add-on products, which serve specific design functions, such as designing signs, hydraulic systems, or vehicle turning paths. DeSantis Engineering software was also mentioned by several respondents. Almost 30 percent of respondents use Autodesk's Civil3D, 13 percent use Autodesk Land Development Desktop, and another 30 percent use Bentley's InRoads software. All three of these highway design programs are built on the AutoCAD platform, which means approximately 73 percent of the respondents are working with design software running through the AutoCAD API.

It is not uncommon for large consultant firms to produce plans for different jobs in different CAD programs to meet the requirements of a State DOT or private client. Therefore, it's expected that many of the larger firms who responded opted to check more than one Design Software.

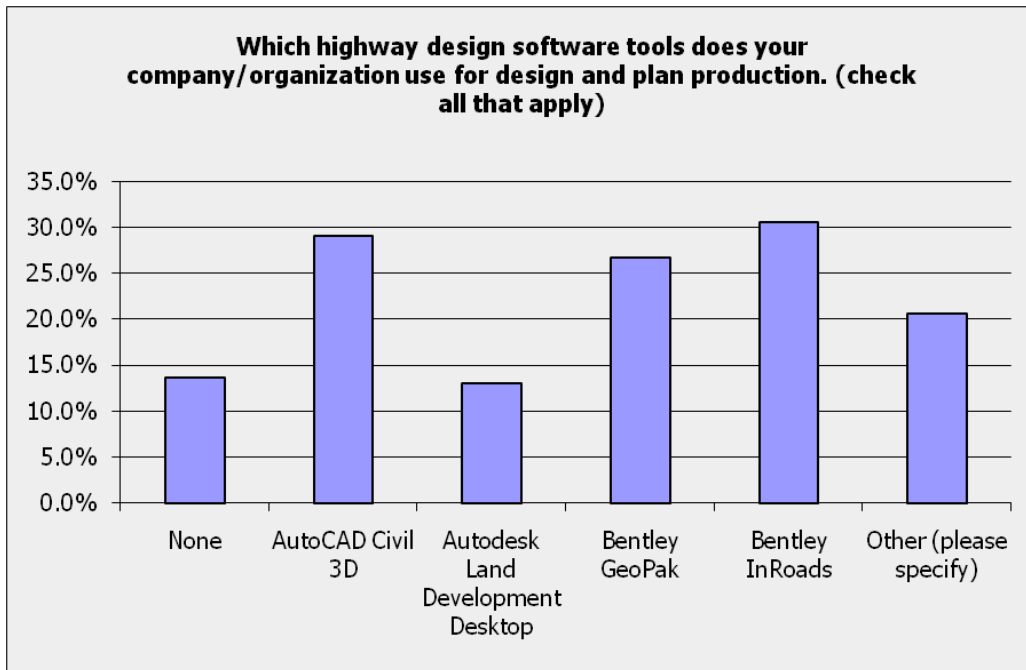


Figure 4-2. Distribution of CAD Software Use.

Question 4: Please list other software tools you use to assist with design decisions and cost analysis.

Survey respondents indicated they use a surprisingly small variety of additional software to support design decisions and cost analysis. This software, in addition to RSAP, primarily includes traffic analysis software, spreadsheets and GIS applications. This would indicate that there is little standardization across the highway design industry for cost analysis procedures and protocol, but potential exists to introduce familiar software tools to help industry personal, such as spreadsheet or GIS applications.

Question 5: The Roadside Safety Analysis Program (RSAP) has been developed for risk analysis and cost-benefit analysis of roadside safety and design. It is distributed with the Roadside Design Guide. How frequently do you use RSAP?

The responses to this question indicate that RSAP is not used as often as it could be. Sixty eight percent of the respondents do not use RSAP at all while 26 percent use RSAP one to five times per year. Designing improvements to the roadside can be challenging, especially in an environment where funds are limited. A tool such as RSAP can provide valuable insight to help a project designer, but RSAP appears to be underused as shown in Figure 4-3. Understanding why RSAP is underused will help improve use statistics and project designs.

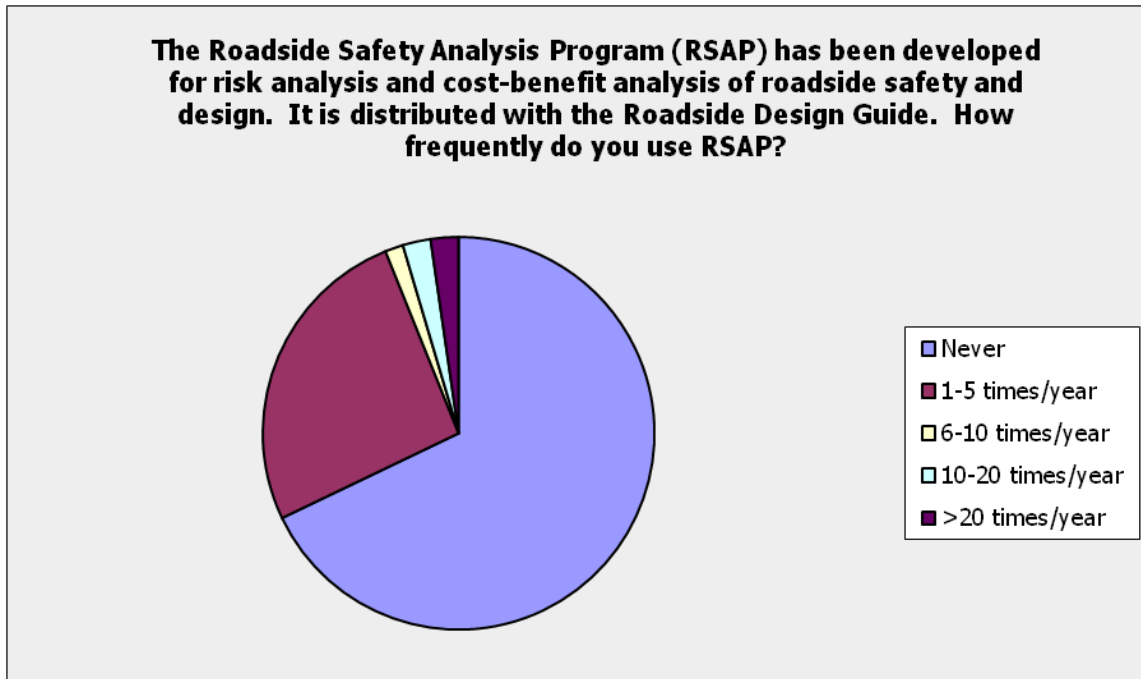


Figure 4-3. Distribution of RSAP Use Frequency.

Question 6: What have you used RSAP to evaluate?

A majority of the respondents, who have used RSAP, have used it to evaluate specific design alternatives (i.e., 77 percent). A smaller percentage of the total respondents (40 percent) have used RSAP to evaluate policy alternatives, which could be a reflection of the number of policies made as compared to the number of designs prepared. Others note the use of RSAP in research and teaching applications alternatives (i.e., 23 percent). These results are encouraging for improving roadside designs, but more widespread use is needed, as discussed above.

Question 7: Do you like the RSAP user interface?

While 60 percent of the respondents said they like the user interface, a number of comments were received about improving the data entry methods. Some suggestions included improving the highway geometrics data entry time through a more graphically-based user interface. It appears that respondents would be in favor of maintaining the windows-based user interface while adding a graphical component to ease highway design data entry. A few quotes from the survey are presented here:

- “Time consuming to enter in data and make sure that the data is correct.”
- “Needs a graphical interface.”
- “Visual representation of model – graphics”

Question 8: Do you like RSAP functionalities?

Seventy-seven percent of the respondents like the RSAP functionalities, however, many suggested improvements. These suggested improvements again include mention of a graphical interface for data entry of the highway elements. Additional improvements suggested include referencing a project baseline for measurements rather than “distance from beginning” and more flexibility with the default features. Again, the concern about entering highway elements through a graphically based environment was noted and should be addressed in the updated version of RSAP. A select number of specific suggestions are presented here:

- “Making the functionalities more specific, with more availability to detail situations and have a more accurate model of the alternatives you are trying to evaluate.”
- “Because it is difficult to input data it is hard to check and make sure that this is correct, Some type of graphical interface for cross section data would be appreciated”
- “The program should be redesigned to work around the standard industry practice for building roads that uses a control line of stationing to define the longitudinal location of features. All of our data is based on this method including profile grades, locations of features, survey data, right-of-way, etc. The RSAP currently requires us to build a spreadsheet that correlates all of the data we gather using the control line method to the "distance from beginning of project" method used by the programmer. It is the most important thing that needs to be changed in order for this product to be accepted by the industry.”
- “Continuous slope hazards, contingent on trajectory dependence rather than fixed-location hazard envelopes, would be desirable. Example: some severity is present for a 2 ft lateral encroachment on a 2:1 slope, a higher severity is present for a 10 ft encroachment, and a higher severity for a 30 ft encroachment etc. It should be both longitudinally and laterally-dependent for severity estimation.”
- “A multiple-run option should be included to allow users to name the parameters to be updated and multiple analyses conducted without intensive user input. Reducing the effort required to run multiple jobs will save time and money in the evaluation, and will reduce the number of user-caused errors in the evaluations.”

Question 9: Do you find the RSAP default data tables appropriate?

Seventy percent of the respondents agree that the default data tables are appropriate. Comments received and suggestions for improvements include concerns over the age of the crash costs and the appropriateness of the severity indices. Specifically culvert grates and trees were mentioned for consideration and investigation of severity. Also suggestions were received to improve documentation abilities by allowing the user to print default data table choices as part of the report summary. Comments received indicate that improving the user’s ability to interface with the data tables and update the default data will improve the user-friendliness of this program and help keep the program up-to-date between whole version updates. A selected sample of survey quotes are presented here:

- “need to be updated with current data - costs, vehicle trajectories, damages”
- “You need to include a means for printing them out. They are critical to the cost/benefit analysis but there is no way of easily including them in a final report so managers and posterity have the details of what the decisions are based on. Plus, we use the severity index tables for other purposes and the only way we can refer to them is in an out-dated

edition of the RDG”

- “ Modeled severities of vertical drops are incorrect. Slope drop-off severities should be the same for the same height of drop-off for both intersecting slopes and foreslopes.”
- “ Rigid object sizes are very large; there should be some smaller rigid-object size classifications.”
- “Culvert grates ought to be investigated as an additional hazard class.”
- “The Severity Indices are incomplete and what is there needs updating.”
- “Crash costs should reflect more recent data.”

Question 10: Do you like the RSAP methodology?

General responses to this question include requests for better documentation within the software and the manuals to allow users to explain and compare the results. Eighty percent of the respondents agree with the choice of RSAP methodology, however, some feel the encroachment data is weak and would prefer a different methodology which does not rely on this data. Specific suggestions were made to incorporate a scaling effect, based on yaw degree, for side impact to increase the severity of those crashes and possibility incorporate a secondary trajectory algorithm to account for vehicles which may slide along a roadside feature such as guardrail. Respondents generally agree with the methodology, but would like to see updated encroachment data and the possibility of more modification factors incorporated into the updated version of RSAP. Specific suggestions are presented here:

- “Incorporation of scaling effects based yaw degree from impact should be incorporated. For example, scale severities of rigid objects when impacted in the side by a factor of 1.5; this may over represent the severity of side-impact crashes, but it will lead to possibly more accurate severity indices for most other object types through in-service evaluations and validation rather than a fixed severity regardless of yaw angle.”
- “The encroachment data is a very weak link in the chain. Given this fundamental weakness, I would prefer a program that is probabilistic-oriented, as opposed to the current deterministic style.”
- “Cannot get realistic output”

Question 11: Do you find the RSAP User's Manual helpful?

Most people responding do find the User’s Manual helpful (72 percent). Specific comments for improving the User’s Manual include incorporating more discussion on the limitations of RSAP and discussion about the different computational steps of the program. Suggestions for graphical representations of measurements to ensure properly entering data into RSAP were also made. Concerns about difficulty of data entry persist.

Question 12: Do you find the Engineer's Manual helpful?

While 80 percent of the respondents found the Engineer's Manual helpful, several respondents were not even aware there was an Engineer's Manual. Some respondents suggested that improvements should be made to clarify the distinction between ditches and foreslope/backslope combinations and the use of RSAP in median evaluations.

Generally, there was concern about the documentation and improvements should be made.

Specific suggestions are presented here:

- "Only marginally helpful."
- "I'm not sure when it is Ok to use foreslope and backslopes verses 'parallel ditches'."
- "When should/ how should a person decide to use 'user defined features'."
- "Add discussion on the use of RSAP for median applications for divided highway."
- "Not enough detail."

Question 13: While using RSAP, have you encountered any incidents where your analysis results from RSAP were inconsistent with your experience/expectations/judgment?

Concerns were expressed over the precision of the reported numbers, given the amount of engineering judgment the program is founded upon. Some of specific incidents identified are as follows:

- "Analyzing bridge rails with different shoulder widths gives the rail with the narrowest shoulder as the lowest user cost because the narrow shoulder presumably does not allow a higher impact angle. Intuitively, a wider shoulder should be better."
- "RDG indicates 4:1 to 4:1 ditches are not desirable. I would guess that RSAP would have a larger SI."
- "Whenever the user attempts to run a one way one lane roadway an error message occurs that states "Unexpected Termination of Analysis Module". This makes it impossible to run one lane ramps."
- "Problems have been reported when attempting to run user defined features. When a user inputs small increases to the severity values at 100 km/hour, sometimes the output does not show increases in average severity or annual crash cost."
- "When crash costs are changed from User-Defined Costs- KABCO to the Roadside Design Guide's values, the annual crash cost does not change significantly."
- "In order to enter English units the user must use the pull down menu under view-options, then change into metric units and back to English units. If the user does not do this step, the input screens will request input in feet and require the user to use metric values. Even though the input is in metric units, the output is in English units."
- "The rigid-object hazards were at times less severe than guardrail."
- "A bridge requires extensive coding increments of the drop-offs adjacent to the bridge, since otherwise the bridge drop-offs are not accurately modeled. Placement of the slope immediately next to the bridge results in an odd recommendation. Slopes in general are difficult since they are often large rectangular hazards with constant severity, though this is not physically observed in the field."
- "Flat ground "severity" should be automatically incorporated into the model everywhere that there is no other hazard."
- "There are inconsistencies between RSAP and the HSM."

These quotes illustrate that there are perceived issues with the severity coding, the units coding and precision of answers. It appears that frequent users have found some “work-arounds” for some problems but the appropriateness or correctness of these techniques is unknown.

Question 14: Are you aware of reports or papers about RSAP documenting its use? Please list them here.

Respondents suggested that many reports are currently being developed, but none were listed or provided.

Question 15: What improvements would you like to see made to RSAP?

The improvements suggested can be separated into five general categories including RSAP’s reporting features, user interface, documentation, methodology, default data, and items the respondents would like to see added to RSAP.

Suggested improvements to RSAP *reports* include adding the ability to produce PDFs and reporting the information in a more concise manner. Additionally, the ability to report and print the severity index table and the costs for fatal and injury crashes would be helpful. Many respondents suggested the *user interface* could be improved by adding a means to graphically input cross-sectional and roadway information. Respondents suggested improving the software’s internal and external *documentation* with example diagrams and pictures to help define data entry measurements and terms as well as more comprehensive manuals would help reduce user input error.

Respondents suggested updating the *default* roadside features to include a range of cable barrier, among other recent changes, to the roadside inventories. Additionally, integration of Length of Need calculations into RSAP would help designers. Furthermore, it was suggested that construction costs for roadside features could be added to the program.

Regarding the *methodology*, suggestions were made to include more user adjustment factors and better document the use of the adjustment factor. Updates should be made to the algorithms used to calculate the trajectory (a cubic function, for example) and yaw-related severity scaling and what some respondents view as methodology weaknesses should be addressed in this update (i.e. S.I. and encroachment rates)

Question 16: Which features of RSAP would you like to see remain unchanged in the next release?

There is some interest among respondents in retaining the windows-style user interface, the use of the Cooper data, the ability to customize crash values, and RSAP’s name.

Question 17: Do you see value in integrating RSAP with popular highway design software tools such as AutoCAD Civil 3D or Bentley InRoads?

Eighty-five percent of the respondents agree that integrating RSAP with design tools like AutoCAD Civil 3D and Bentley InRoads would add value but there is also a strong desire to maintain the current ability to run RSAP independent of CAD based software.

Question 18: Do you see a potential use for evaluating the Cost/Benefit of roadside design alternatives using software integrated with your highway design software?

Seventy-eight percent of the respondents do see a potential use for evaluating the Cost/Benefit of roadside design alternatives. Some feel it needs to be a simple tool and some are not sure how it will apply across all roadway design scenarios.

Question 19: Do you believe safety, or the potential for crashes should be considered when designing highway improvements?

One-hundred percent of respondents believe safety should be considered when designing highway improvements. Respondents noted a need for tools and processes that explicitly include safety consequences, to assist designs in making decisions. Respondents also noted that safety should be considered but not required.

Question 20: Thank you for your time. If you would like to be a beta tester for the RSAP upgrade, please list your contact information, including your e-mail, here.

Twenty-four people were identified as Beta testers including some panel members, state engineers, highway consultants, researchers, and software developers.

Conclusions

Most of the respondents use some type of CAD-based highway design software to assist in the production of the highway designs, however, only 35 percent of the respondents use or have used RSAP. Of the RSAP user population, approximately 75 percent have used it to assess specific design alternatives. Therefore, it's probably no surprise that approximately 80 percent of respondents see value in integrating RSAP with highway design software such as Civil3D or InRoads but many would like to maintain the ability to manually input data and run RSAP independently.

General respondent comments include a preference to maintain the current windows user interface, however, many respondents suggested a more visual or graphical representation of the project to improve clarity. Integration of RSAP with Civil 3D or InRoads would address respondents concerns over creating a graphic interface for highway element data entry.

Respondents suggested improving the ability to change or edit default values as well as more flexibility when entering roadside features. Allowing for easy user updates of RSAP will grant users more flexibility and keep RSAP more up-to-date at a national level as well as relevant at a regional level.

CHAPTER 5

PROPOSED DESIGN PRACTICE

The current highway engineering workflow, discussed previously, is long-established and rooted in the design community. It lacks formal documentation, but allows for great amounts of flexibility. This flexibility must remain, but an improved understanding of the consequences (i.e., construction cost, capacity, highway safety, etc.) is needed. This improved understanding can be accomplished through establishing a highway design process which is performance-based rather than prescriptive (e.g., warrants). Any changes to the current design process, however, must account for the long and rich history and the massive existing body of knowledge.

A generic design process is shown in figure 5-1. This process could represent that used for designing a variety of items ranging from the design of a chair to the design of a tall building. Adapting this general process and merging it with the existing workflow will allow for the introduction of performance-based design while maintaining the knowledge which has accumulated in this history-rich field.

The proposed performance-based design process is demonstrated and discussed below using highway safety as the measurable outcome. This process can be extended across a range of highway engineering practices, including highway capacity, environmental impacts and economic and land-use planning. This process capitalizes on the extensive use by practitioners of CAD-based design suites such as Autodesk Civil 3D (Civil 3D) and Bentley Inroads within the highway engineering field. This process will be demonstrated using Civil 3D, but can be extended to all CAD-based highway design and documentation suites.

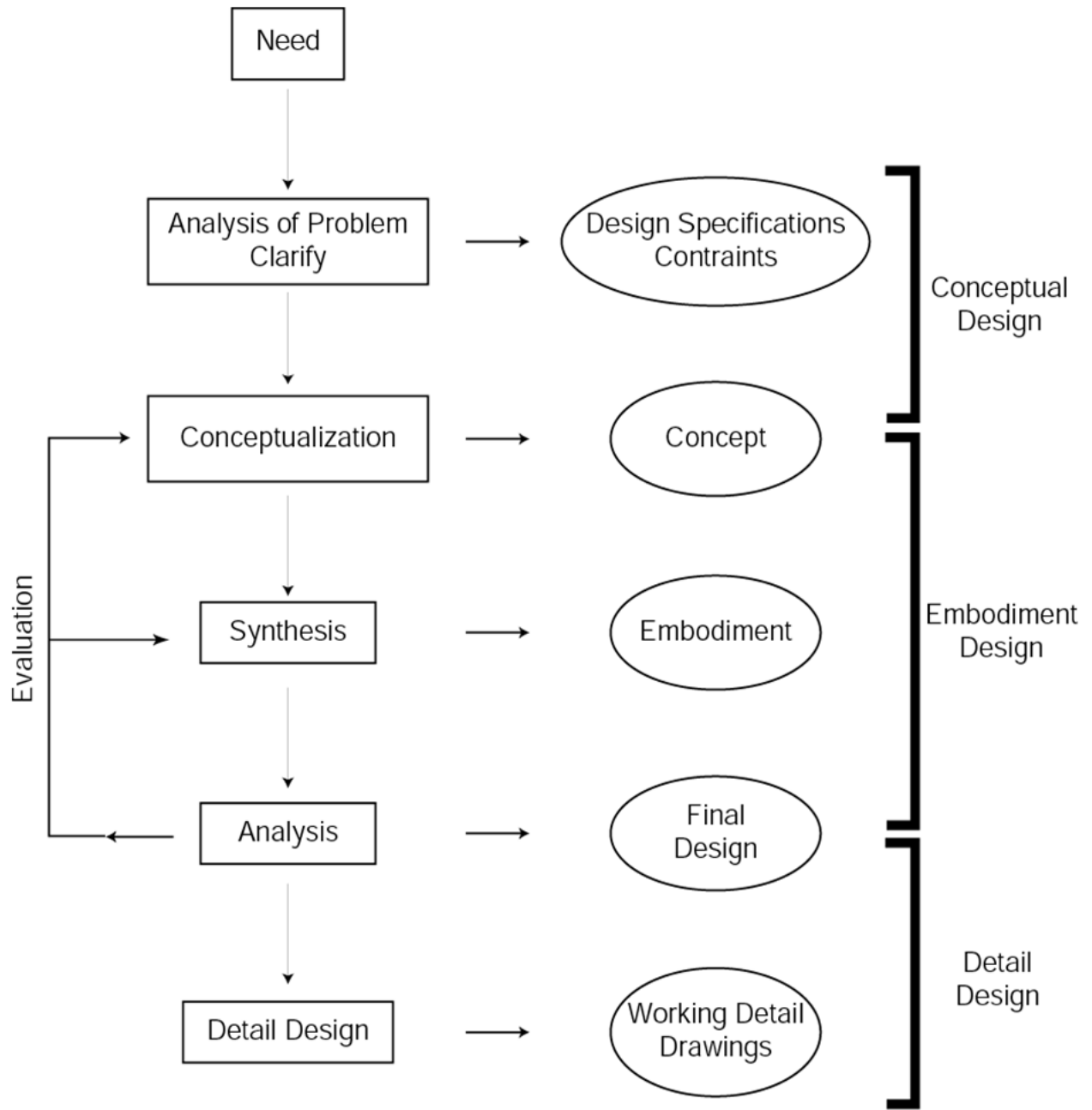


Figure 5-1. Typical Design Process.¹³³

Highway engineers design using the series of workflow steps discussed previously and summarized in figure 5-2.

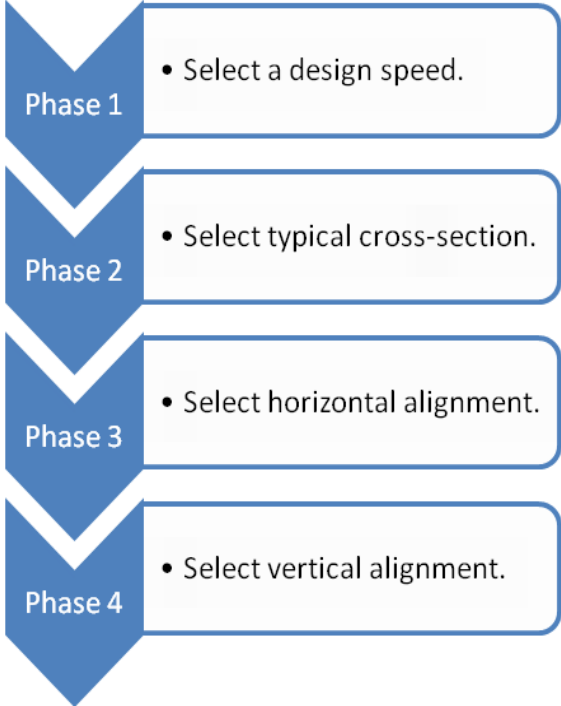


Figure 5-2. Existing Highway Design Workflow.¹³⁴

Highway engineers designing highways today typically employ the CAD software tools discussed in the Literature Review. These tools have coded workflows which support the existing highway design workflow. Figure 5-3 depicts the Civil 3D workflow for creating a corridor model. The similarities between these workflows are obvious and are well established within the highway engineering community.

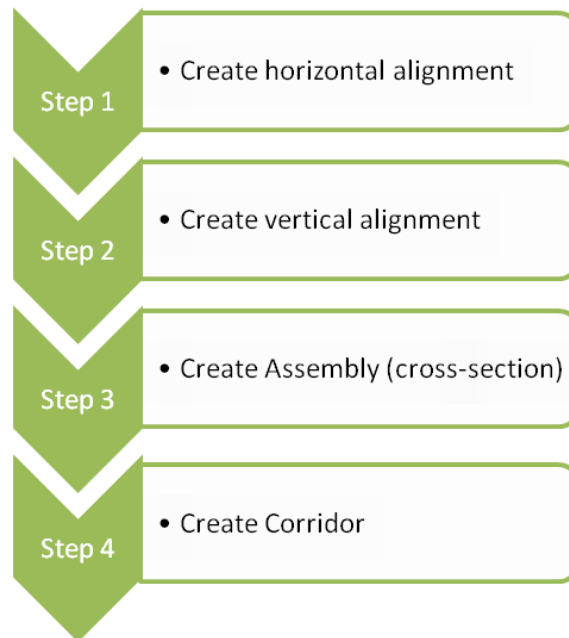


Figure 5-3. Civil 3D Workflow for Creating a Highway Model.¹³⁵

Successfully implementing a performance-based highway design process requires merging the current highway design workflow (i.e., Figure 5-2), the CAD-based highway design tools (i.e., Figure 5-3) and more general design practice (i.e., Figure 5-1). Much of the typical design practice outlined in Figure 5-1 is touched on in Figures 5-2 and 5-3, however, Synthesis and Analysis are currently lacking in highway engineering.

Currently, highway engineers start the design with a given objective, perhaps to “improve safety.” The Green Book provides the standards the engineer uses to progress through the existing process. After determining the functional classification of the road, the appropriate geometric design is determined. At no point does the designer check how each separate geometric design decision has impacted the previous or conduct an analysis to determine if safety has been improved. After determining a project need, conducting a synthesis allows the engineer to determine how the various design decisions impact each other and the analysis allows the engineer to determine if the design objectives have been met.

Successfully moving highway engineering toward performance-based design requires more acknowledged synthesis and analysis steps. Figures 5-4a, b, and c provide the proposed performance-based highway design process.

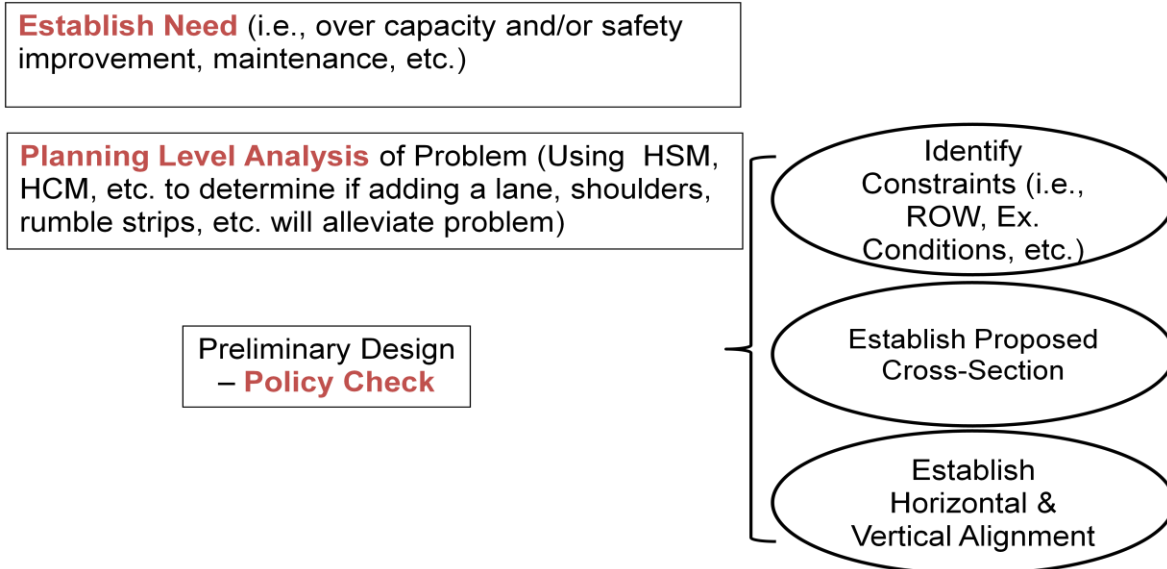


Figure 5-4a. Proposed Planning and Preliminary Phases.

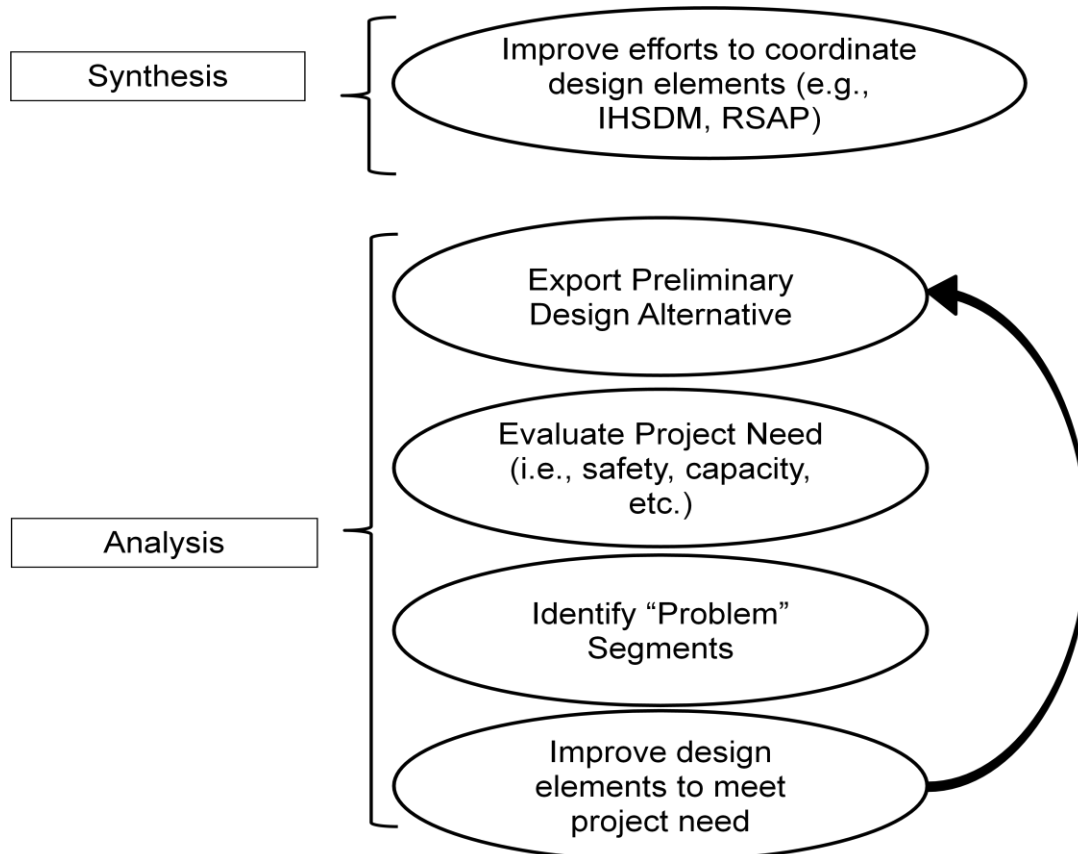


Figure 5-4b. Proposed Synthesis and Analysis Phases.

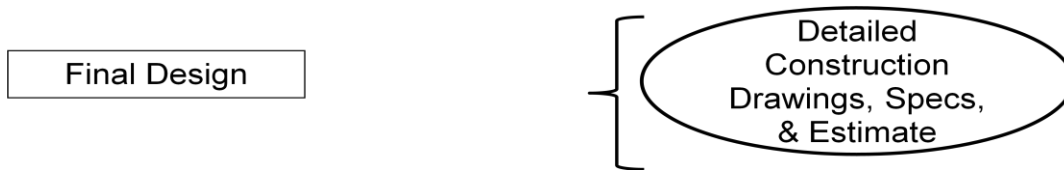


Figure 5-4c. Proposed Final Design Phase.

The implementation of this process, the software tools currently available, and the software tools developed during this research are discussed in more detail below. Reference will be made to the “Steps” which are currently part of the existing highway design workflow and are proposed to be integrated into the proposed process. These existing “Steps” are shown here for convenience:

0. Pre-design preparation: Collect necessary field data (e.g., topographical surveys, existing right-of-way, traffic volumes, etc.).
1. Step 1: Determine if the existing number of lanes is sufficient or additional lanes are necessary to accommodate future traffic volumes.
2. Step 2: Determine the functional classification of the road and the corresponding design criteria.
3. Step 3: Simultaneously design and draft the horizontal alignment electronically in a CAD program overlaid on the electronic field survey data, using the established horizontal alignment criteria.
4. Step 4: Simultaneously design and draft the proposed ground profile using the previously established vertical alignment criteria.
5. Step 5: Draft a typical cross-section using the proposed number of lanes and produce cross-sections of the corridor.
6. Step 6: Edit these cross-sections, horizontal and vertical alignments as needed to minimize impacts such as right-of-way (ROW) and environmentally sensitive areas.
7. Step 7: Produce a Construction Cost Estimate and submit preliminary plans and estimate for review, sometimes called the 80% review
8. Step 8: Address reviewing agency concerns with the geometric design. Produce a pavement stripping and signing plan, construction specifications, more detailed construction plans and cost estimate. Submit Final plan set for review, often called the 100% review.
9. Step 9: Address reviewing agency concerns with construction documents and produce final Plans, Specifications, and Estimate (PS&E).
10. Step 10: Project is Bid and Constructed. Areas of safety concern are often identified after the project is constructed and opened to traffic.

Establish Need

Prior to commencing a project, a formal documentation step should be undertaken to establish the need for the project. For example:

- Is the subject road unsafe; is it experiencing an unacceptable number of crashes; are there particular types of problem crashes?
- Is the subject road operating over capacity and experiencing significant delays? (similar to existing Step one)
- Is the subject road in need of pavement maintenance to improve the ride quality?
- Is more access needed to promote economic development or perhaps there are too many access points and access needs to be limited to improve mobility?
- Is there an engineering solution to the disproportional number of crashes between the senior center and the senior village in town?

It is possible that the highway has more than one need for improvement. Conducting this step will allow for all project participants to agree on the goals for the project and for planners and engineers to determine if the project's goals have been met. Failure to conduct this step could result in losing sight of the project's original purpose and scope creep.

Planning Level Analysis

After determining the need for a project, the ability to meet the established need with highway engineering should be evaluated at the planning level. Successful highways depend on the interaction of the highway design, the vehicles, and human beings. This planning level analysis should be conducted to determine which highway engineering principals will improve the highway the most for the smallest investment. Specific, detailed analysis should not be conducted at this level. One should focus on the comparison of design concepts which can be considered with minimum field data collection. One should not design specifics such as each driveway, intersection grading alternatives, longitudinal barrier alternatives, impact attenuators, etc. Consider the following:

Using available GIS information and historic traffic volumes, one can determine if adding a lane will significantly reduce congestion, widening the shoulders and installing rumble strips will improve safety, and/or resurfacing the road will improve the ride quality. Each one of these improvement alternatives has a direct cost for the improvement, indirect costs for items such as the environmental impacts and costs (benefits) associated with the improvements. Conducting a cost/benefit analysis of each alternative will allow the engineer to determine which alternative to pursue.

Sufficient research does not exist to quantify the interaction of each of these improvements on the other, however, one can be reasonably sure that resurfacing the road and/or widening the shoulders would also improve capacity and increase speeds. When such research becomes available, this step will become increasingly more important.

Preliminary Design: Policy Check and Corridor Model Assembly

After one determines through cost/benefit analysis which alternative should be designed, the preliminary design of the alternative should follow. Preliminary design includes several parts which progress simultaneously:

- Identify Constraints,
- Establish Proposed Cross-section and
- Establish Proposed Horizontal and Vertical Alignments.

Identify Constraints

Currently, highway engineers gather field data, including field survey and traffic volumes, at the onset of design. This should continue and the field data should be included in the project's electronic model. At this time increased efforts should be made to identify and document constraints which may hinder the implementation of the selected alternative. A detailed review of field data may reveal areas of narrow right-of-way, challenging side slopes or underground utilities which were not initially evident from field visits or planning-level study. These constraints which may impact the project's budget and/or ability to progress should be noted, but the design should be modeled using the prescribed warrants in the Green Book¹³⁶ and RDG¹³⁷. Changes to the design to accommodate the constraints will be assessed later in this design process.

Established Proposed Cross-section

Using the capacity analysis performed during the Planning Level Analysis with the Highway Capacity Manual (HCM)¹³⁸ to establish the number of lanes, the Green Book¹³⁹ warrants for lane and shoulder width, and the Roadside Design Guide (RDG)¹⁴⁰ to establish clear zones, the highway engineer should determine the desirable proposed cross-section. This step represents portions of steps two and five of the existing highway design workflow.

It is entirely possible and often probable that the desirable cross-section cannot be accommodated without impacts to the identified constraints (i.e., the cross-section may not fit within the available right-of-way). A design level assessment of alternatives which can be accommodated will be analyzed following the complete assembly of the project model. At this stage, the cross-section should be established and modeled in CAD using the published warrants. It is plausible and often warranted to have more than one cross-section throughout the length of a project. In this case, all warranted cross-sections, the start and end stations, and transitions should be documented at this time.

Establish Proposed Horizontal and Vertical Alignments

Using the Green Book¹⁴¹ warrants for horizontal and vertical alignments previously discussed, the highway engineer should determine the desirable alignments. This step represents portions of steps two, three, and four of the existing highway design workflow.

Again, it is possible that accommodating the alignments suggested by the Green Book will impact the identified constraints or incur costs beyond those budgeted, however, these alignments should be initially included in the CAD model and modifications assessed in the following steps.

Synthesis: Improve efforts to coordinate design elements and reduce speed inconsistencies

The existing design workflow lacks emphasis on coordinating design elements, however research indicates that increased attention to this area will improve visibility, highway safety and reduce speed inconsistencies.^{142,143,144} CAD-based highway design software suites such as Civil 3D contain tools which aid the engineer in conducting this step manually. Figure 5-5 shows a CAD model of a proposed ground profile. The vertical blue lines indicate where the horizontal curves begin and end. Coordinating the start and end of horizontal and vertical curves allows for improved visual appearance of highway elements and reduces possible sight obstructions of highway elements caused by the highway itself.

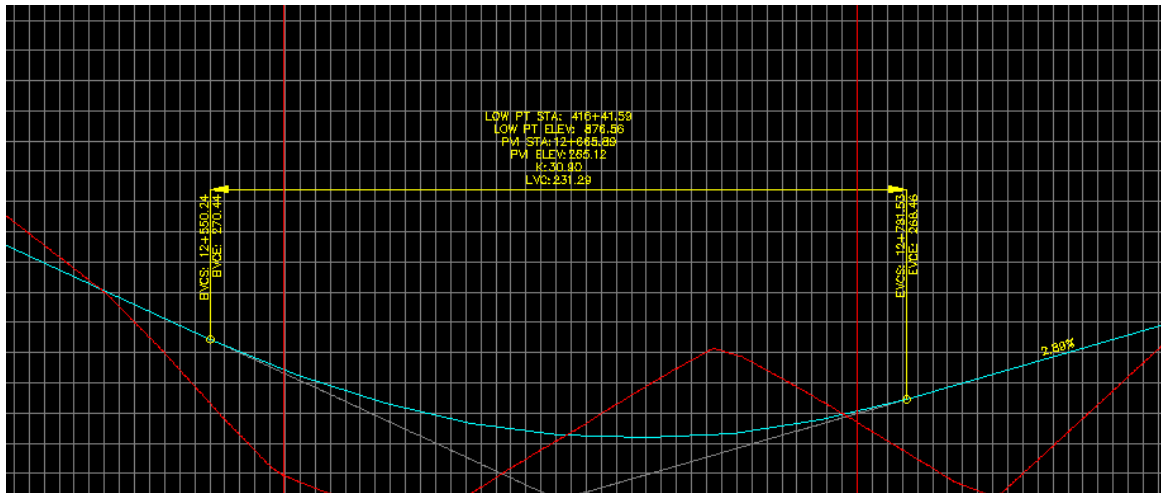


Figure 5-5. Proposed Ground Profile with Horizontal Curve PCs and PTs Labeled.

The Green Book states “the alignment is comprised of a variety of elements joined together to create a facility that serves the traffic in a safe and efficient manner, consistent with the facility’s intended function. Each element should complement others to produce a consistent, safe, and efficient design.”¹⁴⁵ There are no warrants provided within the text to ensure a coordinated design has been provided, however, research has been conducted and yielded models which can be used to predict the eighty-fifth percentile speed based on geometric features (Figure 5-6)¹⁴⁶ and the suggested allowable variation from one segment to the next (Figure 5-7).¹⁴⁷

The Interactive Highway Safety Design Model (IHSDM) has five modules, discussed in the literature review of this report. The *Design Consistency Module* helps diagnose safety concerns at horizontal curves. Crashes on two-lane rural highways are overrepresented at horizontal curves, and speed inconsistencies are a common contributing factor to crashes on curves. This module provides estimates of the magnitude of potential speed inconsistencies between segments.

The design consistency module estimates 85th percentile vehicle speeds at each point along a roadway. The speed-profile model combines estimated 85th percentile speeds on horizontal and vertical curves, desired speeds on long tangents, acceleration and deceleration rates at points of curvature and tangency, and a model for estimating speeds on vertical grades.¹⁴⁸

Increased effort should be given to using the tools available to highway engineers to coordinate design elements (figure 5-5) and evaluate geometric influences on speed (e.g., the IHSDM).

Additional development of this research should focus on integrating the tools available through the IHSDM into CAD software to facilitate an interactive design environment. Currently, designers must export CAD files to LandXML and import the LandXML file into the IHSDM. This process is discussed in detail in the literature review.

Germany, ISE ⁴³¹		
$V_{85} = \frac{10^6}{8270 + 8.01 CCR_y}$	$R^2 = 0.73$	(8.15)
where speed limit = 100 km/h		
Greece ^{431,586}		
$V_{85} = \frac{10^6}{10150.1 + 8.529 CCR_y}$	$R^2 = 0.81$	(8.16)
where speed limit = 90 km/h		
United States—New York ^{406,408}		
$V_{85} = 93.85 - 1.82 DC = 93.85 - 0.05 CCR_y$	$R^2 = 0.79$	(8.17)
where speed limit = 90 km/h		
Germany, old ^{241,243}		
$V_{85} = 60 + 39.70 e^{(-3.90 \times 10^{-3} CCR_y)}$		(8.18)
where lane width = 3.50 m speed limit = 100 km/h		
United States ⁵⁶⁵		
$V_{85} = 103.04 - 1.94 DC = 103.04 - 0.053 CCR_y$	$R^2 = 0.80$	(8.14)
where speed limit = 90 km/h		
France ^{641,700}		
$V_{85} = \frac{102}{1 + 346 (CCR_y/63,700)^{1.5}}$		(8.19)
where speed limit = 90 km/h		
Australia ⁵⁰⁵		
$V_{85} = 101.2 - 1.56 DC = 101.2 - 0.043 CCR_y$	$R^2 = 0.87$	(8.20)
where speed limit = 90 km/h		
Lebanon ¹⁰⁸		
$V_{85} = 91.03 - 2.06 DC = 91.03 - 0.056 CCR_y$	$R^2 = 0.81$	(8.21)
where speed limit = 80 km/h		
Canada ^{508,527}		
$V_{85} = e^{(4.561 - 5.86 \times 10^{-3} DC)} = e^{(4.561 - 5.27 \times 10^{-4} CCR_y)}$	$R^2 = 0.63$	(8.22)
where speed limit = 90 km/h		
<p>Note: DC_y (degree/100 ft) $36.5 = CCR_y$ (gon/km) and DC_m (degree/100 m) $11.13 = CCR_y$ (gon/km) (without taking transition curves into consideration).</p>		

Figure 5-6. Regression Models for Operating Speed for Two-Lane Rural Roads.

Case 1: Good design

$$|V_{85_i} - V_d| \leq 10 \text{ km/h}$$

No adaptations or corrections are necessary. A balanced speed behavior can be expected especially at curved sites.

Case 2: Fair design

$$10 \text{ km/h} < |V_{85_i} - V_d| \leq 20 \text{ km/h}$$

At these curve locations:

1. The speed behavior should be brought down through speed limits and/or appropriate traffic control devices.
 2. The superelevation rates should be related to V_{85} to ensure that side friction assumed would accommodate side friction demanded. For stopping sight distances, V_{85} should be relevant too.
-

Case 3: Poor design

$$|V_{85_i} - V_d| > 20 \text{ km/h}$$

Critical discrepancies between design speed and actual driving behavior of motorists are present. The expected severe accident situation may lead to uneconomic, unsafe operation. Therefore, redesigns are normally recommended. The decision whether or not to institute reconstruction measures should be based on the local situation. If redesigns are not possible, the installation of very stringent traffic control devices like, for example, speed limits combined with chevrons and guardrails or even automatic radar devices may serve sometimes as a surrogate measure.

Note: V_d = design speed, km/h, and V_{85_i} = expected 85th-percentile speed of design element i , km/h.

Figure 5-7. Recommended Ranges for Good, Fair, and Poor Design Levels.

Analysis

Step six and seven of the existing highway design process work to evaluate highway designs to minimize impacts, but fail to quantify design decisions. It is not formal and relies heavily on engineering judgment. Three different engineers could design the same road to the same standards and the result could be three different designs. Highway engineering and design has a good deal of flexibility, but highway engineers lack the analytical resources necessary to assess the impacts of exploiting that flexibility. For example, a road with two twelve foot lanes and three foot shoulders could have any of the following roadside treatments:

1. Flat ground with twenty-four foot clear zones
2. 4:1 side slopes with twenty-four foot clear zones
3. 3:1 side slopes with guard-rail to protect the errant vehicles from the side slopes

While each one of these alternatives may meet the suggested warrant, the cost for constructing and maintaining these alternatives is different and the potential for crashes is different. No one alternative is the correct choice for every two-lane road and each road should be analyzed individually to find the most cost-beneficial safety treatment for the particular project constraints.

At this point in the proposed highway design process, the engineer has a corridor (horizontal and vertical alignments and cross-sections) for the roadway which meets Green Book and RDG warrants. Constraints have been identified. The engineer should conduct a Cost/Benefit analysis for the proposed corridor design to determine the potential change in safety and project cost over the life cycle of the project needed to minimize environmental and ROW impacts, avoid constraints, reduce construction costs, etc.

Recall Figure 5-4b. This step should be persistent as changes are made to the corridor, until a satisfactory design is achieved. Software has been developed as part of this research to support this step. Software specifics are discussed in Chapter Six and the user's manual is presented in Appendix B. Construction cost estimates may be prepared external to the software or using Civil 3D tools. The engineer should load the software developed as part of this research from within Civil 3D, follow the prompts to select the corridor or manually enter the data. Selecting the corridor grants access to the database of geometric information electronically stored with the corridor. This information includes the horizontal and vertical geometry of the corridor.

The engineer should evaluate the potential for crashes, considering the combined effect of the corridor geometrics, for the existing conditions (Alternative Zero) and the alternative which meets design guidelines (Alternative One). Alternative zero and one can then be compared to any changes (Alternative Two, Three, etc.). Upon selecting a preferred alternative, the established project need should be revisited to determine if the preferred alternative meets the project need. Provided the project need is met, the design can proceed to the next step. In the event the project need is not met, analysis should continue until the project need is met. At this point, corridor alternatives/changes under evaluation should be minor in nature and should primarily be made to accommodate the constraints which have been previously identified. Recall that major geometric and cross-section alternatives were evaluated earlier, during the planning phase. In the event Alternative One does not impact any identified constraints, meets the project needs, and is within the established budget, Alternative One should be the preferred alternative.

A report should be prepared documenting the project constraints, Alternative Zero, alternatives considered, the construction cost, maintenance and crash costs of each alternative, the expected crashes of each alternative and the resulting cost-benefit ratios. This report and accompanying preliminary design plans should be submitted to the reviewing agency for comments. The reviewing agency should focus on whether the alternative meets the project's stated need; concurrence with the identified constraints and identifying any other constraints; and the analysis of the costs and project safety. Evaluation for agreement with governing policy becomes less important than in the existing highway design workflow, as the engineer's report documents Alternative One and impacts, the deviations from Alternative One have been stated and the safety impacts have been quantified.

Final Design

Following the receipt of funding agency comments, the selected design alternative proceeds to Final Design. Final Design is similar to Step eight of the existing highway design process. After addressing any review comments and prior to construction document preparation, a public hearing should be held to allow for public review and comment.

Following a public hearing, a detailed design and construction documents are prepared and submitted for review. These plans are prepared as outlined in Step 8 of the existing highway design workflow. The construction documents are submitted once again for review. At this point, the construction documents are reviewed for oversights or lack of coordination in the documents which could lead to cost overruns in construction. The geometric design is not reviewed at this time.

Next the project will proceed to Steps nine and ten as outlined in the existing highway design workflow. These steps include bidding the project and constructing the project.

Summary

The proposed performance-based design process can be easily implemented using the tools, research and published design documentation which already exists within the highway engineering community. This process will reduce workload for reviewing agencies and coordinate efforts throughout different regions. Efforts will be focused on performance outcomes such as improving highway safety and reducing highway related fatalities rather than policies and warrants. This process capitalizes on existing workflow and tools for increase receivership among highway designers and can be expanded to include a full array of performance-based highway engineering. Implementation will lead to an improved understanding of the impacts to safety and other outcomes caused by relaxing design standards to accommodate existing ROW, environmental constraints, and other items traditionally viewed as constraints. This improved understanding will lead to more informed decision making.

CHAPTER 6

SOFTWARE SUPPORT

The accompanying software implements a modified version of the existing Roadside Safety Analysis Program (RSAP)¹⁴⁹. RSAP is discussed in detail in the Literature Review. Modifications to RSAP include replacement of the Copper encroachment model¹⁵⁰ with the encroachment model developed by Miaou¹⁵¹; the use of the industry standard Baseline Station and Offset for geometric data and feature data entry; and the use of Accident Modification Factors (AMF) from the Highway Safety Manual (HSM)¹⁵².

The development of this software was made with the possible future integration of this software with other highway design and safety analysis software in mind. A review of existing safety analysis and highway design software and programming platforms is included in the Literature Review. This review assessed the capabilities and voids that exist within each application and includes the Interactive Highway Safety Design Model (IHSDM) by the FHWA, AutoCAD Civil 3D, Bentley InRoads and GeoPak, and the current version of RSAP. This review included documenting the current capabilities and limitations of each software package and the language the software is coded in. Additionally, an open dialog was initiated with developers of the following software:

- FHWA IHSDM,
- Bentley InRoads and Geopak and
- Autodesk AutoCAD Civil 3D and Land Development Desktop.

Each of these other software developers has expressed interest in the project and a willingness to help integrate this research into their respective highway/roadside design platforms. The software platform alternatives indentified for this software must include this possibility of future integration with other analysis software. Additionally, user-friendliness and familiarity should be considered to promote early adoption among industry users.

As previously discussed, the first publication of the HSM is imminent. The HSM has an abundant number of applicable AMFs for modifying encroachment rates and hazard severities. AMFs have been used to demonstrate how the other AMFs may be used if this program is integrated with other highway safety software.

User Interface, Results Display, and Computational Engine

Several alternatives have been investigated which included coding the analysis and User Interface (UI) in Visual Basic.Net, coding the analysis portions in C# or F# and the UI using WinForms or Windows Presentation Forms (WPF) or various combinations of these options. Using visual basic.Net, will improve the ability to integrate with other highway design/safety software applications in the future, as it is known for its strong ability to integrate different programs and languages.

This software is coded with the computational engine in Microsoft Excel and the graphical user interface in visual basic.NET. Excel was chosen because of its widespread use among engineers and scientists, because it is structured for multiple worksheets, for its power in performing high-

level extensive calculations, and because it can be easily updated as the statistical models are updated. The use of Excel for the computational engine makes integration with the users who do not have the application much simpler, promoting adoption across the industry while removing fears of cross-platform compatibility.

This software has been developed with the ability to receive geometric data, from an electronic highway design file, for risk analysis. Civil 3D was chosen for demonstration purposes because Autodesk grants some developers access to their APIs and support for developers, while Bentley does not offer this type of support. This application could be extended to the Bentley family of Highway Design software with support from the company.

From within this software, the user can click a button to import the geometric data. Alternatively, the user can manually enter the data external to CAD software. The ability to manually enter data was a concern that many echoed in the user survey.

The computations are performed and the results displayed in MS Excel. The results of the analysis are saved in a MS Excel file. In the event the user chooses to share the results with another party, the user has the option of sending the second party an Excel file. This method of documenting analysis results was incorporated in the recently completed NCHRP project for computing pavement designs, the Mechanistic-Empirical Pavement Design Guide (MEPDG). Results can be printed from the “Results” Tab at the bottom of the workbook. User Inputs can be printed from the “UI” tab.

Software Verification

Historically, models used to develop relationships between run off road (ROR) crashes and roadside features such as utility poles, traffic sign posts, trees, guardrail, median barriers and sideslopes, have been categorized as either *crash-based* or *encroachment-based* approaches. These approaches are discussed in detail in the Literature Review. The encroachment-based approach is incorporated in the Roadside Design Guide (RDG) whereas the crash-based approach is used in the Highway Safety Manual (HSM).^{153,154} Both approaches have their strengths and weaknesses and it is not the purpose of this research to assess the suitability of either approach but rather to simply compare the two approaches, a standard example that has been published in the RDG for nearly a decade, and the software developed to support the proposed highway design method.

The RDG includes software support for the encroachment-base approach using the Roadside Safety Analysis Program (RSAP). The Crash Prediction Module (CPM) of the Interactive Highway Safety Design Module (IHSDM) provides software support for the HSM. RSAP models individual ROR crashes and the severity of each crash whereas the IHSDM CPM predicts ROR crashes for a segment of a road, not distinguishing between either side of the road or different roadside features within a given segment. While both products approach the modeling of ROR crashes differently and the methods cannot be directly compared, the resulting prediction of total ROR crashes within a road segment for a given study period should be similar. The objective of this comparison is to review the crash predictions presented in the 2006 Roadside Design Guide Appendix A example problem¹⁵⁵ with the crash predictions for the

current version of RSAP¹⁵⁶, the current version of the IHSDM CPM¹⁵⁷, and the software presented herein. The results are presented below.

Example Problem

Appendix A of the RDG provides a summary of RSAP. Within this appendix, an example problem is used to demonstrate the cost-effectiveness analysis procedure. This example problem concerns the hypothetical treatment of a culvert headwall on a resurfacing project. The sample problem has three alternatives for consideration:

- Alternative 1: Baseline – an unprotected headwall,
- Alternative 2: Install Guardrail and crashworthy end treatments, or
- Alternative 3: Extend the Culvert and re-grade the slopes.

Additional information regarding these alternatives is presented in Table 6-1.

Table 6-1. Input data for sample application ¹⁵⁸

Data Element	Baseline Conditions Alternative 1	Install Guardrail Alternative 2	Extend Culvert Alternative 3
Cost Data			
Project Life	25 Years	25 Years	25 Years
Discount Rate	4%	4%	4%
Installation Cost	\$0	\$15,000	\$50,000
Annual Maintenance Cost	\$0	\$100	\$0
Highway Data			
Functional Class	Rural Minor Arterial	Same	Same
Highway Type	2-lane undivided	Same	Same
Lane Width	3.7m [12 ft]	Same	Same
Shoulder Width	2.0m [6.5 ft]	Same	Same
Speed Limit	100 km/h [60 mph]	Same	Same
ADT	5,000	Same	Same
Percent Truck	10%	Same	Same
Traffic Growth Factor	1% per year	Same	Same
User-Defined Adj Factor	1.0	Same	Same
Segment Data			
Segment 1:			
Segment Length	100m [329 ft]	Same	Same
Vertical Grade	-3.00%	Same	Same
Horizontal Alignment	Straight	Same	Same
Segment 2:			
Segment Length	150m [492 ft]	Same	Same
Vertical Grade	Level	Same	Same

Horizontal Alignment	Curve to left, 450m [1476 ft] radius	Same	Same
Segment 3:			
Segment Length	100m [329 ft]	Same	Same
Vertical Grade	3.00%	Same	Same
Horizontal Alignment	Straight	Same	Same
Feature Data			
Culvert Headwall, Type C:	2m [6.5 ft] High	Same	Same
Length	13m [43 ft]	Same	Same
Width	0.3m [1.0 ft]	Same	Same
Lateral Offset	2.5m [8 ft]	Same	10.0m [30 ft]
Distance from beginning of first segment	150m [492 ft]	Same	Same
Intersection Slopes,			
1V:3H (Negative):	2m [6.5 ft] High	Same	Same
Lateral Offset	2.8m [8 ft]	Same	10.3m [34 ft]
Distance from beginning of first segment	150m [492 ft]	Same	Same
Intersection Slopes,			
1V:3H (Positive):	2m [6.5 ft] High	Same	Same
Length	6.0m [20 ft]	Same	Same
Width	20m [66 ft]	Same	12.5m [41 ft]
Lateral Offset	3.5m [11.5 ft]	Same	10.3m [34 ft]
Distance from beginning of first segment	157m [515 ft]	Same	Same
W-Beam Strong Post:			
Length	N/A	70m [230 ft]	N/A
Width	N/A	0.5m [1.5 ft]	N/A
Lateral Offset	N/A	2m [6.5 ft]	N/A
Distance from beginning of first segment	N/A	116m [380 ft] upstream	N/A
Crashworthy End Terminals:			
Length	N/A	15m [50 ft]	N/A
Width	N/A	0.5m [1.5 ft]	N/A
Lateral Offset	N/A	2m [6.5 ft]	N/A
Distance from beginning of first segment		101m [331 ft] upstrm	

N/A

186m [610 ft]
dnstrm

N/A

This analysis was conducted with all roadside features on the right side of the road, as the RDG documented in its example problem. The user input differences in the software and the differences in the predicted number of crashes are presented in the following sections.

Compare with Existing Software

A direct comparison between the methods used in RSAP and the IHSDM CPM is difficult because of the inherent differences in the methods used to model ROR crashes. The proposed method combines the strengths of both approaches through the chosen encroachment model and the use of AMFs. Regardless of the approach taken the resulting predictions of ROR crashes within a road segment for a given study period should be similar in magnitude. Table 6-2 provides a summary of the similarities and differences between the data used by RSAP, the IHSDM CPM, and the proposed method. Where discrepancies exist in the available data entry fields, assumptions were made and are discussed here.

Table 6-2. Differences between the RSAP, IHSDM CPM, and this Research Input Data.

Data Element	RDG App A Example	Recalc using RSAP	IHSDM CPM	Proposed Method
Cost Data				
Project Life	Yes	Yes	No	Yes
Discount Rate	Yes	Yes	No	No
Installation Cost	Yes	Yes	No	Yes
Annual Maintenance Cost	Yes	Yes	No	Yes
General Highway Data				
Functional Class	Yes	Yes	Yes	Yes
Highway Type	Yes	Yes	Yes	Yes
Pavement Material	No	No	Yes	Yes*
Shoulder Material	No	No	Yes	Yes*
Speed Limit	Yes	Yes	No	Yes*
Design Speed	No	No	Yes	Yes*
Desired Speed	No	No	Yes	Yes*
85th Percentile Speed	No	No	Yes	Yes*
Current Year ADT	Yes	Yes	No	Yes
Future Year ADT	No	No	Yes	Calculated
Traffic Growth Factor	Yes	Yes	No	Yes
Percent Truck	Yes	No	No	Yes*
User-Defined Adjustment Factor	Yes	No	No	No
Highway Geometrics				
Segment Length	Yes	Yes	Yes	Yes
Vertical Alignment	Yes	Yes	Yes	Yes
Horizontal Alignment	Yes	Yes	Yes	Yes

Lane Width	Yes	Yes	Yes	Yes
Shoulder Width	Yes	Yes	Yes	Yes
Roadside Elements				
Culvert Headwall, Type C	Yes	Yes	RHR	Yes
Intersection Slopes, Slope	Yes	Yes	Yes	Yes
Lateral Offset	Yes	Yes	No	Yes
W-Beam Strong Post: Crashworthy End	Yes	Yes	RHR	Yes
Terminals	Yes	Yes	RHR	Yes

*Part of proposed method, not specifically included in the software developed.

Data Input Fields

The IHSDM CPM allows the user to input the roadway and shoulder treatment. Given the problem statement included mention of a resurfacing project, a paved roadway and shoulder cross-section was assumed while conducting the IHSDM CPM analysis. RSAP does not allow the user to analyze the impact of roadway and shoulder treatments. The proposed method allows the user to use the Accident Modification Factor (AMF) for shoulder treatment.

The RDG uses the term “Speed Limit” in its example problem. The current version of RSAP also uses “Speed Limit” as the label for the data entry field, but does not use this entry in the computations. The IHSDM CPM has several options for entering speed data, which include the design speed, the desired speed and the 85th percentile speed. While the 85th percentile speed and the posted speed should generally coincide, the CPM analysis was conducted using the example problem’s 100 km/h “speed limit” as the design speed. The proposed method uses the traditional definitions of design speed and speed limit, discussed in Chapter five, prior to software implementation. A speed limit data entry field, however, is not provided in the software because it is not needed in the crash prediction method recommended for implementation.

The RSAP analysis uses a current year ADT and allows the user to input the expected traffic growth over the project life. RSAP uses an average volume over the project life to account for traffic growth. The IHSDM CPM allows the user to input the future traffic volume and does not make a provision for traffic growth over the project life. The HSM discusses a process for using different volumes for different years in Part C,¹⁵⁹ but this appears to have not been implemented in the IHSDM CPM. The user could, however, analyze each year independently and sum each year’s results to avoid over-predicting crashes by multiplying a higher traffic volume than is reflective of reality. As currently coded, the proposed method reflects a traffic growth compounded annually over the design life of the project. This future traffic volume is then used as a multiplier alongside the project life to determine the number of encroachments, resulting in slightly over-predicting the number of encroachments. More sophisticated modeling of the traffic growth, similar to what is suggested in the RSAP EM¹⁶⁰ could provide a more realistic traffic volume.

RSAP allows the user to specify an ADT, but assumes a directional distribution of traffic equal to 50 percent. The user does not have an option to change the RSAP directional distribution. The IHSDM CPM allows the user to specify the Design Hour Volume (D) in percent and the Peak Hour Volume. The Peak Hour volume allows the user to specify the direction of travel where the volume is heaviest. This feature has the potential to be used extensively in ROR crash predictions and has been incorporated in the proposed method.

RSAP provides the ability to adjust the analysis for regional influences through a User Adjustment Factor, however, the RSAP Engineering Manual gives little guidance on the application of this factor. For this example problem, the RSAP adjustment factor was not changed from the default value of 1.0. The HSM procedure has a series of adjustments of base data, through AMFs, to reflect project characteristics. Regional crash data can also be added to the IHSDM CPM for further refinement of the analysis, but this data was not used for the example problem. Without considering these factors and procedures, the results presented herein

are a comparison of software "default" conditions from both methods and models for the regions the data was collected from.

This problem has been reanalyzed using the currently available version of RSAP (i.e., version 2.0.3),¹⁶¹ the current version of the IHSDM CPM,¹⁶² and the software developed to support the proposed method. For the purposes of the example problem analysis, a RHR of five was chosen for Alternative 1 (Baseline Conditions), a RHR of four was used for Alternative 2 (Install Guardrail), and a RHR of three was used for Alternative 3 (Extend Culvert).

Results

The results of the analysis are presented in Table 6-3. The results are presented using the terminology and units used by each respective program. The terms incident, crash, and accident are often used interchangeably by non-engineers to describe crashes, however the results displayed below indicate that the authors of the programs used these terms intentionally to describe different events. The original terminology/units have been maintained in an effort to remain consistent with the original literature and software program.

Table 6-3. Results of Alternatives Analysis Using RSAP, IHSDM CPM, and this Research.

Results	Baseline Conditions Alternative 1	Install Guardrail Alternative 2	Extend Culvert Alternative 3
<i>2006 RDG:</i>			
Expected Incident Frequency (Inc./Year)	0.397	0.495	0.295
Annual Crash Cost	\$12,428	\$6,628	\$1,254
Annual Installation Cost	\$0	\$960	\$3,200
Annual Maintenance Cost	\$0	\$136	\$0
<i>RSAP 2.0.3 in SI units:</i>			
Expected Crash Frequency (Acc./Year)	0.029	0.05	0.002
Annual Crash Cost	\$7,028	\$5,925	\$671
Annual Installation Cost	\$0	\$960	\$3,200
Annual Maintenance Cost	\$0	\$100	\$0
Annual Repair Cost	\$0	\$13.34	\$0
<i>IHSDM CPM in SI units:</i>			
Roadside Hazard Rating (RHR)	RHR 5	RHR 4	RHR 3
Total ROR Crashes	7.56	7.07	6.61
Crashes/Year	0.302	0.283	0.264

CEC Method (modified RSAP):

Expected Encroachment Frequency (Encroachments/Year)	0.594		
Encroachments/Year per Segment Length	0.265		
ROR crashes in Segment per year	0.033	0.058	0.003
Annual Crash Cost	\$11,256	\$19,708	\$1,076
Annual Installation Cost	\$0	\$960	\$3,200
Annual Maintenance Cost	\$0	\$100	\$0
Annual Repair Cost	\$0	\$13.34	\$0
Number of Iterations	10,000		

As previously discussed above, RSAP presents results of the expected crash costs for ROR crashes for each alternative, where the IHSDM CPM predicts total crashes for a segment of road and does not distinguish between the ROR crash severities, therefore cannot estimate the crash cost. The RDG Example Problem results for Incidents/Year are plotted in Figure 6-1 versus the RSAP recalculation of Accidents/Year and the proposed software (CEC) in units of ROR crashes/year. The IHSDM CPM presents results as total crashes over a study period. The example problem had a study period of 25 years, therefore, the total crashes were divided by 25 and plotted in Figure 6-1 for a direct comparison of magnitude with the RDG and RSAP values. The values presented in the RDG and generated by the IHSDM CPM software are approximately ten times larger than the other two software programs. Figure 6-2 is a modified version of figure 6-1, plotted at a 0.10 scale for improved visual comparison of the smaller scale results.

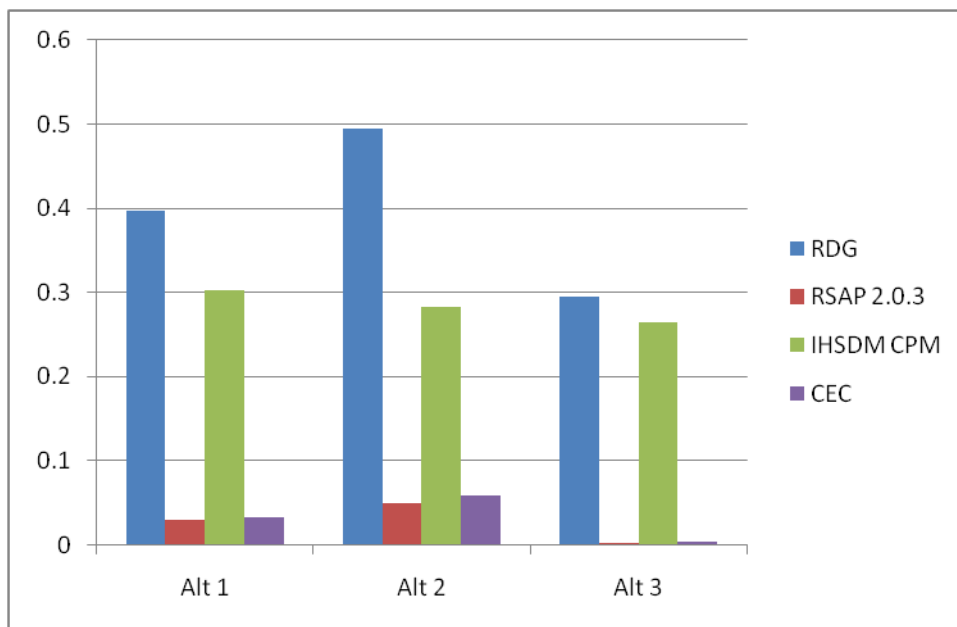


Figure 6-1. ROR Crash Predictions Using RSAP, IHSDM CPM, and this Research.

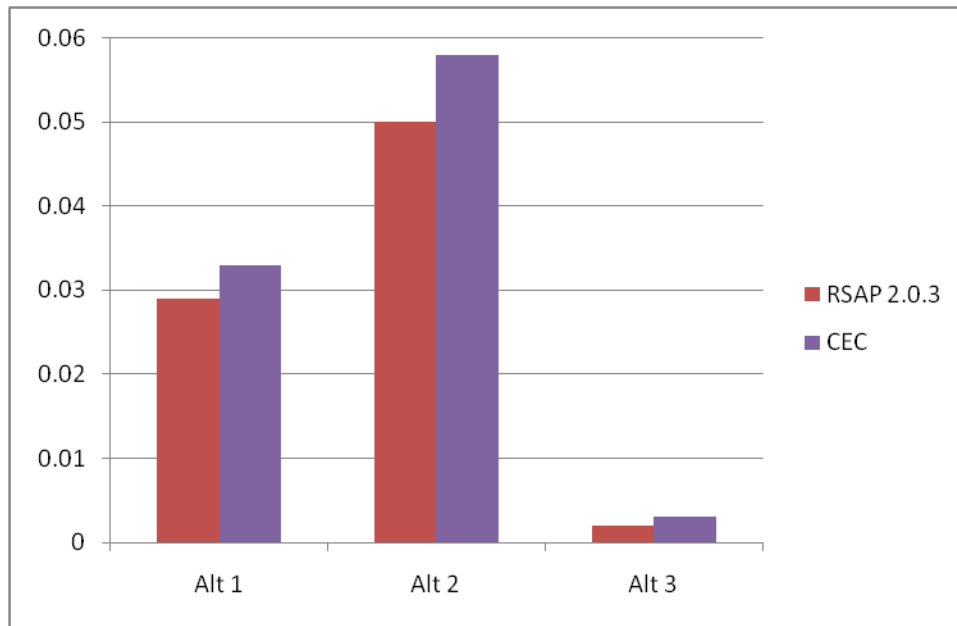


Figure 6-2. ROR Crash Predictions Using RSAP and this Research.

There is a substantial difference between what is published in the RDG (RSAP version 1.0) and what is currently produced by RSAP version 2.0.3 with results varying by more than a factor of ten. The example problem shown in Appendix A of the RDG is dated May 1, 2001 and lists the version of RSAP as 1.0.¹⁶³ The current version of RSAP is version 2.0.3. The 2006 RDG encroachment rate for an ADT of 5,000 vpd is 2.6 enc/km/yr¹⁶⁴ while the RSAP Engineering Manual uses an encroachment rate of about 1.5 enc/km/yr¹⁶⁵ which would explain some discrepancies in RSAP values.

Discussions with RSAP update authors indicate some changes were made to correct reporting errors between the first and second versions of RSAP. Additionally, the change from reporting in incidents/year to accidents/year was simply done to make the results more self-explanatory. Unfortunately, there is no documentation to accompany the RSAP update from version 1.0 to 2.0.3 to determine which encroachment rate is used in the code or other coding changes that may have been made. Given the update of RSAP from version 1.0 to version 2.0.3, the results of version 1.0 were considered inaccurate and were disregarded.

The software developed under this research generally agrees with the most recent version of RSAP, predicting a slightly higher number of ROR crashes per year than RSAP version 2.0.3 through all three alternatives (Figure 2), most likely the result of a different encroachment model. This workbook implements the procedures outlined in the RSAP Engineer's Manual and provides some reassurance that the Engineer's Manual and the current version of RSAP generally agree.

As previously discussed, comparisons between the CPM and RSAP are difficult, but one should expect results on the same order of magnitude. The methods used by the HSM do not recognize the addition of guardrail in alternative two, therefore the expected increase in crashes is not noted. The results obtained from the CPM are considerably higher than those predicted by RSAP version 2.0.3 and the workbook, along the order of ten times as many crashes. The CPM is predicting all ROR crashes. One could argue that this example problem only considered hazards on the right side of the road and therefore divide the CPM predictions in half, but the predictions are still considerably higher than those of RSAP and this software. The RHR AMF used to modify the ROR crash potential results in only minor changes to the predicted ROR crashes, regardless of the RHR chosen. Refinement of this modification factor is needed to allow the CPM to accurately predict ROR crash potential.

Calibration

The software developed for this research is considered validated by this example problem. Actual crash data should be used to calibrate the encroachment model on a case-by-case basis. First, the crash predictions for existing conditions should be analyzed. Then, using historic crash data, the results should be adjusted by a multiplier to match existing crash history. All future crash predictions for the same corridor should be adjusted by the same multiplier, thereby calibrating the model.

Summary

Immediate attention should be given to the discrepancies between the 2006 RDG Appendix A and the current version of RSAP. The RDG and RSAP have been in circulation for over seven years and are used by design practitioners and policy makers to promote safe roadside designs. Appendix A of the RDG should be updated immediately to reflect the current version of RSAP.

The ROR crash predictions from the HSM are troubling and require improvements to allow practitioners to use the HSM successfully. The use of one modification factor to encompass the entire roadside environment is disconcerting and should be revisited.

Additional attention should be given to coordinating efforts between the development of the HSM, the continued development of the RDG and the software which supports both manuals. The data gathered in the study and development of the HSM can be used to further refine encroachment models. The development of the RSAP update can be used to develop and refine roadside AMFs.

CHAPTER 7

EXAMPLE DESIGN

A hypothetical sample problem regarding the redesign of approximately 1.6 kilometers (one mile) of road is presented in this Chapter for demonstration and discussion purposes. The highway is a two-lane rural collector in Spencer, Massachusetts. The specific highway characteristics are provided in Table 7-1. The road is primarily residential in nature with both horizontal and vertical curves, tangents, and sight obstructions. The pavement is showing signs of age. The centerline of the road is marked with a double yellow centerline (DYCL) and the outside edges of the road are marked by a solid white edge line (SWEL). The road does not have street lighting or pedestrian facilities. Beyond the edge of road, there are trees, street signs, mail boxes, and utility poles. There is not a closed drainage system, however, the land adjacent to the road slopes away from the roadway bed to promote drainage (e.g, country drainage). It is a typical rural collector for the region, however, the crash rate is double the state crash rate and the road has experienced several injury and fatal ran-off-road crashes in the last five years. The series of photographs in Figure 7-1 illustrates the general character of the road.

Table 7-1. Highway Characteristics of Sample Problem.

Functional Classification	Rural collector
Lane width	3.6 m (12 ft)
Right shoulders	1 m (3 ft)
Left shoulders	N/A
Vertical granite curbing height	N/A
Sloped granite edging height	N/A
Clear zone	Varies from 1.5m (5 ft) to 10m (32 ft)
Sideslopes	1V:4H (typ)
Median width	N/A
Average Daily Traffic (ADT)	7,000 vpd
Posted Speed Limit	70 kph (45mph)



Figure 7-1. Baseline STA 11+750m looking North (left) and looking South (right)

Example Design Problem Using Traditional Design Process

The example problem has been designed using the traditional design process and is documented below.

Pre-design preparation: Collect necessary field data.

A CAD file has been generated of this roadway using AutoCAD Civil 3D with existing ground elevations imported from Google Earth on March 3, 2010. Google Earth lists the source of its information as MassGIS at the time the data was imported.¹⁶⁶ Typically, detailed survey information would be gathered in the field, however, a detailed field survey was not conducted due to the cost of a survey and the example nature of this project. Highway surveys traditionally involve measuring and computing horizontal and vertical angles, elevations, and distances using a variety of data-gathering equipment. Data gathered in the field can be transformed, through a series of calculations and manipulations, into a base map with contour lines and highway alignments.

Recently, more sophisticated survey data collection techniques have been developed. These techniques include either measuring of distances and elevations from a remote location (i.e., airplanes, satellites, etc.) or field data collectors, which can automate some of the post-processing of field data. The accuracy and precision, as well as the amount of data gathered, govern which method is used.

Google Earth¹⁶⁷, one of several public domain sources for information gathered through remote sensors, contains geographically referenced images and terrain information of varying degrees of precision and accuracy for locations throughout the globe. The precision and accuracy of the information displayed varies by original source of Google Earth's information, noted at the bottom of the screen.¹⁶⁸

Step 1: Determine if the existing number of lanes is sufficient or additional lanes are necessary to accommodate future traffic volumes.

A capacity analysis was conducted using the HCS2000 and the results are shown in figure 7-2. The current and future year analysis resulted in a level of service of C, which is considered acceptable, therefore additional capacity need not be considered for this project.

Input Data					
Highway class	Class 2				
Shoulder width	3.0	ft	Peak-hour factor, PHF	0.95	
Lane width	12.0	ft	% Trucks and buses	0	%
Segment length	1.0	mi	% Recreational vehicles	1	%
Terrain type	Level		% No-passing zones	100	%
Grade: Length		mi	Access points/mi	5	/mi
Up/down		%			
Two-way hourly volume, V	700	veh/h			
Directional split	50	/	50	%	
Average Travel Speed					
Grade adjustment factor, fG	1.00				
PCE for trucks, ET	1.2				
PCE for RVs, ER	1.0				
Heavy-vehicle adjustment factor,	1.000				
Two-way flow rate, (note-1) vp	737	pc/h			
Highest directional split proportion (note-2)	369	pc/h			
Free-Flow Speed from Field Measurement:					
Field measured speed, SFM	-	mi/h			
Observed volume, VF	-	veh/h			
Estimated Free-Flow Speed:					
Base free-flow speed, BFFS	50.0	mi/h			
Adj. for lane and shoulder width, fLS	2.6	mi/h			
Adj. for access points, fA	1.3	mi/h			
Free-flow speed, FFS	46.2	mi/h			
Adjustment for no-passing zones, fnp	3.3	mi/h			
Average travel speed, ATS	37.1	mi/h			
Percent Time-Spent-Following					
Grade adjustment factor, fG	1.00				
PCE for trucks, ET	1.1				
PCE for RVs, ER	1.0				
Heavy-vehicle adjustment factor, fHV	1.000				
Two-way flow rate, (note-1) vp	737	pc/h			
Highest directional split proportion (note-2)	369				
Base percent time-spent-following, BPTSF	47.7	%			
Adj. for directional distribution and no-passing zones, fd/np	17.0				
Percent time-spent-following, PTSF	64.7	%			
Level of Service and Other Performance Measures					
Level of service, LOS	C				
Volume to capacity ratio, v/c	0.23				
Peak 15-min vehicle-miles of travel, VMT15	184	veh-mi			
Peak-hour vehicle-miles of travel, VMT60	700	veh-mi			
Peak 15-min total travel time, TT15	5.0	veh-h			

Figure 7-2. Level-of-Service Analysis using HCS2000.

Step 2: Determine the functional classification, design speed, and the corresponding design criteria.

A summary of the design warrants applicable for a rural collector, provided in the “Green Book” are shown in table 7-2.¹⁶⁹

Table 7-2. Highway Design Warrants for Rural Collectors.

Design Traffic Volumes	Design for “specific traffic volumes and specified acceptable levels of service”
Design Life	20 years
Design Speed	<ul style="list-style-type: none"> • 70 km/h (45 mph) for rolling or mountainous terrain or where environmental conditions dictate. • 80 km/h (50 mph) for level terrain and favorable environmental conditions. • Exhibit 6-1: 80 km/h (50 mph)
Alignment	“Frequent opportunities for passing should be provided, where practical.”
Stopping Sight Distance (SSD)	130m (425 ft)
K values for crest/sag curves without Passing Sight Distance (PSD)	26/30 SI units (84/96 English units)
K values for crest curves with Passing Sight Distance (PSD)	438 (1203 English units)
Maximum grades	6 percent
Cross Slope	1.5 to 2 percent
Superelevation	<ul style="list-style-type: none"> • Should not exceed 12 percent for rural collectors. • Should not exceed 8 percent for cold weather regions. • Superelevation should be used when warranted for rural collectors.
Number of Lanes	“should be sufficient to accommodate the design volumes for the desired level of service.”
Width of roadway	7.2m (24 ft)
Foreslopes	Preferably, 1V:4H Minimum, 1V:3H
Clear zone	1V:4H Foreslope: 7.5-8.5m (24-28 ft) 1V:3H Foreslope: not desirable per RDG
Minimum Radius (Rmin)	229m (750 ft)

Step 3: Simultaneously design and draft the horizontal alignment electronically in a CAD program overlaid on the electronic field survey data, using the established horizontal alignment criteria.

Using the prescriptions outlined above, the horizontal geometry was calculated and the results are outlined in Table 7-3 for this example project. A typical plan view (the horizontal alignment) is provided in figure 7-3 from STA 12+120m to 12+880m.

Table 7-3. Horizontal Alignment Geometrics.

Type	Length	Radius	Direction	Start Station	End Station	Delta angle
Line	164.244m		N15° 39' 23"E	11+250.00m	11+414.24m	
Curve	158.017m	450.000m		11+414.24m	11+572.26m	20.1194 (d)
Line	89.465m		N35° 46' 32"E	11+572.26m	11+661.73m	
Curve	188.977m	420.000m		11+661.73m	11+850.70m	25.7800 (d)
Line	290.483m		N9° 59' 44"E	11+850.70m	12+141.19m	
Curve	108.159m	400.000m		12+141.19m	12+249.35m	15.4927 (d)
Line	325.099m		N5° 29' 49"W	12+249.35m	12+574.44m	
Curve	190.334m	300.000m		12+574.44m	12+764.78m	36.3511 (d)
Line	123.125m		N30° 51' 15"E	12+764.78m	12+887.90m	



Figure 7-3. Example Problem Plan View, STA 12+120m to12+880m.

Step 4: Simultaneously design and draft the proposed ground profile using the previously established vertical alignment criteria.

Again using the prescribed warrants, the vertical geometrics are calculated and graphically represented. The results are outlined in Table 7-4 for this example project. The crest curve with a PVI Station of 12+182.18m does not meet passing sight distance requirements, however, the Green Book suggests passing sight distance should only be provided where practical. Providing passing sight distance at this location would have required a good deal of additional excavation, therefore it was not provided.

Table 7-4. Vertical Alignment Geometrics.

PVI Station	PVI Elevation	Grade In	Grade Out	A	Curve	Length	K
11+305.00m	240.792m		5.31%				
12+182.18m	287.371m	5.31%	-4.60%	9.91%	Crest	317.342m	32.025
12+665.89m	265.124m	-4.60%	2.89%	7.49%	Sag	231.287m	30.899
12+883.18m	271.395m	2.89%					

An example of the profile (the vertical alignment), is provided in figure 7-4 from STA 12+420m to 12+883.18m. The vertical red lines represent the start and end of horizontal curves. The horizontal, jagged red line is the existing ground. The sweeping cyan line is the proposed vertical alignment and the yellow text is labels. The green book suggests that an effort should be made to coordinate design elements. Changes to the vertical curve shown would have resulted in a K value below the recommendation or vertical grades above the recommendation. The elements shown here are not coordinated for these reasons.

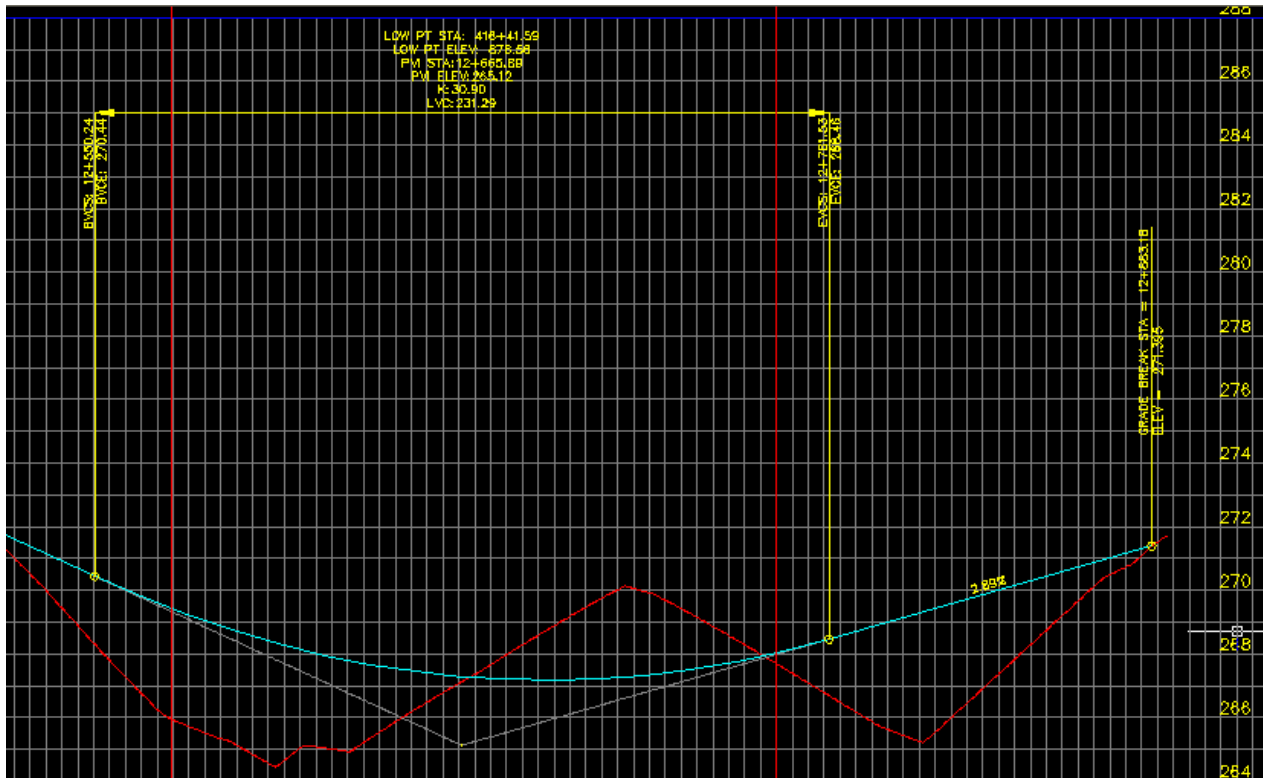


Figure 7-4. Example Problem Profile View, STA 12+420m to 12+883.18m.

Step 5: Draft a typical cross-section using the proposed number of lanes and produce cross-sections of the corridor.

A view of the typical section is shown in figure 7-5. The proposed section consists of two 3.6m (12 ft) lanes. The existing 1m (3 ft) shoulder is also proposed for the new section. The existing 1V:4H side slopes meet the RDG warrants for traversable side slopes, therefore, the “country drainage” is proposed to remain and curbing and/or edge treatment is not proposed.

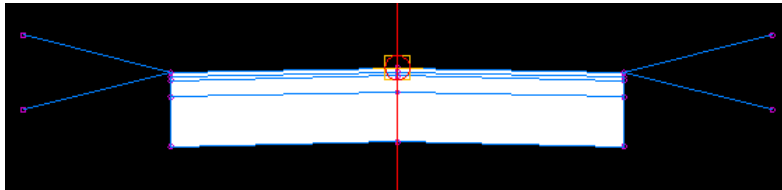


Figure 7-5. Example Problem Typical Section.

The blue lines represent the internal coding for “daylighting” to existing ground. The edge of the typical section is programmed to tie into the existing ground surface conditions (e.g., daylight) based on a variety of factors which include:

- The elevation of the existing ground versus the elevation of the proposed edge of road and the proposed slope;
- The possibility that the right-of-way limit may define the proposed slope;
- The prescribed 8.5m clear zone and 4H:1V slope; and
- Given the constraints, the need for guardrail, riprap, slope stabilization, or alternative treatments is evaluated based on the criteria the designer has entered or manually by the designer.

This behavior is illustrated in figure 7-6.

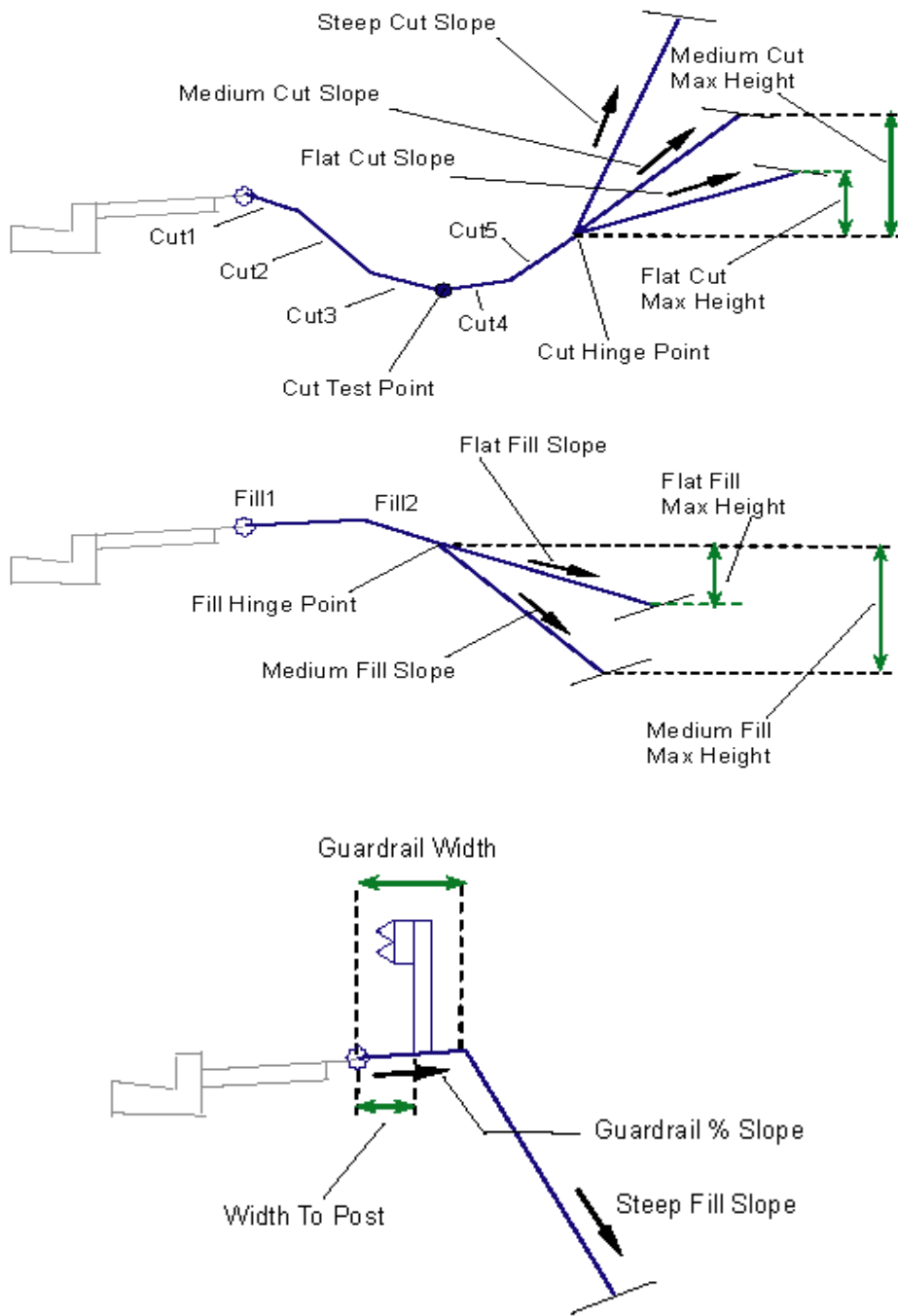


Figure 7-6. Cross-section daylight programmable behavior.

Step 6: Edit these cross-sections, horizontal and vertical alignments as needed to minimize impacts such as right-of-way (ROW) and environmentally sensitive areas.

The resulting corridor design has significant impacts to the existing ROW with the corridor limits of grading impacting several residences (figures 7-7 and 7-8). Given these impacts (i.e., high cost of acquiring right of way and the lengthy process), it is likely the existing roadway geometry would be maintained and the road bed would be resurfaced or reclaimed to provide a longer design life, limiting the possible improvements to the clear zone to what is available within the existing right-of-way. Resurfacing or reclaiming the existing roadway allows the owner to improve the roadway surface while not meeting geometric design guidelines because the project would be considered a maintenance project and the Green Book does not apply to maintenance projects.



Figure 7-7. Impacts to Existing Residence STA 12+120 to 12+280.



Figure 7-8. Impacts to Existing Residence STA 12+320 to 12+420.

Remaining Steps of Existing Design Process

Steps seven through ten have been skipped for this example problem analysis as they include items that are not feasibly demonstrated as part of an example problem, such as:

- Step 7: Produce a Construction Cost Estimate and submit preliminary plans and estimate for review, sometimes called the 80% review
- Step 8: Address reviewing agency concerns with geometric design. Produce a pavement stripping and signing plan, construction specifications, more detailed construction plans and cost estimate. Submit Final plan set for review, often called the 100% review.
- Step 9: Address reviewing agency concerns with construction documents and produce final Plans, Specifications, and Estimate (PS&E).
- Step 10: Project is Bid and Constructed. Areas of Safety Concern are often identified after the project is constructed and opened to traffic.

Summary of Existing Design Process

The engineer decided to not change the geometry of the existing highway due to costly right-of-way impacts. This decision was made absent of any knowledge of how this would impact highway safety over the twenty year design life of this roadway. Many highway agencies are faced with these decisions due to the nature of this business. Some agencies will not construct a project if they cannot meet all of the warrants, while others may proceed if they can improve the roadway just a little. While this is only one example, the process described below considers a different approach which allows the agency to focus on some improvement and quantify that improvement rather than meeting all of the warrants, as justification to construct a safety improvement project.

Example Problem Using Proposed Process

Successful completion of a performance-based design requires that a project need be established at the onset of a project. The description of the example project given at the beginning of this chapter states that there is an issue with run-off-road (ROR) crashes and the pavement needs repair, but neither need was definitively established as the driving force behind the project, stating exactly why this project should be undertaken. Either need could justify the project independently or concurrently. For the purpose of this example, we will move forward with the primary object of reducing ROR crashes.

Planning Level Analysis

Recall this analysis should be conducted to determine which highway engineering principals may reduce the ROR crashes. A review of literature, including the pending HSM, provides guidance on possible measures which should be considered. Alternatives considered are discussed below.

The existing shoulder is 1m (3 ft) wide and paved. Changes to the width of a paved shoulder do not modify the ROR crash potential. One may consider installing crash cushions at all the fixed roadside features to reduce the ROR crash severity. The crash cushions will not reduce the frequency, but the reduction in severity is welcome and will lead to a reduction in the societal cost associated with each crash, however, the sheer number of trees and poles needing protection renders this alternative unreasonable.

Exhibit 13-26 of the HSM (figure 7-9) outlines the potential crash effects on single vehicle crashes of flattening sideslopes. The impact of flattening the sideslopes appears to reduce crashes and should be considered. A review of the existing sideslopes and the 2005 crash history for this site is presented in Table 7-5 alongside the number of predicted annual crashes that could be expected by flattening the sideslopes. It should be noted that the existing sideslopes do meet RDG warrants for traversable slopes. STA 11+662m to 11+851m experienced the highest number of fatal and injury crashes in 2005, with a total of four.

This section is marked by a broken-back reverse curve (e.g, two curves with opposite directions separated by a short tangent) and a five percent grade. This section is also where the clear zone transitions from 5.9m to 10.9m. While all of these features meet design standards individually, the combined effect of what is accepted as poor horizontal alignment with the steep grade and changing roadside design appears to impact the crash rate.

Flattening the sideslopes from 1V:4H to 1V:7H is predicted to reduce this fatal and injury annual crashes from four to about 3.25 crashes annually.

Treatment	Setting (Road type)	Traffic Volume	Accident type (Severity)	AMF				
				Sideslope in Before Condition	Sideslope in After Condition			
					1V:4H	1V:5H	1V:6H	1V:7H
Flatten Sideslopes	Rural (Two-lane Road)	Unspecified	Single Vehicle (Unspecified)	1V:2H	0.90	0.85	0.79	0.73
				1V:3H	0.92	0.86	0.81	0.74
				1V:4H		0.94	0.88	0.81
				1V:5H			0.94	0.86
				1V:6H				0.92
				1V:7H				

Base Condition: Existing sideslope in *before* condition.

451 NOTE: Standard error of the AMF is unknown.

Figure 7-9. Potential Crash Effects on Single Vehicle Accidents of Flattening Sideslopes ¹⁷⁰

Table 7-5. Existing Sideslopes and Crash Frequency Compared to RDG Warrants and AMFs

Start STA (m)	Start STA (ft)	Existing Slope	Existing meets RDG	2005 Injury & Fatal ROR crashes	Flatten Slope to 1V:5H 0.94AMF	Flatten Slope to 1V:6H 0.88AMF	Flatten Slope to 1V:7H 0.81AMF
11+250	369+09	1V:4H	Yes	0	0.00	0.00	0.00
11+414	374+48	1V:4H	Yes	0	0.00	0.00	0.00
11+572	379+66	1V:4H	Yes	0	0.00	0.00	0.00
11+662	382+60	1V:4H	Yes	4	3.76	3.52	3.24
11+851	388+80	1V:4H	Yes	1	0.94	0.88	0.81
12+141	398+33	1V:4H	Yes	0	0.00	0.00	0.00
12+249	401+88	1V:4H	Yes	0	0.00	0.00	0.00
12+574	412+54	1V:4H	Yes	0	0.00	0.00	0.00
12+765	418+79	1V:4H	Yes	0	0.00	0.00	0.00

Exhibit 13-28 of the HSM (figure 7-10) outlines the potential crash effects on increased distance to roadside features (e.g., clear zone). The impacts of larger clear zones appear to reduce crashes and should be considered during design. A review of the existing clear zones and the 2005 crash history is presented in Table 7-6 alongside the number of predicted annual crashes that could be expected by increasing the clear zones. It should be noted that some of the clear zones within the study area already meet RDG warrants (e.g., 24-28'). Widening the clear zones to 9.1m (30 ft), the equivalent of 13.7m (45 ft) offset from the baseline, is expected to drop the annual crash frequency.

Treatment	Setting (Road type)	Traffic Volume	Accident type (Severity)	AMF	Std. Error
Increase distance to roadside features from 3.3-ft to 16.7-ft	Rural (Two-lane roads and Freeways)	Unspecified	All types (All severities)	0.78	0.02
Increase distance to roadside features from 16.7-ft to 30.0-ft				0.56	0.01
Base Condition: Distance to roadside features of 3.3-ft or 16.7-ft depending on original geometry.					

473
474
475

NOTE: Based on US studies: Cirillo (1967), Zegeer et al. (1988)

Bold text is used for the most reliable AMFs. These AMFs have a standard error of 0.1 or less.

Distance measured from the edgeline or edge of travel lane

Figure 7-10. Potential Crash Effects of Increased Distance to Roadside Features ¹⁷¹

Table 7-6. Existing Clear Zones and Crash Frequency Compared to RDG Warrants and AMFs

Start STA (m)	Start STA (ft)	Existing CZ offset (m)	Existing CZ offset (ft)	Existing meets RDG 8.5m CZ	2005 Injury & Fatal ROR crashes	Increase CZ offset to 13.7m (45 ft) 0.56AMF
11+250	369+09	5.9	19	No	0	0.00
11+414	374+48	5.9	19	No	0	0.00
11+572	379+66	5.9	19	No	0	0.00
11+662	382+60	5.9	19	No	4	2.24
11+851	388+80	10.9	36	No	1	0.56
12+141	398+33	10.9	36	No	0	0.00
12+249	401+88	10.9	36	No	0	0.00
12+574	412+54	10.9	36	No	0	0.00
12+765	418+79	12.0	40	No	0	0.00

The influence of modification factors is multiplicative, therefore when used in combination, the predicted reduction in crashes increases. Table 7-7 demonstrates the possible reduction in crashes for two different options: 1) changing the sideslopes to 1V:5H widening the clear zone 5.1m; or 2) changing the sideslopes to 1V:7H and widening the clear zone 9.1m.

Table 7-7. Combined Affect of Flattening Sideslopes and Widening Clear Zones

Start STA (m)	Start STA (ft)	2005 Injury & Fatal ROR crashes	1V:5H and 5.1m CZ	1V:7H and 9.1m CZ
11+250	369+09	0	0.00	0.00
11+414	374+48	0	0.00	0.00
11+572	379+66	0	0.00	0.00
11+662	382+60	4	2.93	1.81
11+851	388+80	1	0.73	0.45
12+141	398+33	0	0.00	0.00
12+249	401+88	0	0.00	0.00
12+574	412+54	0	0.00	0.00
12+765	418+79	0	0.00	0.00

Other possible considerations for reducing ROR crashes include the installation of rumble strips and improved delineation of the edge of road. Sufficient modeling of rural collectors has not been conducted to date to understand the impact these treatments have on this classification of roads.

Horizontal and vertical alignment as well as lane width is recognized in the literature as contributing factors in ROR crashes. The selection of the horizontal and vertical alignment is logistically constrained in reconstruction projects due to the development adjacent to the roadway which has taken place over the course of the road's history. A planning level analysis of significant changes to the geometrics is only warranted when a new construction project is proposed. The software developed for this research incorporated an encroachment model which includes adjustments for the horizontal and vertical curvature of the road as well as the roadway lane widths. The analysis conducted during the design phase will include a review of the geometric features and their impact on roadside encroachments. The detailed design level analysis of geometrics includes the impact of minor changes to either alignment on predicted crashes.

In summary, it appears conclusive modeling has been conducted for rural collectors and ROR crashes could be reduced with an increase in clear zones and/or a flattening of side slopes. These alternatives should be evaluated further during the design analysis phase.

Preliminary Design: Policy Check and Corridor Model Assembly

Preliminary design phase of this proposed process is remarkably similar to the existing design process and includes establishing a proposed cross-section, horizontal alignment and vertical alignment. Additionally, efforts should be made to identify and document constraints. As previously discussed, regardless of the constraints identified, the project should be initially designed using the desired design standards (alternative one). This design is documented above

in figures 7-3 through 7-5 and tables 7-3 and 7-4 using the nationally accepted design standards (e.g, Green Book and RDG).

Given the rural nature of the road, constraints are limited and include the watershed of two ponds, the existing ROW, residential buildings and trees. Impacts to residential buildings require the successful relocation of the residents, including all costs associated with finding a new home and moving to a similar home in the same region. Infringing on the existing ROW requires assessment of the land's value and compensation of the land owners. Regardless of the costs associated, relocation of residents is generally considered a last resort alternative which is used only in dire situations.

State environmental regulations require the replacement of trees removed for roadway construction at a rate of 2 to 1. That is, for every one tree removed, two trees must be planted. Again considering the ROW, these trees must be planted within the public ROW unless permission has been granted or rights obtained from the property owner to plant trees on their property. Therefore, when removing trees, one must consider where to plant the replacement trees. One of the improvement alternatives under consideration includes widening of the clear zone which would impact trees. This regulation should be kept in mind.

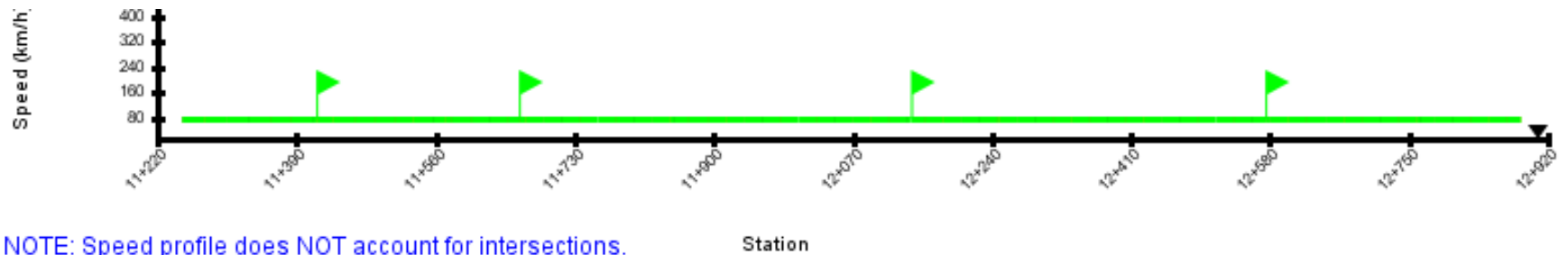
Alternatives also under consideration include changes to the roadside slope. Currently, the roadway sideslopes are 1V:4H away from the road to promote drainage. There are no existing drainage structures along the roadway. Drastic changes to the sideslopes may require the installation of a closed drainage system. The closed drainage system would require piping, structures, detention basins, and permitting of the outlets. Again, this should be kept in mind as the design progresses.

In summary, constraints include the limited ROW, the lack of existing drainage structures, and the environmental permitting requirements.

Synthesis: Improve efforts to coordinate design elements and reduce speed inconsistencies

The design is documented above in figures 7-3 through 7-5 and tables 7-3 and 7-4 meets all design standards, which are based on design speed, but the predicted travel speed is unknown. This phase of the proposed design process is used to analyze the design for speed inconsistencies and to coordinated design elements.

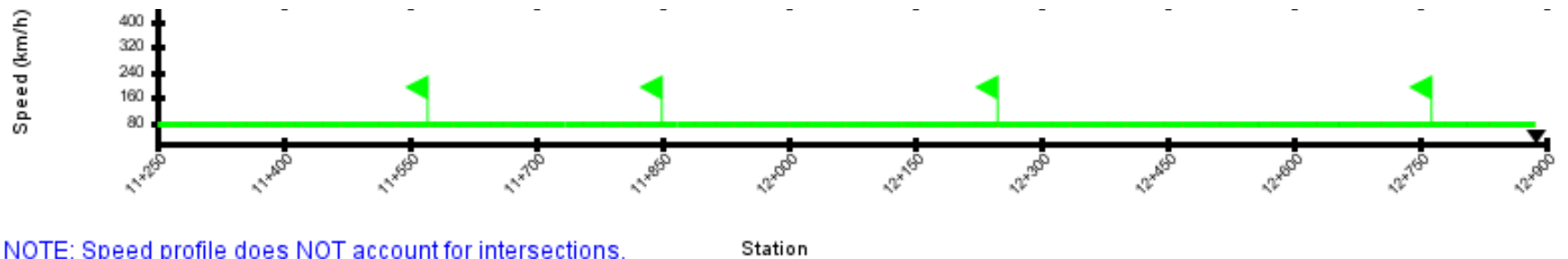
The IHSDM design consistency module was used to diagnose any inconsistencies in speed between the horizontal curves and tangents. As previously discussed, crashes on two-lane rural highways are overrepresented at horizontal curves, and speed inconsistencies are a common contributing factor to crashes on curves. This module provides estimates of the magnitude of potential speed inconsistencies between segments and presents the results in a color-coordinated graph with green representing a good design and red representing a poor design. The design is assessed in both directions for bi-directional roads. The results of this analysis are presented in figures 7-11 and 7-12. The results show the driver can expect to travel a consistent speed throughout the roadway in both directions (e.g., green line). While these results are positive, they only consider the horizontal alignment. The clear zone width, sideslopes and the probability of crashes given an encroachment have not been evaluated yet.



NOTE: Speed profile does NOT account for intersections.

- █ V85 Speed; km/h; differential between design and V85 speed ≤ 10 km/h
- █ V85 Speed; km/h; differential between design and V85 speed > 10 km/h, ≤ 20 km/h
- █ V85 Speed; km/h; differential between design and V85 speed > 20 km/h
- ▲ Criteria 2; V85 speed differential of adjacent horizontal elements ≤ 10 km/h
- ▲ Criteria 2; V85 speed differential of adjacent horizontal elements > 10 km/h, ≤ 20 km/h
- ▲ Criteria 2; V85 speed differential of adjacent horizontal elements > 20 km/h

Figure 7-11. Speed Consistency Analysis for Increasing Stations.



NOTE: Speed profile does NOT account for intersections.

Figure 7-12. Speed Consistency Analysis for Decreasing Stations.

Analysis

This new phase of the highway design process has been added to allow the engineer to evaluate the potential for crashes given the combined influence of the horizontal, vertical and cross-sectional geometry of the proposed improvements. A baseline alternative (Alternative one), which meets all prescribed warrants, is compared to any changes (Alternative two, three, etc.). A preferred alternative is selected which meets the originally established project need and the design proceeds to the next step. In the event the project need is not met, analysis should continue until the project need is met.

This analysis will consider four alternatives in addition to alternative one. These alternatives are as follows:

- Alternative 0: Existing conditions.
- Alternative 1: Meets all Green Book and RDG warrants with full depth reconstruction of the roadway.
- Alternative 2: Maintains existing geometry; resurfaces the roadway, improves sideslopes and clear zones
- Alternative 3: Maintains existing geometry and side slopes; resurfaces the roadway and improves clear zones.
- Alternative 4: Maintains existing geometry and clear zones; resurface the roadway and improves sideslopes.

The horizontal alignment of alternative one was evaluated in the previous step for speed consistency. It should be noted that the alternative one horizontal alignment meets the existing horizontal alignment, therefore all five alternatives have good speed consistency.

Existing sideslopes and clear zones are noted in Tables 7-5 and 7-8 respectively. The Clear Zone (CZ) offset is measured from the Baseline. Table 7-9 summarized the alternatives considered.

Table 7-8. Existing Clear Zones.

Start STA (m)	Start STA (ft)	Existing CZ offset (m)	Existing CZ offset (ft)
11+250	369+09	5.9	19
11+414	374+48	5.9	19
11+572	379+66	5.9	19
11+662	382+60	5.9	19
11+851	388+80	10.9	36
12+141	398+33	10.9	36
12+249	401+88	10.9	36
12+574	412+54	10.9	36
12+765	418+79	12.0	40

Table 7-9. Summary of Design Alternatives.

Data Element	Meets All Warrants Alternative 1	Impr Slope & CZ, Resurface Alternative 2	Impr CZ & Resurface Alternative 3	Impr Slopes & Resurface Alternative 4	Exist. Cond. Alternative 0
Cost Data					
Project Life	20 Years	Same	Same	Same	Same
Discount Rate	4%	Same	Same	Same	Same
Construction Cost	\$2,006,200	\$1,566,200	\$506,200	\$1,566,200	\$0
Highway Data					
Functional Class	Rural Collector	Same	Same	Same	Same
Highway Type	2-lane undivided	Same	Same	Same	Same
Lane Width	3.6m [12 ft]	Same	Same	Same	Same
Shoulder Width	1.0m [3 ft]	Same	Same	Same	Same
Design Speed	80 km/h [50 mph]	Same	Same	Same	Same
ADT	7,000	Same	Same	Same	Same
Traffic Growth Factor	1% per year	Same	Same	Same	Same
Feature Data					
Intersecting Slopes, 1V:4H (Negative) Offset from Baseline	4.6m [15 ft]	N/A	4.6m [15 ft]	N/A	4.6m [15 ft]
Intersecting Slopes, 1V:7H (Negative) Offset from Baseline	N/A	4.6m [15 ft]	N/A	4.6m [15 ft]	N/A
Tree Line at back of CZ Offset from Baseline	13.1m [43 ft]	11.9m [39 ft]	11.9m [39 ft]	Existing (Table 7-8)	Existing (Table 7-8)

The existing horizontal geometry satisfies Green Book warrants, however, the vertical geometry does not. Table 7-3 provides the geometric information for maintaining the existing horizontal alignment. Table 7-10 provided the geometric information for maintaining the vertical geometry. Segments 3-4, 5-6, and 12-13 exceed the recommended maximum grade of eight percent. Additionally, this design does not accommodate any passing zones. Some would consider the Green Book standards not applicable for Alternatives two, three, and four, because these alternatives may be considered maintenance projects. As previously discussed, many agencies choose to employee Green Book warrants regardless of flexibility, to avoid tort liability.

Table 7-10 Vertical Alignment Geometrics (Alternatives 2 through 4)

	PVI Station	PVI Elevation	Grade In	Grade Out	A	Curve	Length	K
1	11+304.17m	240.776m		2.40%				
2	11+453.78m	244.361m	2.40%	4.79%	2.39%	Sag	71.709m	30
3	11+628.23m	252.712m	4.79%	10.00%	5.21%			
4	11+673.60m	261.124m	10.00%	4.58%	5.42%			
5	11+915.16m	272.182m	4.58%	10.00%	5.42%			
6	11+981.71m	279.348m	10.00%	3.41%	6.59%			
7	12+120.41m	284.080m	3.41%	2.00%	1.41%	Crest	63.851m	26
8	12+268.89m	285.501m	2.00%	-4.13%	6.13%	Crest	132.155m	26
9	12+415.23m	279.462m	-4.13%	-7.78%	3.65%	Crest	94.998m	26
10	12+608.60m	264.417m	-7.78%	5.29%	13.07%			
11	12+720.65m	270.350m	5.29%	-5.86%	11.15%			
12	12+809.28m	265.159m	-5.86%	8.44%	14.30%			
13	12+883.18m	271.395m	8.44%					

The crash costs of these five alternatives were evaluated over the project life using the software created for this research. This software pulled data from published literature to relate the severity of specific hazards with the speed of impact. Currently, this is expressed by a Severity Index (SI) per unit of speed. For example, the SI for W Beam strong post is 0.312848 per mile per hour. The SI for a 200mm (4 inch) diameter tree is 0.13502 per mile per hour. This would indicate, at the same speed, a crash with W Beam would be more severe then with a small diameter tree. An SI does not exist in the literature for a tree line. Tree lines are quite prevalent in the New England region and function as a longitudinal hazard, but are not designed to redirect the vehicle such as a crash-tested barrier should.

This example problem has clear zones which are defined by tree lines. The hazard has been modeled as a linear hazard, similar to W Beam, not a point hazard like a single tree. This means that every time a vehicle leaves the road and the hazard is within the vehicle swatch and the lateral extent of encroachment, the vehicle will impact the hazard. It is more likely that the vehicle would hit the tree line hazard a certain percentage of the time and other times get wedged between the trees or even pass between trees and brush without a collision. Additional research is needed in this area to properly identify the severity of tree line crashes and the probability of

impacting the hazard given the density of trees, however, this modeling technique can be used in the interim. In order to determine the crash severity of the tree line at the back of the clear zone, an SI was calibrated using the 2005 crash data.

A review of the 2005 crash data revealed four injury crashes and one fatal crash within the project limits. These crashes would cost society \$3,320,000 in 2005. Several model runs resulted in a predicted crash existing conditions (Alternative zero) crash cost of \$3,143,637. This prediction was made with an SI equal to 0.097214, which is approximately 72% of the small tree SI. The Alternative zero analysis is presented in Table 7-11.

The calibrated SI was used to predict the crash costs of the other alternatives under consideration. The results for the annual crash costs for each alternative are presented in Tables 7-12 through 7-15. Recall these predicted crash costs should be compared with the existing conditions (Alternative zero).

Table 7-11. Alternative Zero: Modeling of Crash Costs.

Seg #	Start STA	End STA	ADT	Horiz. Curvature (°)	Vertical Grade (%)	# In Prim Dir	# In Opp Dir	Lane Width (ft)	D (%) - Primary Direction	Enc. per year	ROR crashes modeled	Annual Crash Cost
1	369+09	374+48	7000	0	2.4	1	1	12	0.5	0.3996	0.456738	\$20,591
2	374+48	379+66	7000	20.1194	4.79	1	1	12	0.5	4.845	5.537682	\$130,935
3	379+66	382+60	7000	0	10	1	1	12	0.5	0.3183	0.363829	\$15,762
4	382+60	388+80	7000	25.78	4.58	1	1	12	0.5	11.309	12.92566	\$535,745
5	388+80	398+33	7000	0	10	1	1	12	0.5	1.0335	0.303922	\$50,785
6	398+33	401+88	7000	15.4927	2	1	1	12	0.5	1.6555	0.486841	\$79,744
7	401+88	412+54	7000	0	4.13	1	1	12	0.5	0.8624	0.253612	\$42,860
8	412+54	417+34	7000	36.3511	7.78	1	1	12	0.5	36.516	10.73827	\$1,797,502
9	417+34	418+79	7000	36.3511	5.86	1	1	12	0.5	10.026	2.320199	\$451,610
10	418+78	422+82	7000	0	8.44	1	1	12	0.5	0.4052	0.093781	\$18,102
											Total	\$3,143,637

Table 7-12. Alternative One: Analysis of Crash Costs.

Seg #	Start STA	End STA	ADT	Horiz. Curvature (°)	Vertical Grade (%)	# In Prim Dir	# In Opp Dir	Lane Width (ft)	D (%) - Primary Direction	Enc. per year	ROR crashes modeled	Annual Crash Cost
1	369+09	374+48	7000	0	5.31	1	1	12	0.5	0.4623	0.077737	\$23,813
2	374+48	379+66	7000	20.1194	5.31	1	1	12	0.5	4.9684	0.835404	\$20,020
3	379+66	382+60	7000	0	5.31	1	1	12	0.5	0.2522	0.042402	\$11,906
4	382+60	388+80	7000	25.78	5.31	1	1	12	0.5	11.73	1.972252	\$569,620
5	388+80	398+33	7000	0	5.31	1	1	12	0.5	0.8174	0.137445	\$41,423
6	398+33	401+88	7000	15.4927	4.6	1	1	12	0.5	1.8862	0.317143	\$85,577
7	401+88	412+54	7000	0	4.6	1	1	12	0.5	0.8825	0.148381	\$38,521
8	412+54	418+79	7000	36.3511	2.89	1	1	12	0.5	37.251	6.263508	\$1,767,754
9	418+79	422+83	7000	0	2.89	1	1	12	0.5	0.307	0.051626	\$14,285
10	+	+	0	0	0	0	0	0	0	0	0	\$0
											Total	\$2,572,917

Table 7-13. Alternative Two: Analysis of Crash Costs.

Seg #	Start STA	End STA	ADT	Horiz. Curvature (°)	Vertical Grade (%)	# In Prim Dir	# In Opp Dir	Lane Width (ft)	D (%) - Primary Direction	Enc. per year	ROR crashes modeled	Annual Crash Cost
1	369+09	374+48	7000	0	2.4	1	1	12	0.5	0.3996	0.207176	\$9,340
2	374+48	379+66	7000	20.1194	4.79	1	1	12	0.5	4.845	2.511893	\$59,392
3	379+66	382+60	7000	0	10	1	1	12	0.5	0.3183	0.165033	\$7,149
4	382+60	388+80	7000	25.78	4.58	1	1	12	0.5	11.309	5.863079	\$243,013
5	388+80	398+33	7000	0	10	1	1	12	0.5	1.0335	0.137859	\$23,036
6	398+33	401+88	7000	15.4927	2	1	1	12	0.5	1.6555	0.220831	\$36,171
7	401+88	412+54	7000	0	4.13	1	1	12	0.5	0.8624	0.115038	\$19,441
8	412+54	417+34	7000	36.3511	7.78	1	1	12	0.5	36.516	4.870879	\$815,346
9	417+34	418+79	7000	36.3511	5.86	1	1	12	0.5	10.026	1.052442	\$204,850
10	418+78	422+82	7000	0	8.44	1	1	12	0.5	0.4052	0.042539	\$8,211
											Total	\$1,425,953

Table 7-14. Alternative Three: Analysis of Crash Costs.

Seg #	Start STA	End STA	ADT	Horiz. Curvature (°)	Vertical Grade (%)	# In Prim Dir	# In Opp Dir	Lane Width (ft)	D (%) - Primary Direction	Enc. per year	ROR crashes modeled	Annual Crash Cost
1	369+09	374+48	7000	0	2.4	1	1	12	0.5	0.3996	0.116019	\$5,230
2	374+48	379+66	7000	20.1194	4.79	1	1	12	0.5	4.845	1.40666	\$33,259
3	379+66	382+60	7000	0	10	1	1	12	0.5	0.3183	0.092418	\$4,003
4	382+60	388+80	7000	25.78	4.58	1	1	12	0.5	11.309	3.283324	\$136,087
5	388+80	398+33	7000	0	10	1	1	12	0.5	1.0335	0.077201	\$12,900
6	398+33	401+88	7000	15.4927	2	1	1	12	0.5	1.6555	0.123665	\$20,256
7	401+88	412+54	7000	0	4.13	1	1	12	0.5	0.8624	0.064422	\$10,887
8	412+54	417+34	7000	36.3511	7.78	1	1	12	0.5	36.516	2.727692	\$456,594
9	417+34	418+79	7000	36.3511	5.86	1	1	12	0.5	10.026	0.589368	\$114,716
10	418+78	422+82	7000	0	8.44	1	1	12	0.5	0.4052	0.023822	\$4,598
											Total	\$798,534

Table 7-15. Alternative Four: Analysis of Crash Costs.

Seg #	Start STA	End STA	ADT	Horiz. Curvature (°)	Vertical Grade (%)	# In Prim Dir	# In Opp Dir	Lane Width (ft)	D (%) - Primary Direction	Enc. per year	ROR crashes modeled	Annual Crash Cost
1	369+09	374+48	7000	0	2.4	1	1	12	0.5	0.3996	0.093975	\$4,237
2	374+48	379+66	7000	20.1194	4.79	1	1	12	0.5	4.845	1.139394	\$26,940
3	379+66	382+60	7000	0	10	1	1	12	0.5	0.3183	0.074859	\$3,243
4	382+60	388+80	7000	25.78	4.58	1	1	12	0.5	11.309	2.659493	\$110,231
5	388+80	398+33	7000	0	10	1	1	12	0.5	1.0335	0.062533	\$10,449
6	398+33	401+88	7000	15.4927	2	1	1	12	0.5	1.6555	0.100169	\$16,408
7	401+88	412+54	7000	0	4.13	1	1	12	0.5	0.8624	0.052181	\$8,819
8	412+54	417+34	7000	36.3511	7.78	1	1	12	0.5	36.516	2.209431	\$369,841
9	417+34	418+79	7000	36.3511	5.86	1	1	12	0.5	10.026	0.477388	\$92,920
10	418+78	422+82	7000	0	8.44	1	1	12	0.5	0.4052	0.019296	\$3,725
											Total	\$646,812

The estimated construction costs of each alternative are presented in figure 7-13. The Green Book suggests that Rural Collects have a 20 year design life. Some highway agencies may program an improvement project based on the available construction funding. Using this mentality, Alternative three would be the preferred alternative. Recall this alternative would increase the clear zone to the prescribed twenty-eight feet and resurface the road. Some highway agencies will only consider the alternative which meets all design warrants, therefore alternative one would be the preferred alternative.

Using the process proposed herein, the societal cost of crashes should also be considered in a cost-benefit analysis of alternatives with the costs equal to the construction investment and the benefits equal to the reduction in crash costs. The present worth crash costs are shown in figure 7-14, considering a 4% discount rate and a 20 year design life. A cost-benefit analysis of each alternative compared with the existing conditions (alternative zero) is presented in Table 7-16. The alternative with the highest cost-benefit ratio should be the preferred alternative. Alternative three, increasing the clear zones while resurfacing the roadway appears to be the most cost-beneficial alternative and should proceed to final design and construction. This analysis assumes the country drainage remains. If room is not available within the existing ROW, one may consider alternative four which maintains the clear zone while flattening the ditches.

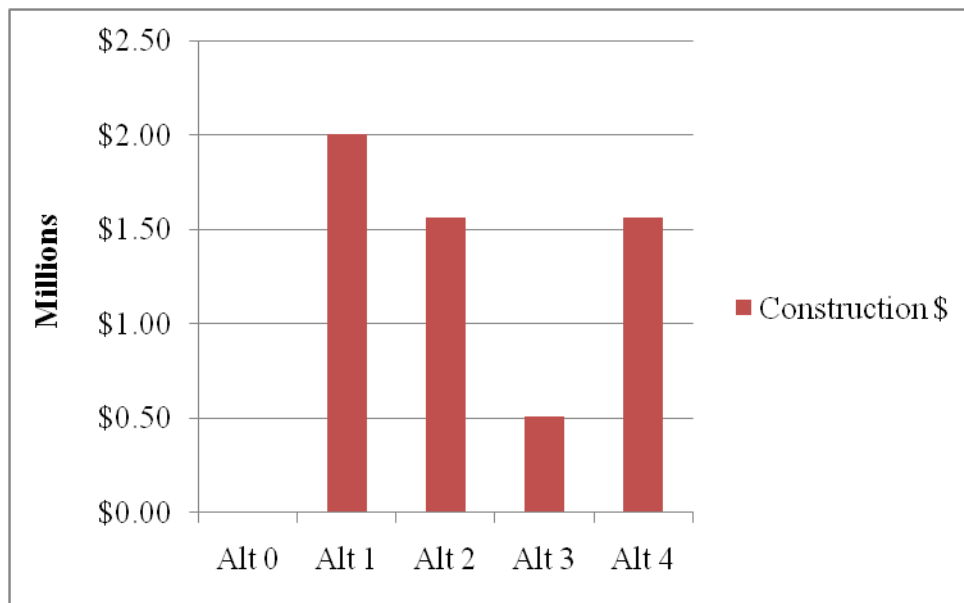


Figure 7-13. Projected Construction Costs for Each Alternative.

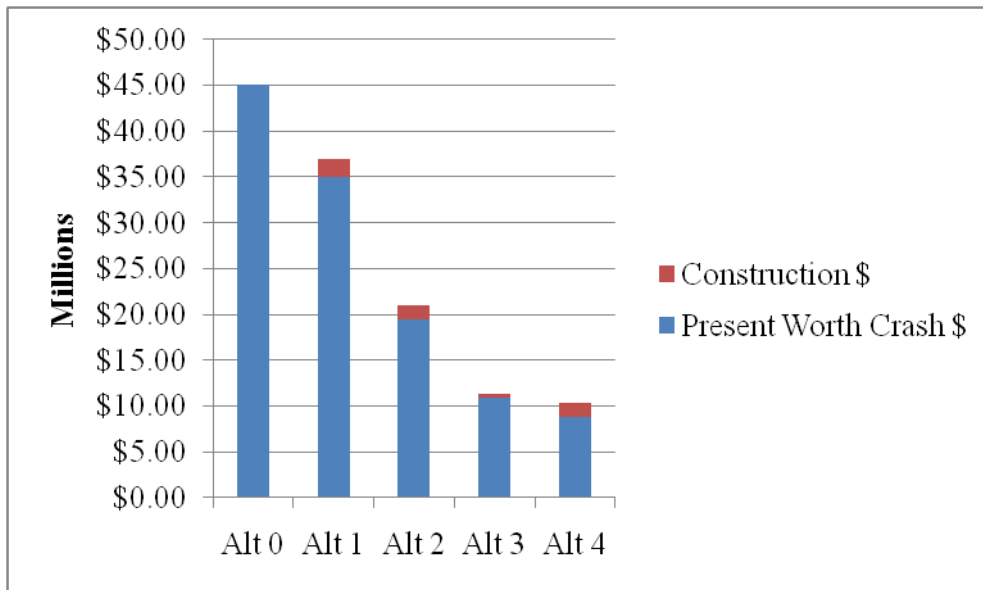


Figure 7-14. Present Worth Crash Costs and Construction Costs for Each Alternative.

Table 7-16. Cost-Benefit Analysis of Alternatives.

	Annual Crash Cost	Present Worth Crash \$	Const.Cost	B/C to Alt 0
Alt 0	\$3,320,000	\$45,118,800	\$0	
Alt 1	\$2,572,919	\$34,965,969	\$2,006,200	0.37
Alt 2	\$1,425,953	\$19,378,701	\$1,566,200	1.21
Alt 3	\$798,534	\$10,852,077	\$506,200	4.98
Alt 4	\$646,812	\$8,790,175	\$1,566,200	1.71

Final Design and Construction

A more detailed analysis of the preferred alternative is needed within problem segments to try to reduce encroachment rates. This can be accomplished through minor changes to the alignments and cross-section as well as the tools previously discussed. This effort should be focused on only the problem segments to limit increases in expected funding needs.

Following the completion of the analysis of a preferred design alternative, the project will then proceed to final design and documentation, bidding and construction.

Summary

Motor vehicle crashes claim approximately 41,000 lives each year. Roughly 37 percent of these fatal crashes are with fixed objects along the roadside.¹⁷² An obvious solution for improving roadside safety would be to remove or shield all fixed objects along the roadside. This would certainly decrease the number of fatal and serious injury crashes but could result in the removal

of many roadside trees and the installation of hundreds of miles of roadside barrier to shield items such as utility poles, leaving an unacceptable aesthetic environment to road users and costing millions of dollars. Removing trees entirely or installing hundreds of miles of roadside barrier, therefore, is not a viable option. A better approach is to understand the highway geometrics that make some roadside objects more potentially harmful than others and to develop strategies for identifying these most hazardous objects. The process demonstrated herein helps to identify problem segments which need additional attention and elevate needless spending on the overdesign of whole highways.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

The warrants and guidelines used during a typical highway design were established based on physics and “engineering judgment.” This extensive body of knowledge is long-established and rooted in the design community and is the basis of every design. Only minor updates have been made over time as, for example, when the vehicle fleet changed. A design practice, which is relatively similar throughout the nation, has emerged to meet legal concerns and business needs of highway owners, designers and builders. This current process, however, has not been revisited or reviewed to ensure the engineering community is accomplishing the intended goals of improving highway safety and avoiding unnecessary spending. The pending publication of the Highway Safety Manual (HSM) provides new information which should be incorporated into the process. The time has come for the review of existing practice and establishment of a formal though flexible process in light of new safety publications and evolving practice.

The design process and accompanying software presented in this report builds on the existing flexibility in the design process, incorporating synthesis and analysis phases which will improve the designer’s and decision maker’s understanding of the consequences (i.e., construction cost, capacity, highway safety, etc.) of design decisions.

The process and software contained herein are not intended to replace existing design manuals or engineering judgment, rather supplement the existing body of knowledge to allow for quantitative analysis of any proposed improvements, moving highway engineering from a prescriptive process to a performance-based process.

Performance-based design was demonstrated and discussed using highway safety as the measurable outcome. The existing highway design process lacks the proposed Synthesis and Analysis phases, which are essential to accomplishing performance-based design. Currently, highways are designed and built without knowledge of the degree to which the financial investment will solve the identified problem. The proposed process provides a means to assess highway improvement projects against the identified need.

The synthesis phase ensures the highway elements are designed in a coordinated fashion, rather than in isolation. The analysis phase provides engineers with the ability to assess the likely performance of alternatives systematically against each other at the design level, which has never been provided before.

Design efforts will be focused on demonstrating performance outcomes such as improving highway safety and reducing highway related fatalities rather than meeting design policies and warrants and assuming without proof that the objectives will be met. This process capitalizes on existing workflow and tools for increased receivership among highway designers and can be expanded to include a full array of performance-based highway engineering including highway capacity. Implementation will lead to an improved understanding of the impacts to safety and other outcomes caused by relaxing design standards to accommodate existing ROW, environmental constraints, and other items traditionally viewed as constraints. This improved understanding will lead to more informed decision making.

This process will reduce redundant workload for reviewing agencies and design engineers while coordinating efforts throughout different regions. Efforts will be focused on performance outcomes such as improving highway safety and reducing highway related fatalities rather than policies and warrants.

The software created for this research combined models from published literature to relate the severity of crashes with specific hazards to the speed of impact. Some additional research needs have been identified over the course of this research and should be considered for future study. Specifically, additional research is needed to properly identify the severity of tree line crashes and the safety impacts of improved delineation and rumble strips in rural areas.

It is recommended that future research of performance-based highway design include several case studies by DOTs which document the time invested in design as well as the time invested in similar projects designed using the traditional process. It is further recommended that researchers more familiar with performance outcomes other than safety, possibility highway capacity, consider the process presented and how these outcomes may be incorporated in this proposed process prior to implementation. The goal is to have one new process which can accommodate all performance outcomes.

Every effort should be made to improve the coordination between software vendors, transportation research engineers and Departments of Transportations to move efforts forward on improving highway safety and other outcomes at the geometric design stage. These coordination efforts should embrace the different software options and work to create a “plug in” to various commercial highway design suites to allow for performance analysis during design. For many years the highway engineering community has tried to move toward a performance-based process. This type of process is data and calculation intense and will require a corporative approach from all areas of highway engineering for successful implementation. These efforts will be rewarded over time with improvements in highway safety and the reduction in needless spending. A long-term implementation plan is necessary and should be evaluated.

REFERENCES

- ¹ “A Policy on Geometric Design of Highways and Streets”, 4th edition”, American Association of State Highway and Transportation Officials (AASHTO), Washington D.C., 2001.
- ² “AASHTO Roadside Design Guide, 3rd edition”, American Association of State Highway and Transportation Officials (AASHTO), Washington D.C., 2006
- ³ “A Policy on Geometric Design of Highways and Streets”, 4th edition”, American Association of State Highway and Transportation Officials (AASHTO), Washington D.C., 2001.
- ⁴ FHWA Safety, http://safety.fhwa.dot.gov/state_program/hsip/hsip_over.htm, April 17, 2008
- ⁵ FHWA Safety, <http://safety.fhwa.dot.gov/facts/index.htm>, April 17, 2008
- ⁶ Garber, N.J., Hoel, L.A., “Traffic and Highway Engineering, Fourth Edition,” Cengage learning, Toronto, ON, 2009.
- ⁷ “A Policy on Geometric Design of Highways and Streets”, 4th edition”, American Association of State Highway and Transportation Officials (AASHTO), Washington D.C., 2001.
- ⁸ *Roadside Design Guide*, 3rd edition with 2006 Chapter 6 Update, American Association of State Highway & Transportation Officials, Washington, DC.
- ⁹ *Manual on Uniform Traffic Control Devices*, 2003, U.S. Department of Transportation—Federal Highway Administration, Washington, DC.
- ¹⁰ *Highway Capacity Manual (HCM 2000)*, 2000 edition, Transportation Research Board—National Research Council, Washington, DC.
- ¹¹ “User Benefit Analysis for Highways Manual,” American Association of State Highway and Transportation Officials (AASHTO), Washington D.C., 2003, page 2-8.
- ¹² “User Benefit Analysis for Highways Manual,” American Association of State Highway and Transportation Officials (AASHTO), Washington D.C., 2003.
- ¹³ Task Force for Roadside Safety, “Roadside Design Guide, 3rd edition”, American Association of State Highway and Transportation Officials, Washington D.C., 2006
- ¹⁴ Letter to US Senate Subcommittee on Financial Management Budget and Committee on Governmental Affairs, November 3, 2003
- ¹⁵ Letter to US Senate Subcommittee on Financial Management Budget and Committee on Governmental Affairs, November 3, 2003
- ¹⁶ http://www.wsdot.wa.gov/biz/Construction/pdf/I-C_Const_Cost.pdf, accessed September 11, 2009

-
- ¹⁷ http://www.wsdot.wa.gov/biz/Construction/pdf/I-C_Const_Cost.pdf, accessed September 11, 2009
- ¹⁸ http://www.wsdot.wa.gov/biz/Construction/pdf/I-C_Const_Cost.pdf, accessed September 11, 2009
- ¹⁹ http://www.wsdot.wa.gov/biz/Construction/pdf/I-C_Const_Cost.pdf, accessed September 11, 2009
- ²⁰ “User Benefit Analysis for Highways Manual,” American Association of State Highway and Transportation Officials (AASHTO), Washington D.C., 2003, page 3-11.
- ²¹ “User Benefit Analysis for Highways Manual,” American Association of State Highway and Transportation Officials (AASHTO), Washington D.C., 2003, page 2-13.
- ²² <http://www.fhwa.dot.gov/legregs/directives/techadvs/t75702.htm>, accessed August 23, 2009
- ²³ <http://www.fhwa.dot.gov/legregs/directives/techadvs/t75702.htm>, accessed August 23, 2009
- ²⁴ <http://www.fhwa.dot.gov/legregs/directives/techadvs/t75702.htm>, accessed August 23, 2009
- ²⁵ Meyer, M.D., “Crashes vs. Congestion-What’s the Cost to Society?,” Cambridge Systematics, Inc., 4800 Hampden Lane, Suite 800, Bethesda, Maryland 20814, March 5, 2008
- ²⁶ Meyer, M.D., “Crashes vs. Congestion-What’s the Cost to Society?,” Cambridge Systematics, Inc., 4800 Hampden Lane, Suite 800, Bethesda, Maryland 20814, March 5, 2008
- ²⁷ Meyer, M.D., “Crashes vs. Congestion-What’s the Cost to Society?,” Cambridge Systematics, Inc., 4800 Hampden Lane, Suite 800, Bethesda, Maryland 20814, March 5, 2008
- ²⁸ Blincoe, L., Seay, A., Zaloshnja, E., Miller, T., Romano, E., Luchter, S., Spicer R., “The Economic Impact of Motor Vehicle Crashes, 2000,” Report No. DOT HS 809 446, online version, <http://www-nrd.nhtsa.dot.gov/Pubs/809446.PDF>, accessed November 1, 2009
- ²⁹ Blincoe, L., Seay, A., Zaloshnja, E., Miller, T., Romano, E., Luchter, S., Spicer R., “The Economic Impact of Motor Vehicle Crashes, 2000,” Report No. DOT HS 809 446, online version, <http://www-nrd.nhtsa.dot.gov/Pubs/809446.PDF>, accessed November 1, 2009
- ³⁰ Blincoe, L., Seay, A., Zaloshnja, E., Miller, T., Romano, E., Luchter, S., Spicer R., “The Economic Impact of Motor Vehicle Crashes, 2000,” Report No. DOT HS 809 446, online version, <http://www-nrd.nhtsa.dot.gov/Pubs/809446.PDF>, accessed November 1, 2009
- ³¹ Blincoe, L., Seay, A., Zaloshnja, E., Miller, T., Romano, E., Luchter, S., Spicer R., “The Economic Impact of Motor Vehicle Crashes, 2000,” Report No. DOT HS 809 446, online version, <http://www-nrd.nhtsa.dot.gov/Pubs/809446.PDF>, accessed November 1, 2009

-
- ³² Blincoe, L., Seay, A., Zaloshnja, E., Miller, T., Romano, E., Luchter, S., Spicer R., "The Economic Impact of Motor Vehicle Crashes, 2000," Report No. DOT HS 809 446, online version, <http://www-nrd.nhtsa.dot.gov/Pubs/809446.PDF>, accessed November 1, 2009
- ³³ American Association of State Highway and Transportation Officials, " The Draft Highway Safety Manual," Washington, D.C., current as of April 6, 2009.
- ³⁴ John W. Hutchinson, "The significance and nature of vehicle encroachments on medians of divided highways," Highway Engineering Series Report No. 8, University of Illinois, December 1962.
- ³⁵ Cooper, P., Analysis of Roadside Encroachments--Single Vehicle Run-Off-Road Accident Data Analysis for Five Provinces, Interim Report, B.C. Research Council, Vancouver, British Columbia, Canada., 1980
- ³⁶ John W. Hutchinson, "The significance and nature of vehicle encroachments on medians of divided highways," Highway Engineering Series Report No. 8, University of Illinois, December 1962.
- ³⁷ John W. Hutchinson, "The significance and nature of vehicle encroachments on medians of divided highways," Highway Engineering Series Report No. 8, University of Illinois, December 1962.
- ³⁸ John W. Hutchinson, "The significance and nature of vehicle encroachments on medians of divided highways," Highway Engineering Series Report No. 8, University of Illinois, December 1962.
- ³⁹ Cooper, P., Analysis of Roadside Encroachments--Single Vehicle Run-Off-Road Accident Data Analysis for Five Provinces, Interim Report, B.C. Research Council, Vancouver, British Columbia, Canada., 1980
- ⁴⁰ Cooper, P., Analysis of Roadside Encroachments--Single Vehicle Run-Off-Road Accident Data Analysis for Five Provinces, Interim Report, B.C. Research Council, Vancouver, British Columbia, Canada., 1980
- ⁴¹ McGinnis, R.G., "Reexamination of Roadside Encroachment Data," *Transportation Research Record* 1690, Transportation Research Board, National Research Council, pp. 42-58, 1999.
- ⁴² McGinnis, R.G., "Reexamination of Roadside Encroachment Data," *Transportation Research Record* 1690, Transportation Research Board, National Research Council, pp. 42-58, 1999.
- ⁴³ Miaou, Shaw-Pin "Estimating Roadside Encroachment Rates with the Combined Strengths of Accident and Encroachment-Based Approaches," FHWA-RD-01-124, September 2001.
- ⁴⁴ Miaou, Shaw-Pin "Estimating Roadside Encroachment Rates with the Combined Strengths of Accident and Encroachment-Based Approaches," FHWA-RD-01-124, September 2001.

-
- ⁴⁵ Washington, S.P., Mannering, F.L., Karlaftis, M.G., “Statistical and Econometric Methods for Transportation Data Analysis,” Chapman&Hall, 2003.
- ⁴⁶ Washington, S.P., Mannering, F.L., Karlaftis, M.G., “Statistical and Econometric Methods for Transportation Data Analysis,” Chapman&Hall, 2003.
- ⁴⁷ Washington, S.P., Mannering, F.L., Karlaftis, M.G., “Statistical and Econometric Methods for Transportation Data Analysis,” Chapman&Hall, 2003.
- ⁴⁸ Miaou, Shaw-Pin “Estimating Roadside Encroachment Rates with the Combined Strengths of Accident and Encroachment-Based Approaches,” FHWA-RD-01-124, September 2001.
- ⁴⁹ DefineThat, <http://www.definethat.com/define/113.htm>, January 9, 2008
- ⁵⁰ Wekopedia, <http://www.webopedia.com/TERM/C/CAD.html>, January 9, 2008
- ⁵¹ Civil 3D08 <http://usa.autodesk.com/adsk/servlet/index?siteID=123112&id=8777353>
- ⁵² InRoads, <http://www.bentley.com/en-US/Products/InRoads/Tech+Reqs.htm>, May 3, 2008
- ⁵³ Cadalyst, <http://aec.cadalyst.com/aec/News/Bentley-and-Autodesk-Join-Hands-to-Bridge-DGN-and-/ArticleStandard/Article/detail/529085>, Accessed July 11, 2008
- ⁵⁴ LandXML, Online <http://www.landxml.org/>, Accessed June, 2008
- ⁵⁵ LandXML, <http://www.landxml.org/>
- ⁵⁶ K.K. Max, and D.L. Sicking, “Roadside Safety Analysis Program (RSAP)-Engineer’s Manual”, *National Cooperative Highway Research Program Report 492*, Transportation Research Board, Washington, DC 2003.
- ⁵⁷ Task Force for Roadside Safety, “Roadside Design Guide,” American Association of State Highway and Transportation Officials, Washington, D.C., 1988.
- ⁵⁸ John C. Glennon, “Roadside Safety Improvement Programs on Freeways,” National Cooperative Highway Research Program Report 148, Highway Research Board, Washington, D.C., 1974.
- ⁵⁹ Mak, K.K. and Sicking, D.L., “Roadside Safety Analysis Program (RSAP)—Engineer’s Manual,” National Cooperative Highway Research Program Report No. 492, Transportation Research Board, Washington, D.C., 2003.
- ⁶⁰ Task Force for Roadside Safety, “Roadside Design Guide,” American Association of State Highway and Transportation Officials, Washington, D.C., 2002.

⁶¹ IHSDM Overview, FHWA, [online] <http://www.tfrc.gov/safety/ihsdm/ihsdm.htm>, Accessed April 17, 2008

⁶² American Association of State Highway and Transportation Officials, " The Draft Highway Safety Manual," Washington, D.C., current as of April 6, 2009.

⁶³ American Association of State Highway and Transportation Officials, " The Draft Highway Safety Manual," Washington, D.C., current as of April 6, 2009.

⁶⁴ Zegeer, C.V., R. C. Deen, and J.G. Mayes. Effect of Lane and Shoulder Width of Accident Reduction on Rural, Two-Lane Roads. In Transportation Research Record 806. TRB, National Research Board, 1981.

⁶⁵ American Association of State Highway and Transportation Officials, " The Draft Highway Safety Manual," Washington, D.C., current as of April 6, 2009.

⁶⁶ Interactive Highway Safety Design Module, Crash Prediction Module Beta Version 5.3.0 (Jun 30, 2009)

⁶⁷ Harwood00 Harwood, D.W., Council, F.M., Hauer, E., Hughes, W.E., Vogt, A., "Prediction of the Expected Safety Performance of Rural Two-Lane Highways," Publication No. Fhwa-Rd-99-207, online version <http://www.tfrc.gov/safety/pubs/99207/appd.htm>, December 2000, accessed August 23, 2009

⁶⁸ SafetyAnalyst, <http://www.safetyanalyst.org/>, May 3, 2008

⁶⁹ SafetyAnalyst, <http://www.safetyanalyst.org/>, May 3, 2008

⁷⁰ SafetyAnalyst, <http://www.safetyanalyst.org/>, May 3, 2008

⁷¹ SafetyAnalyst, <http://www.safetyanalyst.org/>, May 3, 2008

⁷² SafetyAnalyst, <http://www.safetyanalyst.org/>, May 3, 2008

⁷³ S. Washington, I. Van Schalkwyk, S. Mitra, M. Meyer, E. Dumbaugh, M. Zoll, "Incorporating Safety Into Long-Range Transportation Planning", *National Cooperative Highway Research Program Report 492*, Transportation Research Board, Washington, DC 2006.

⁷⁴ S. Washington, I. Van Schalkwyk, S. Mitra, M. Meyer, E. Dumbaugh, M. Zoll, "Incorporating Safety Into Long-Range Transportation Planning", *National Cooperative Highway Research Program Report 492*, Transportation Research Board, Washington, DC 2006.

⁷⁵ S. Washington, I. Van Schalkwyk, S. Mitra, M. Meyer, E. Dumbaugh, M. Zoll, "Incorporating Safety Into Long-Range Transportation Planning", *National Cooperative Highway Research Program Report 492*, Transportation Research Board, Washington, DC 2006.

⁷⁶ S. Washington, I. Van Schalkwyk, S. Mitra, M. Meyer, E. Dumbaugh, M. Zoll, “Incorporating Safety Into Long-Range Transportation Planning”, *National Cooperative Highway Research Program Report 492*, Transportation Research Board, Washington, DC 2006.

⁷⁷ Ray, M.H., “Quantifying the Safeness of Highway Designs,” PhD Dissertation, Vanderbilt University, May, 1993

⁷⁸ Ray, M.H., “Quantifying the Safeness of Highway Designs,” PhD Dissertation, Vanderbilt University, May, 1993

⁷⁹ Gaddis, T., Irvine, K., *Starting Out with Visual Basic 2008*, Fourth Edition, Pearson, Addison-Wesley, Boston, MA, 2009.

⁸⁰ Gaddis, T., Irvine, K., *Starting Out with Visual Basic 2008*, Fourth Edition, Pearson, Addison-Wesley, Boston, MA, 2009.

⁸¹ Cadalyst, <http://aec.cadalyst.com/aec/News/Bentley-and-Autodesk-Join-Hands-to-Bridge-DGN-and-/ArticleStandard/Article/detail/529085>, Accessed July 11, 2008

⁸² <http://www.landxml.org/>

⁸³ “A Policy on Geometric Design of Highways and Streets”, 4th edition”, American Association of State Highway and Transportation Officials (AASHTO), Washington D.C., 2001.

⁸⁴ *Roadside Design Guide*, 3rd edition with 2006 Chapter 6 Update, American Association of State Highway & Transportation Officials, Washington, DC.

⁸⁵ *Manual on Uniform Traffic Control Devices*, 2003, U.S. Department of Transportation—Federal Highway Administration, Washington, DC.

⁸⁶ *Highway Capacity Manual (HCM 2000)*, 2000 edition, Transportation Research Board—National Research Council, Washington, DC.

⁸⁷ "The Draft Highway Safety Manual," American Association of State Highway and Transportation Officials, Washington, D.C., current as of April 6, 2009.

⁸⁸ “A Policy on Geometric Design of Highways and Streets”, 5th edition”, American Association of State Highway and Transportation Officials (AASHTO), Washington D.C., 2001, page 13.

⁸⁹ Conron, C.E., Silvestri, C., Gagne, A., Ray, M.H., *Using Public Information and Graphics Software in Graduate Highway Safety Research at Worcester Polytechnic Institute*, American Society for Engineering Education, Engineering Design Graphics Division, 63rd Annual Midyear Meeting Conference Proceedings, January 2009

⁹⁰ Google Earth, [Online]. Retrieved October 14, 2008 from <http://earth.google.com/>.

⁹¹ Conron, C.E., Silvestri, C., Gagne, A., Ray, M.H., *Using Public Information and Graphics Software in Graduate Highway Safety Research at Worcester Polytechnic Institute*, American Society for Engineering Education, Engineering Design Graphics Division, 63rd Annual Midyear Meeting Conference Proceedings, January 2009

⁹² “A Policy on Geometric Design of Highways and Streets”, 5th edition”, American Association of State Highway and Transportation Officials (AASHTO), Washington D.C., 2001, page 58.

⁹³ Transportation Research Board. Highway Capacity Manual, Special Report 209, Washington, D.C., transportation Research Board, 2000.

⁹⁴ “A Policy on Geometric Design of Highways and Streets”, 5th edition”, American Association of State Highway and Transportation Officials (AASHTO), Washington D.C., 2001, page 58.

⁹⁵ “A Policy on Geometric Design of Highways and Streets”, 5th edition”, American Association of State Highway and Transportation Officials (AASHTO), Washington D.C., 2001, page 58.

⁹⁶ “A Policy on Geometric Design of Highways and Streets”, 5th edition”, American Association of State Highway and Transportation Officials (AASHTO), Washington D.C., 2001, page 64.

⁹⁷ “A Policy on Geometric Design of Highways and Streets”, 5th edition”, American Association of State Highway and Transportation Officials (AASHTO), Washington D.C., 2001, page 65.

⁹⁸ “A Policy on Geometric Design of Highways and Streets”, 5th edition”, American Association of State Highway and Transportation Officials (AASHTO), Washington D.C., 2001.

⁹⁹ “A Policy on Geometric Design of Highways and Streets”, 5th edition”, American Association of State Highway and Transportation Officials (AASHTO), Washington D.C., 2001.

¹⁰⁰ “A Policy on Geometric Design of Highways and Streets”, 5th edition”, American Association of State Highway and Transportation Officials (AASHTO), Washington D.C., 2001, page 8.

¹⁰¹ “A Policy on Geometric Design of Highways and Streets”, 5th edition”, American Association of State Highway and Transportation Officials (AASHTO), Washington D.C., 2001, page 67.

¹⁰² “A Policy on Geometric Design of Highways and Streets”, 5th edition”, American Association of State Highway and Transportation Officials (AASHTO), Washington D.C., 2001, page 67.

¹⁰³ “A Policy on Geometric Design of Highways and Streets”, 5th edition”, American Association of State Highway and Transportation Officials (AASHTO), Washington D.C., 2001.

¹⁰⁴ “A Policy on Geometric Design of Highways and Streets”, 5th edition”, American Association of State Highway and Transportation Officials (AASHTO), Washington D.C., 2001, page 53.

¹⁰⁵ “A Policy on Geometric Design of Highways and Streets”, 5th edition”, American Association of State Highway and Transportation Officials (AASHTO), Washington D.C., 2001.

¹⁰⁶ “A Policy on Geometric Design of Highways and Streets”, 5th edition”, American Association of State Highway and Transportation Officials (AASHTO), Washington D.C., 2001.

¹⁰⁷ “A Policy on Geometric Design of Highways and Streets”, 5th edition”, American Association of State Highway and Transportation Officials (AASHTO), Washington D.C., 2001.

¹⁰⁸ “A Policy on Geometric Design of Highways and Streets”, 5th edition”, American Association of State Highway and Transportation Officials (AASHTO), Washington D.C., 2001.

¹⁰⁹ “A Policy on Geometric Design of Highways and Streets”, 5th edition”, American Association of State Highway and Transportation Officials (AASHTO), Washington D.C., 2001.

¹¹⁰ “A Policy on Geometric Design of Highways and Streets”, 5th edition”, American Association of State Highway and Transportation Officials (AASHTO), Washington D.C., 2001.

¹¹¹ “A Policy on Geometric Design of Highways and Streets”, 5th edition”, American Association of State Highway and Transportation Officials (AASHTO), Washington D.C., 2001.

¹¹² “A Policy on Geometric Design of Highways and Streets”, 5th edition”, American Association of State Highway and Transportation Officials (AASHTO), Washington D.C., 2001.

¹¹³ “A Policy on Geometric Design of Highways and Streets”, 5th edition”, American Association of State Highway and Transportation Officials (AASHTO), Washington D.C., 2001.

¹¹⁴ Transportation Research Board. Highway Capacity Manual, Special Report 209, Washington, D.C., transportation Research Board, 2000.

¹¹⁵ “A Policy on Geometric Design of Highways and Streets”, 5th edition”, American Association of State Highway and Transportation Officials (AASHTO), Washington D.C., 2001.

¹¹⁶ “A Policy on Geometric Design of Highways and Streets”, 5th edition”, American Association of State Highway and Transportation Officials (AASHTO), Washington D.C., 2001, page 311.

¹¹⁷ American Association of State Highway and Transportation Officials, " The Draft Highway Safety Manual," Washington, D.C., current as of April 6, 2009.

¹¹⁸ *Roadside Design Guide*, 3rd edition with 2006 Chapter 6 Update, American Association of State Highway & Transportation Officials, Washington, DC.

¹¹⁹ “A Policy on Geometric Design of Highways and Streets”, 5th edition”, American Association of State Highway and Transportation Officials (AASHTO), Washington D.C., 2001, page 109.

¹²⁰ *Manual on Uniform Traffic Control Devices*, 2003, U.S. Department of Transportation—Federal Highway Administration, Washington, DC.

¹²¹ “A Policy on Geometric Design of Highways and Streets”, 5th edition”, American Association of State Highway and Transportation Officials (AASHTO), Washington D.C., 2001, page 101.

¹²² “A Policy on Geometric Design of Highways and Streets”, 5th edition”, American Association of State Highway and Transportation Officials (AASHTO), Washington D.C., 2001, page 102.

¹²³ Taragin, A., “Effect of Length of Grade on Speed of Motor Vehicles,” Proceedings TRB, Vol. 29, Highway Research Board, 1945: 345-353.

¹²⁴ “A Policy on Geometric Design of Highways and Streets”, 5th edition”, American Association of State Highway and Transportation Officials (AASHTO), Washington D.C., 2001, page 102.

¹²⁵ “A Policy on Geometric Design of Highways and Streets”, 5th edition”, American Association of State Highway and Transportation Officials (AASHTO), Washington D.C., 2001, page 102.

¹²⁶ “A Policy on Geometric Design of Highways and Streets”, 5th edition”, American Association of State Highway and Transportation Officials (AASHTO), Washington D.C., 2001, page 102.

¹²⁷ Schwender, H.C., Normann, O.K., Granum., J.O., “New Method of Capacity Determination for rural Roads in Mountainous Terrain,” Bulletin 167 Highway Research Board, 1957: 10-37.

¹²⁸ “A Policy on Geometric Design of Highways and Streets”, 5th edition”, American Association of State Highway and Transportation Officials (AASHTO), Washington D.C., 2001, page 103.

¹²⁹ “A Policy on Geometric Design of Highways and Streets”, 5th edition”, American Association of State Highway and Transportation Officials (AASHTO), Washington D.C., 2001, page 103.

¹³⁰ American Association of State Highway and Transportation Officials, " The Draft Highway Safety Manual," Washington, D.C., current as of April 6, 2009.

¹³¹ Zegeer, C.V., R. C. Deen, and J.G. Mayes. Effect of Lane and Shoulder Width of Accident Reduction on Rural, Two-Lane Roads. In Transportation Research Record 806. TRB, National Research Board, 1981.

¹³² American Association of State Highway and Transportation Officials, " The Draft Highway Safety Manual," Washington, D.C., current as of April 6, 2009.

¹³³ Conron, C.E., Bergendahl, J.A., *Bringing Graphics and Design to First Year Engineering Students*, American Society for Engineering Education, Engineering Design Graphics Division, 63rd Annual Midyear Meeting Conference Proceedings, January 2009

¹³⁴ Conron, C.E., Bergendahl, J.A., *Bringing Graphics and Design to First Year Engineering Students*, American Society for Engineering Education, Engineering Design Graphics Division, 63rd Annual Midyear Meeting Conference Proceedings, January 2009

¹³⁵ Conron, C.E., Bergendahl, J.A., *Bringing Graphics and Design to First Year Engineering Students*, American Society for Engineering Education, Engineering Design Graphics Division, 63rd Annual Midyear Meeting Conference Proceedings, January 2009

¹³⁶ “A Policy on Geometric Design of Highways and Streets”, 5th edition”, American Association of State Highway and Transportation Officials (AASHTO), Washington D.C., 2001.

¹³⁷ *Roadside Design Guide*, 3rd edition with 2006 Chapter 6 Update, American Association of State Highway & Transportation Officials, Washington, DC.

¹³⁸ Transportation Research Board. Highway Capacity Manual, Special Report 209, Washington, D.C., transportation Research Board, 2000.

¹³⁹ “A Policy on Geometric Design of Highways and Streets”, 5th edition”, American Association of State Highway and Transportation Officials (AASHTO), Washington D.C., 2001.

¹⁴⁰ *Roadside Design Guide*, 3rd edition with 2006 Chapter 6 Update, American Association of State Highway & Transportation Officials, Washington, DC.

¹⁴¹ “A Policy on Geometric Design of Highways and Streets”, 5th edition”, American Association of State Highway and Transportation Officials (AASHTO), Washington D.C., 2001.

¹⁴² Lamm, R., Psarianos, B., Mailaender, T., *Highway Design and Traffic Safety Engineering Handbook*, McGraw-Hill, New York, 1999

¹⁴³ Wooldridge, M.D., Fitzpatrick, K., Harwood, D.W., Potts, I.B., Elefteriadou, L., Toric, D.J., “Geometric Design Consistency on High-Speed Rural Two-Lane Roadways”, *National Cooperative Highway Research Program Report 502*, Transportation Research Board, Washington, DC 2003.

¹⁴⁴ Krammes, R.A., Hayden, C., “Making Two-Lane Roads Safer”, *Public Roads*, US Department of Transportation, Volume 66, No 4, January/February 2003

¹⁴⁵ “A Policy on Geometric Design of Highways and Streets”, 5th edition”, American Association of State Highway and Transportation Officials (AASHTO), Washington D.C., 2001, page 109.

¹⁴⁶ Lamm, R., Psarianos, B., Mailaender, T., *Highway Design and Traffic Safety Engineering Handbook*, McGraw-Hill, New York, 1999

¹⁴⁷ Lamm, R., Psarianos, B., Mailaender, T., *Highway Design and Traffic Safety Engineering Handbook*, McGraw-Hill, New York, 1999

¹⁴⁸ Krammes, R.A., Hayden, C., “Making Two-Lane Roads Safer”, *Public Roads*, US Department of Transportation, Volume 66, No 4, January/February 2003

¹⁴⁹ Roadside Safety Analysis Program, Version 2.0.3

¹⁵⁰ Cooper, P., Analysis of Roadside Encroachments--Single Vehicle Run-Off-Road Accident Data Analysis for Five Provinces, Interim Report, B.C. Research Council, Vancouver, British Columbia, Canada., 1980

¹⁵¹ Miaou, Shaw-Pin “Estimating Roadside Encroachment Rates with the Combined Strengths of Accident and Encroachment-Based Approaches,” FHWA-RD-01-124, September 2001.

¹⁵² American Association of State Highway and Transportation Officials, " The Draft Highway Safety Manual," Washington, D.C., current as of April 6, 2009.

¹⁵³ Task Force for Roadside Safety, “Roadside Design Guide, 3rd edition”, American Association of State Highway and Transportation Officials, Washington D.C., 2006

¹⁵⁴ American Association of State Highway and Transportation Officials, " The Draft Highway Safety Manual," Washington, D.C., current as of April 6, 2009.

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- ¹⁵⁵ Task Force for Roadside Safety, “Roadside Design Guide, 3rd edition”, American Association of State Highway and Transportation Officials, Washington D.C., 2006
- ¹⁵⁶ Roadside Safety Analysis Program, Version 2.0.3
- ¹⁵⁷ Interactive Highway Safety Design Module, Crash Prediction Module Beta Version 5.3.0 (Jun 30, 2009)
- ¹⁵⁸ Task Force for Roadside Safety, “Roadside Design Guide, 3rd edition”, American Association of State Highway and Transportation Officials, Washington D.C., 2006
- ¹⁵⁹ American Association of State Highway and Transportation Officials, " The Draft Highway Safety Manual," Washington, D.C., current as of April 6, 2009, page C-9.
- ¹⁶⁰ Mak, K.K. and Sicking, D.L., “Roadside Safety Analysis Program (RSAP)—Engineer’s Manual,” National Cooperative Highway Research Program
- ¹⁶¹ Roadside Safety Analysis Program, Version 2.0.3
- ¹⁶² Interactive Highway Safety Design Module, Crash Prediction Module Beta Version 5.3.0 (Jun 30, 2009)
- ¹⁶³ Task Force for Roadside Safety, “Roadside Design Guide, 3rd edition”, American Association of State Highway and Transportation Officials, Washington D.C., 2006
- ¹⁶⁴ Task Force for Roadside Safety, “Roadside Design Guide, 3rd edition”, American Association of State Highway and Transportation Officials, Washington D.C., 2006
- ¹⁶⁵ Mak, K.K. and Sicking, D.L., “Roadside Safety Analysis Program (RSAP)—Engineer’s Manual,” National Cooperative Highway Research Program
- ¹⁶⁶ Google Earth, [Online]. Retrieved March 3, 2010 from <http://earth.google.com/>.
- ¹⁶⁷ Google (2008). Google Earth, [Online]. Retrieved October 14, 2008 from <http://earth.google.com/>.
- ¹⁶⁸ Conron, C.E., Silvestri, C., Gagne, A., Ray, M.H., *Using Public Information and Graphics Software in Graduate Highway Safety Research at Worcester Polytechnic Institute*, American Society for Engineering Education, Engineering Design Graphics Division, 63rd Annual Midyear Meeting Conference Proceedings, January 2009
- ¹⁶⁹ “A Policy on Geometric Design of Highways and Streets”, 5th edition”, American Association of State Highway and Transportation Officials (AASHTO), Washington D.C., 2001.

¹⁷⁰ American Association of State Highway and Transportation Officials, " The Draft Highway Safety Manual," Washington, D.C., current as of April 6, 2009.

¹⁷¹ American Association of State Highway and Transportation Officials, " The Draft Highway Safety Manual," Washington, D.C., current as of April 6, 2009.

¹⁷² National Highway Traffic Safety Administration (NHTSA), *Traffic Safety Facts 2007*, DOT HS 811 002, National Center for Statistics and Analysis, USDOT, 2008, Washington, DC 20590.

APPENDIX A

Survey Form

NCHRP Project 22-27

**ROADSIDE SAFETY ANALYSIS
PROGRAM (RSAP) UPDATE**

1. RSAP User Survey

1. Please provide the following OPTIONAL information about yourself.

Name:

Company:

Address:

Address 2:

City/Town:

State:

ZIP/Postal Code:

Country:

Email Address:

Phone Number:

2. What type of work do you do? (check all that apply)

- Roadside design
- Highway design
- Policy work
- Roadside research
- Highway design research
- Other (please specify)
-

3. Which highway design software tools does your company/organization use for design and plan production. (check all that apply)

- None
- AutoCAD Civil 3D
- Autodesk Land Development Desktop
- Bentley GeoPak
- Bentley InRoads
- Other (please specify)
-

4. Please list other software tools you use to assist with design decisions and cost analysis.

5. The Roadside Safety Analysis Program (RSAP) has been developed for risk analysis and cost-benefit analysis of roadside safety and design. It is distributed with the Roadside Design Guide. How frequently do you use RSAP?

- Never
- 1-5 times/year
- 6-10 times/year
- 10-20 times/year
- >20 times/year

2. Used RSAP

1. What have you used RSAP to evaluate? (check all that apply)

Specific project design alternatives.

Policy alternatives.

Other (please specify)

2. Do you like the RSAP user interface?

Yes

No

Suggestions for improvements or comment:

3. Do you like RSAP functionalities?

Yes

No

Suggestions for improvements or comment:

4. Do you find the RSAP default data tables appropriate?

Yes

No

Suggestions for improvements or comment:

5. Do you like the RSAP methodology?

Yes

No

Suggestions for improvements or comment:

6. Do you find the User's Manual helpful?

Yes

No

Suggestions for improvements or comment:

7. Do you find the Engineer's Manual helpful?

Yes

No

Suggestions for improvements or comment:

8. While using RSAP, have you encountered any incidents where your analysis results from RSAP were inconsistent with your experience/expectations/judgement?

9. Are you aware of reports or papers about RSAP documenting its use? Please list them here.

10. What improvements would you like to see made to RSAP?

11. Which features of RSAP would you like to see remain unchanged in the next release?

12. Do you see value in integrating RSAP with popular highway design software tools such as AutoCAD Civil 3D or Bentley InRoads?

Yes

No

Comment:

3. Never used RSAP

1. Do you see a potential use for evaluating the Cost/Benefit of roadside design alternatives using software integrated with your highway design software?

Yes

No

Other (please specify)

2. Do you believe safety, or the potential for crashes should be considered when designing highway improvements?

Yes

No

Other (please specify)

4. Last Page

1. Thank you for your time. If you would like to be a beta tester for the RSAP upgrade, please list your contact information, including your e-mail, here.

Survey Results

NCHRP Project 22-27

**ROADSIDE SAFETY ANALYSIS
PROGRAM (RSAP) UPDATE**

SR.1 Please provide the following OPTIONAL information about yourself.

Answer Options	Response Percent	Response Count
Name:	85.1%	86
Company:	85.1%	86
Address:	83.2%	84
Address 2:	19.8%	20
City/Town:	85.1%	86
State:	95.0%	96
ZIP/Postal Code:	86.1%	87
Country:	85.1%	86
Email Address:	77.2%	78
Phone Number:	70.3%	71
<i>answered question</i>		101
<i>skipped question</i>		35

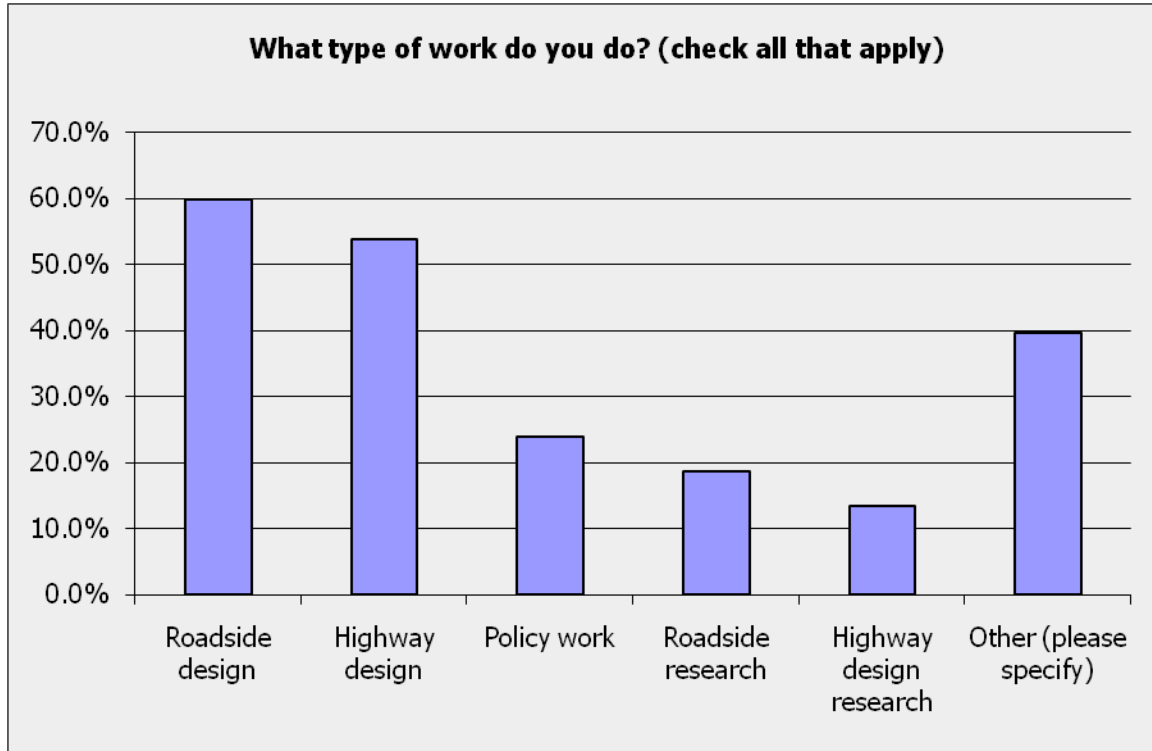
Anoop Admal	Bellecci & Associates, Inc
Bilal Hussein	Wilson & Company Inc.
Bruce	Honisch
Martínez Alfredo	Forjas Metalicas S.A. de C.V.
Steve Walker	Alabama DOT
FRANKLIN JOSEPH KAPUSTKA	
Louis Hutter	
John Durkos	Road Systems, Inc.
Carol Lamb	Youngstown State University
Chris Poole	Iowa DOT
Erin Callahan	The Louis Berger Group
Jason T. Redfern	City of Austin
John Vandergriff	The Louis Berger Group, Inc.
Mark Leiferman	South Dakota Department of Transportation
John Williams	GSI Highway Products
Michael Fazio	Utah Department of Transportation
Mark Di Martino	RoadSafe Traffic Systems, Inc.
Eric Porter	Forsgren Associates, Inc.
Erik Emerson	Wisconsin Department of Transportation
Josh Peterman	Fehr & Peers
Patrick Dressen	Durango Public Works Department
Max Miller	VHB
Ted Mason, P.E.	Idaho Transportation Department
Bob Miller	TranSystems
Dr. Philip V. DeSantis, P.E.	DeSantis Engineering Software Inc
Nicholas Artimovich	FHWA Office of Safety Design
	Midwest Roadside Safety Facility
Karla Lechtenberg	Midwest Roadside Safety Facility

Rod Erickson	Washington State Dept. of Transportation
Dennis Coyle	Nevada Department of Transportation
Siu Ming Cheung	HNTB Corporations
Cody Stolle	Midwest Roadside Safety Facility
Homes Tehrani	VDOT
Richard Voyer	BC Ministry of Transportation
Victor Lund	St. Louis County, Minnesota
Andrea Hall	CDOT
Lloyd Porta Jr.	Louisiana Department of Transportation & Development
Akram Abu-Odeh	Roadside Safety and Physical Security Division
Greg Speier	Speier Road Safety Solutions
Tracy Borchardt	AECOM
Mike Smith	Benham
Michael Hutchinson	TranSystems
William H. Cook	PBSJ/Florida's Turnpike GEC
William D Bryson	
Patricia Davidson	Cowhey Gudmundson Leder, Ltd.
Jane Williams	City of Grand Forks ND
Bernie Clocksin	SDDOT
Phil McConnell	Arkansas Highway & Transportation Department
John Reese	Mississippi DOT
Paul Ferry	Montana Dept of Transportation
David Bizuga	NJDOT
Mark Hodgins	Dent Breakaway Industries
Charles H. Scott Jr.	Scotty's Enterprise LLP
Alex Hanna	Khatib & Alami, CEC
Jim Goddard	Advanced Drainage Systems, Inc.
.	.
Philip DeSantis	DeSantis Engineering Software
Mike Smith	Benham
Doug Sheffer	Kentuckiana Engineering Services
Rafael Riojas	Parsons Brinckerhoff
dale king	bekaert corp
Ivan McCracken	J-U-B Engineers, Inc.
Sandra Pecenka	WYDOT
Brian Kirwan	DRMP
Frank Sullivan	Florida DOT
Rick Mauer	Nucor
ANGEL CESAR HUERTA	FORMET INC
Taylor Goertz	TST Inc. of Denver
Joel A. Dermid, PE	MACTEC Engineering and Consulting, Inc.
Dan Dahlke	St. Clair County
Daryl James	NDOT
Kevin Martin	KYTC
Thomas L. Ervin	RoadSNAP, L.L.C.
Daniel MacDonald	Oregon Department of Transportation
Richard McGinnis	Bucknell University

Nicholas Artimovich
Jeff Chin
Dwight Winterlin
yunus Ghausi
James Riley
Nayna Shah
Eric C. Lohrey
Dave Olson
Joel Aguilar
Chris Speese
Robert Takach
Richard Wilder

FHWA
Caltrans
CalTrans
Caltrans
Caltrans
ECL Engineering, PLLC
Washington State DOT
CA DOT
PennDOT - Highway Safety
Trinity Highway Products
NYSDOT
City of Novato
Caltrans

SR.2 What type of work do you do? (check all that apply)

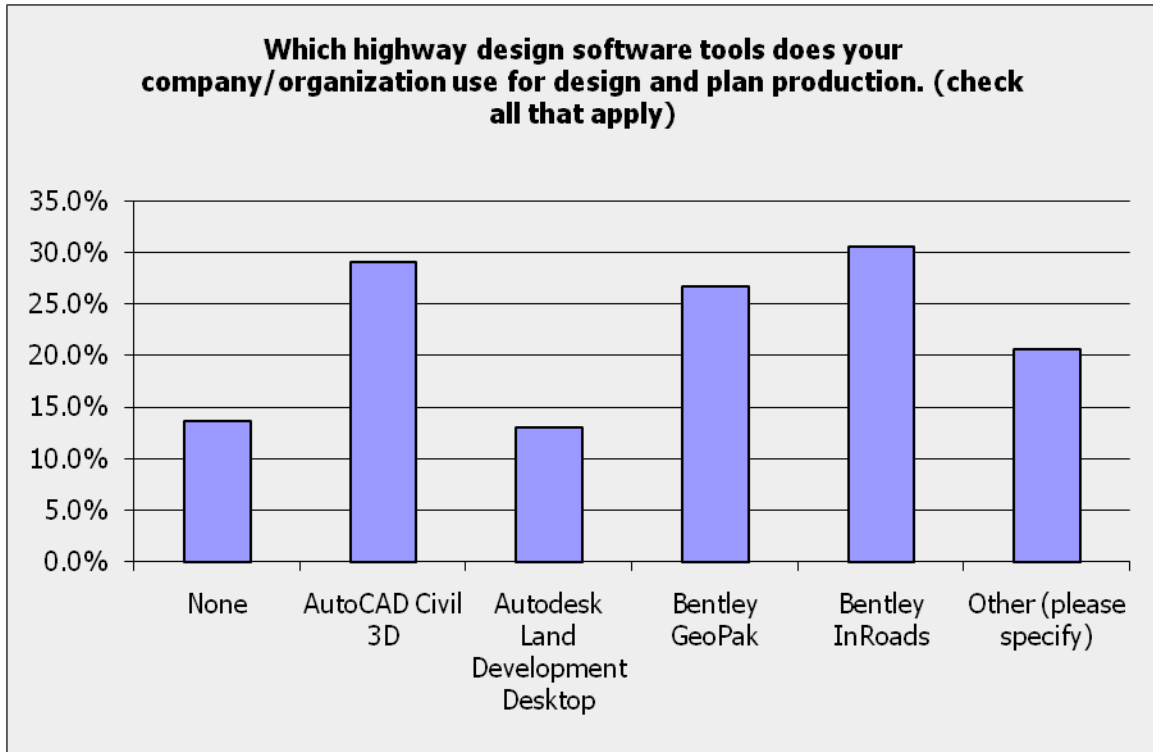


Other (please specify):

- Traffic analysis
- We specified some products for the road construction and design culverts
- Bridge design
- bridge structures
- Manufacturer of Roadside Safety Products
- Consulting
- Traffic Design
- Land Development, Access Road Design
- Fabricator of road side devices
- Highway Construction
- traffic control maintainer
- Electrical systems for Highways
- Traffic Studies
- Geometrics/Standards Engineer for State
- Bridge Design
- Roadside hardware policy
- City street design/construction
- Design Standards Development
- Roadside Design Training
- Safety appurtance design and research
- Geometric Design Guidelines
- Guardrail design

Safety and design technical assistance
Training in Roadside Design
Traffic Engineering Design
MFG
Land Development with Entrance Improvements
Traffic Engineer
Review roadwa plans and constructor schedules
noise barrier manufacturer
Train sign crews for installations
Rail and Track Design
Highway construction
supply steel cable to mfgs of cable median barrier
Local roads
project management of traffic safety related projects
Mfg roadside Safety Hardware & Barrier
Construction management
Traffic Safety & Operations
work zone I.T.S.
Engineering Education
Stream restoration
Stream restoration
Establish roadside policy
Feasibility studies
Traffic/Accident Investigations
traffic safety reviews
Safety Investigation
Product Development
Investigate locations with significant collisions.
Highway Safety Engineering
MFG Highway Safety Products
Local streets design

SR.3 Which highway design software tools does your company/organization use for design and plan production. (check all that apply)



Other (please specify):

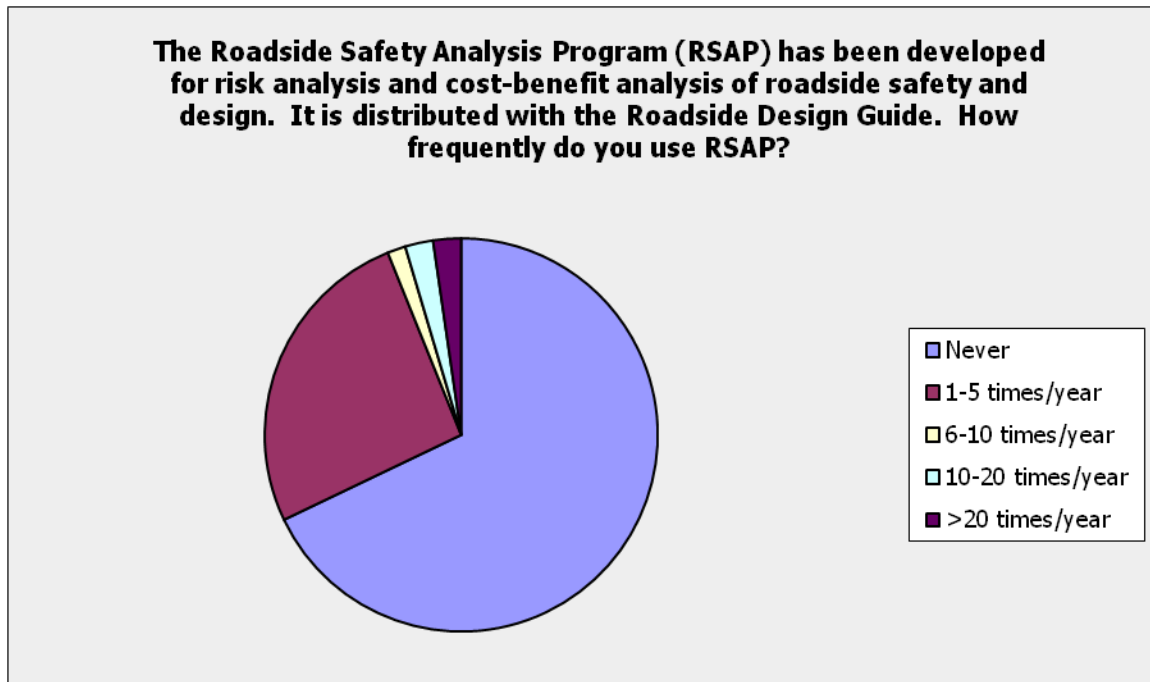
excell by microsoft
 Bentley MX
 Bentley MX
 AutoCad LT, SignCad
 Bentley Microstation
 tapco sign it inventory software and sign making software
 DeSantis Engineering Software Programs
 SolidWorks
 Solidworks
 MicroStation Version 8 & Version XM
 CAICE
 AutoCAD
 AutoCad and SolidWork
 Dyna 3D
 Microstation
 Microstation
 DeSantis Engineering Software
 DeSantis Engineering Software
 Autocad LT
 Rapid Plan by Invarion

Bentley Microstation
 Bently Microstation V8
 Microstation (Bently)
 2D Autocad
 Microstation, HydroCADD, ArcGIS, etc.
 Microstation, CAICE,
 Microstation, Caice

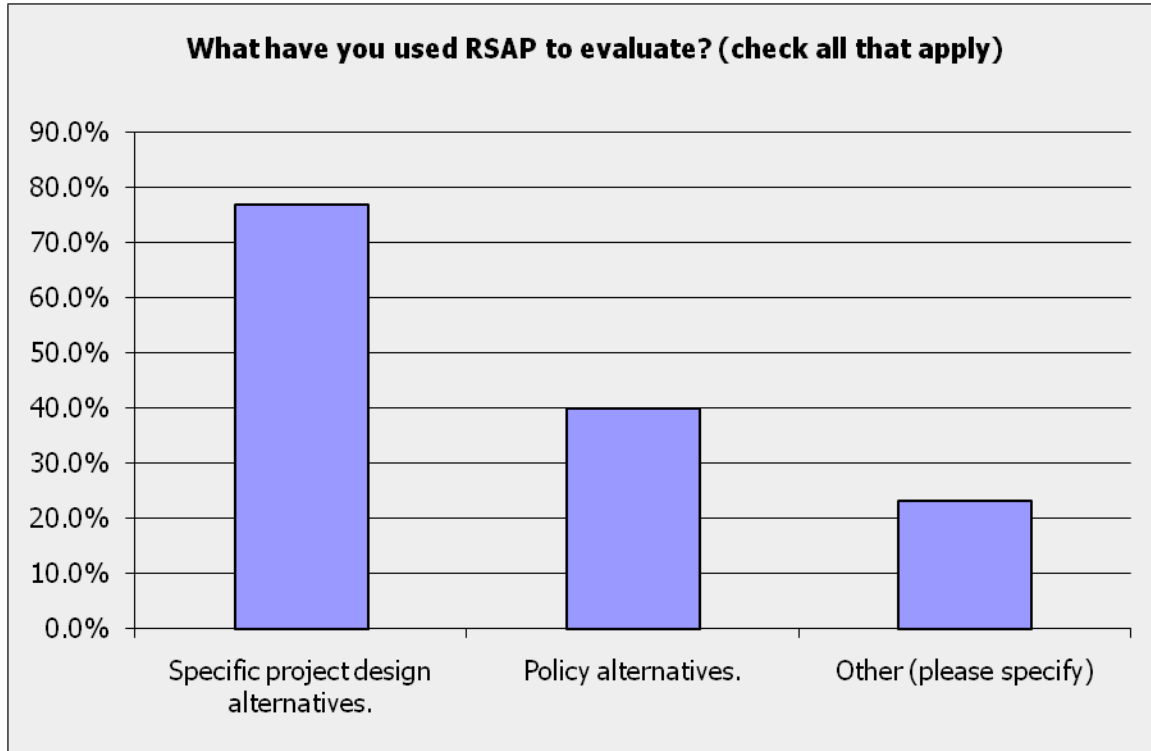
SR.4 Please list other software tools you use to assist with design decisions and cost analysis.

WaterCAD, Pond Pack, Flowmaster, Culvertmaster
staad pro, signit,
None
See the list of software at http://www.sddot.com/pe/roaddesign/office_software.asp
Microsoft Excell
besides RSAP none
ESRI ArcMap 9.3
SYNCHRO, CorSim, Vissim, HCS, Microsoft Project
There is a need to give the District offices a better awareness of the IHSDM as well as RSAP.
AutoTurn
DeSantis Engineering Software Programs - High Mast; Span; End Frame; Mast Arm; Cantilever Sign;
Base Plate; Handhole
Microsoft Excel, TxDOT programs (PSTRS14, BGS, etc.), MDX, RISA
Excel, Fortran, Matlab, AutoCAD, RSAP, LS-DYNA, BARRIER VII
RSAP, BARRIER VII, LS-DYNA
Microsoft Visio, Excel, WSDOT Internal data bases.
Excel and some in-house produced software
GuideSign, Autoturn
iPM, PCES
PathTracker in-house vehicle off-tracking software.
None
Excell, Hawkeye, iRAPtools
AutoTurn, Synchro, HCM
Dyna 3d
TransLink
AutoTurn
AASHTO Estimating software
InRail
Autocad
Excel
In house excel spreadsheets
autoturn
AutoTrack, Bentley Storm & Sanitary
MS Excel
Microstation
Synchro; AutoTurn; HCS; aaSIDRA; SimTraffic
Our internal B/C program
Excel
Microsoft Excel
Microsoft Excel
Synchro, Promics, Traffix
Headquarters software that analyze cost benefit factors.
Estimate using estimator, bid price histories, means, etc. We estimate accident reductions using published ARF's and NYSDOT's accident reduction factors. We use willingness to pay to estimate the savings per FHWA T7570.1. MS Excel to perform B/C ratios per FHWA approved methodology.
EXCEL, Roadview Player by Mandli, Google Maps

SR.5 The Roadside Safety Analysis Program (RSAP) has been developed for risk analysis and cost-benefit analysis of roadside safety and design. It is distributed with the Roadside Design Guide. How frequently do you use RSAP?



SR.6 What have you used RSAP to evaluate? (check all that apply)



Other (please specify):

program usability and reliability

We sometimes used the warrants in the Roadside Design Guided and State Design Manual, which I understand were derived using RSAP or similar application.

Treatment of hazard classes dependent on roadway characteristics, treatment of general hazard classes on low-volume roadways, evaluation of different guardrail designs for varying hazards and roadside configurations

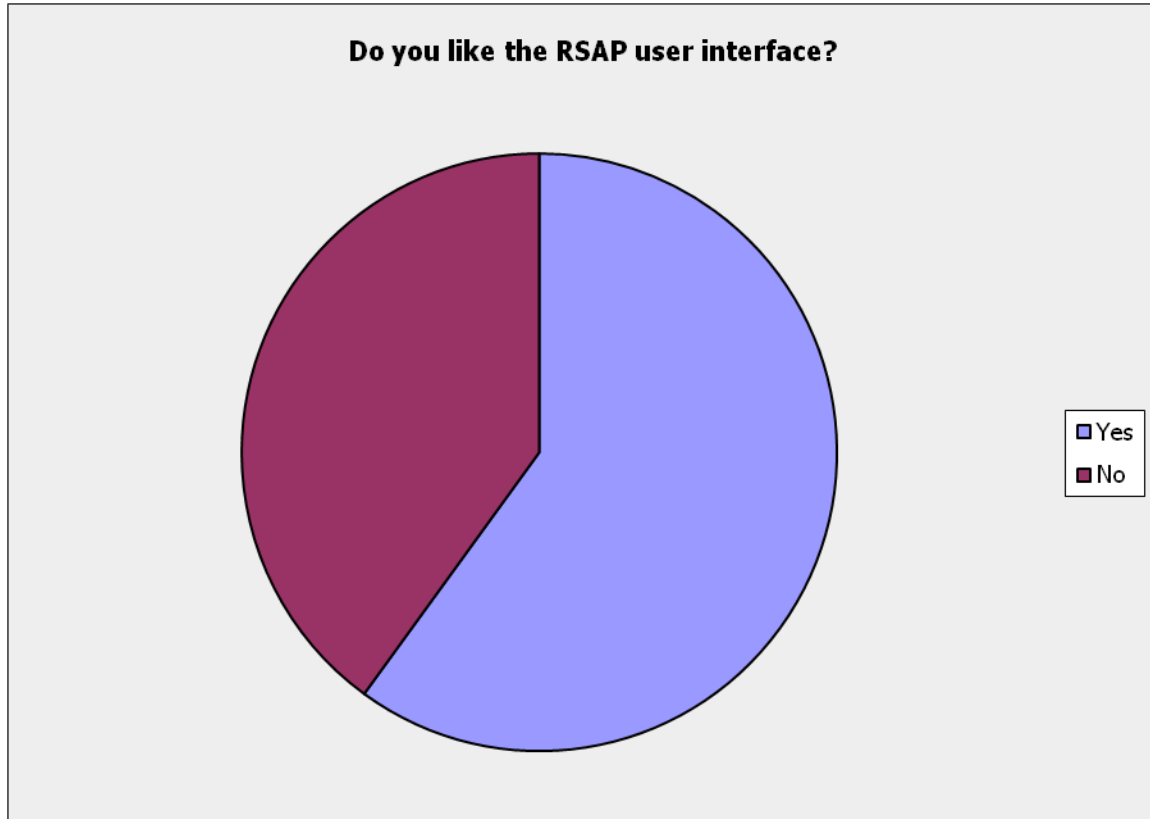
Instructing others on how to perform B/C analyses

Used RSAP only for checking out the software. Do not use it for my work. Others (Planning Engineers) have used the software for work related planning issues.

Research

Sample problems in training courses.

SR.7 Do you like the RSAP user interface?

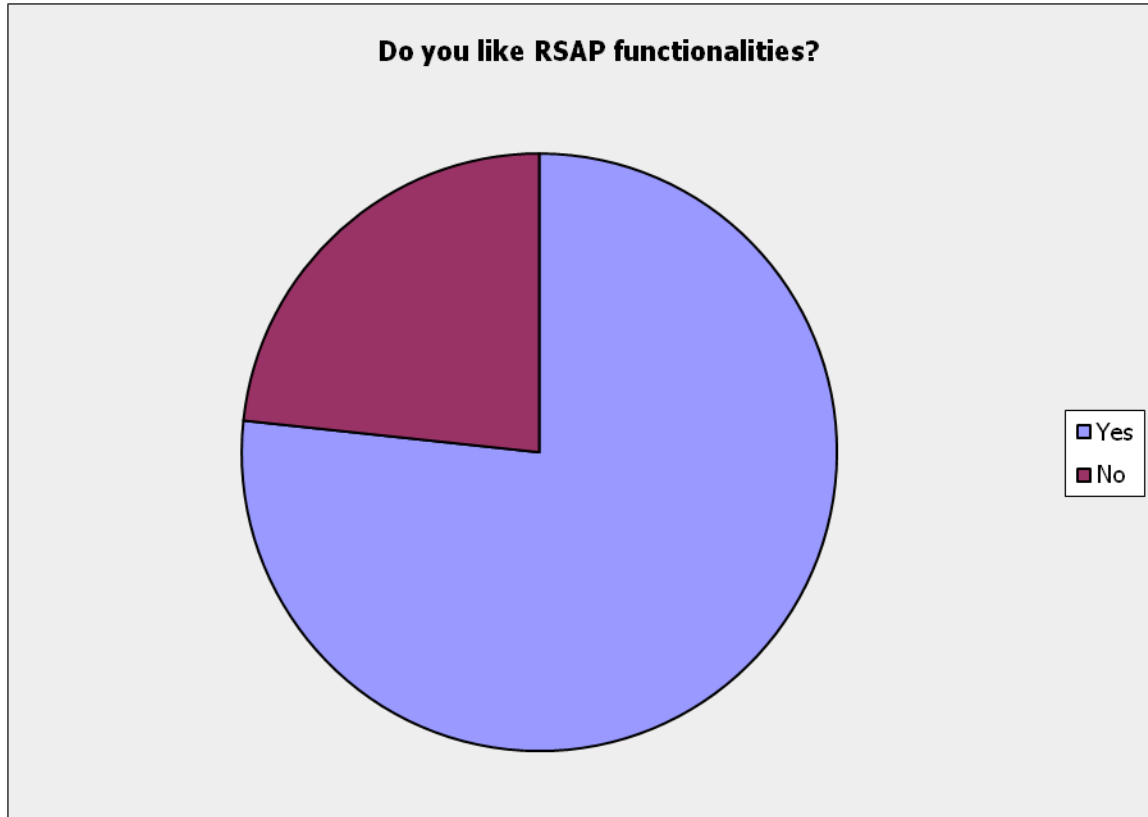


Suggestions for improvements or comment:

- Generally it is OK to use. I would like to see the program automatically input the previous segment length or offset width entered so I don't have to remember the value to avoid an overlap.
- The unit settings within the project don't save, it defaults back to SI units making things frustrating.
- it's way dated
- Time consuming to enter in data and make sure that the data is correct.
Difficult to run analysis over various ADDTs, roadway types, or truck volumes
- I am not sure if it is an interface issue or a terminology issue. Some confusion on filling forms.
- Needs a graphical interface.
- visual representation of model - graphics
- See bullet 8 below.
- The "Window's style" is okay but the arrangement of the UI is not intuitive, it takes users too long to figure it out and it's too long between uses for them to remember it the next time around. It probably needs to be broken down into more screens instead of consolidating all the data input into the larger screens.
- 1. A visual representation of the model would be appreciated. This would be optimized if you can select visual components to build the landscape and the program was intelligent enough to determine the appropriate lengths and offsets to apply for each hazard selected. This would be even better if the program could automatically select depths of slopes or any incrementation of hazards that may be required.
- I would prefer a web-based interface.

- sort of clunking
- There are options like 2.5:1 slopes that are not available to select. Also it would be nice to enter dollar amounts for the different type of guardrail and terminals that way when multiple options are run, it can calculate the installation costs. Same goes for the maintenance for the Guardrail \$ per ft/year. If these were to be inserted in the beginning it would make the program work much better and be more user friendly.
- I have used RSAP enough to get used to the current interface. It could be improved for the beginner or the infrequent user. The default metric values should be revised to english units. A graphical interface would be a good improvement. Picking the barriers, MES, headwalls and side slope graphically would be a suggestion.
- Hard to understand
- I'm such an infrequent user that I haven't developed a familiarity with the interface.

SR.8 Do you like RSAP functionalities?



Suggestions for improvements or comment:

- Making the functionalities more specific, with more availability to detail situations and have a more accurate model of the alternatives you are trying to evaluate.
- Though some are okay, like the data tables
- Because it is difficult to input data it is hard to check and make sure that this is correct, Some type of graphical interface for cross section data would be appreciated
- The comparison on accident cost is easy to understand -- the benefit cost ratio (B/C), questionable and loses a lot of people. Some question at to whether the B/C is working properly.
- See bullet 8 below.
- The program should be redesigned to work around the standard industry practice for building roads that uses a control line of stationing to define the longitudinal location of features. All of our data is based on this method including profile grades, locations of features, survey data, right-of-way, etc. The RSAP currently requires us to build a spreadsheet that correlates all of the data we gather using the control line method to the "distance from beginning of project" method used by the programmer. It is the most important thing that needs to be changed in order for this product to be accepted by the industry.
- 1. Along with the inclusion of the visual aspect (2D or 3D view of scenario), hazards are commonly not perfectly aligned with the roadway, but are angled wrt the road. While the importance of this angle is unknown, it leads to a different type of geometry than is currently modeled. A point-based approach may be better for modeling sign stands, for example.

2. Slope-and-hazard combinations are not realistic as currently defined in RSAP. I believe an improvement in this module would be possible if slope hazards were dependent on lateral

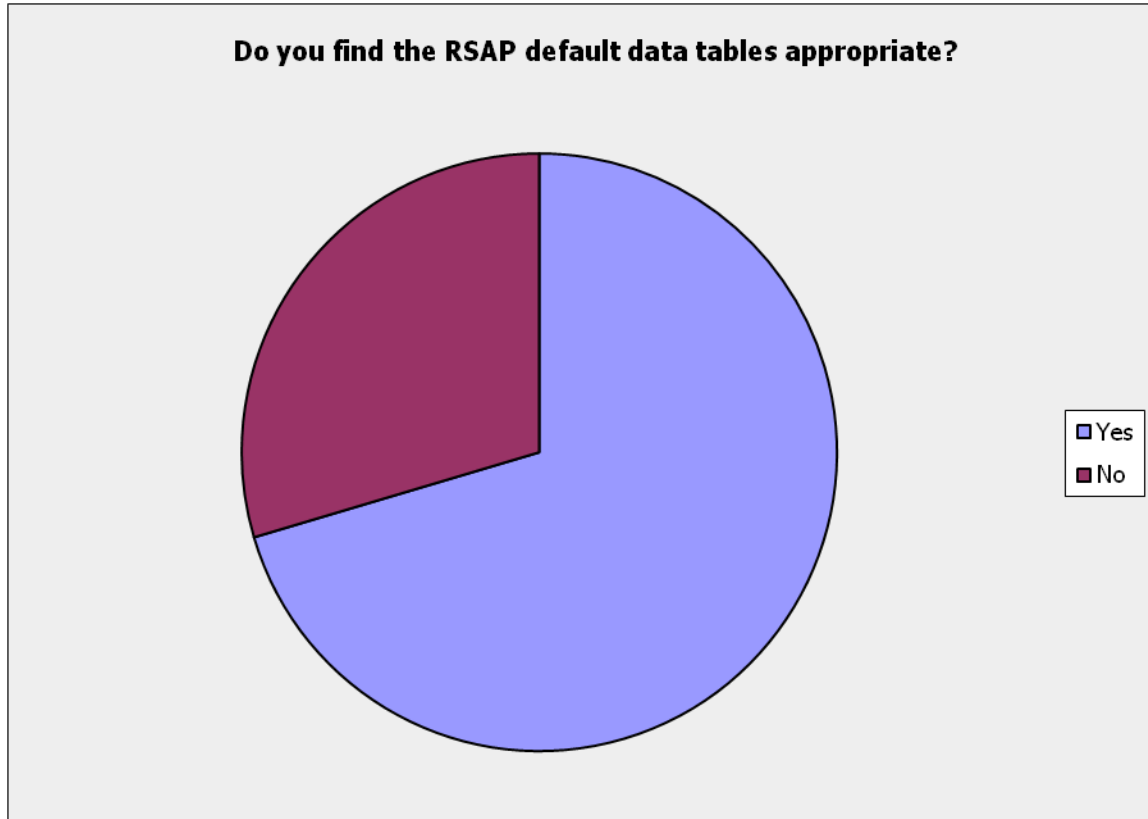
encroachment of the trajectory on the slope rather than an often arbitrary "slope height". Since the steepest slopes are not very hazardous if a vehicle only encroaches 1 ft onto the slopes, inclusion of lateral encroachment effects increases accuracy. Either that, or with the visual aspect, when introducing slopes, appropriate slope depths are incremented laterally from the road based on slope depth; i.e. on a 2:1 slope, a 1-ft drop is present initially, 4-6 ft laterally from the SBP is a 2:1 slope with a 3-ft drop, 10-14 ft laterally from the SBP is a 2:1 slope with a 7 ft drop, 17-20 ft laterally from the SBP is a 2:1 slope with a 10 ft drop etc. to accurately model vehicle trajectory on the perimeters of the slopes without excessive manual input.

3. Continuous slope hazards, contingent on trajectory dependence rather than fixed-location hazard envelopes, would be desirable. Example: some severity is present for a 2 ft lateral encroachment on a 2:1 slope, a higher severity is present for a 10 ft encroachment, and a higher severity for a 30 ft encroachment etc. It should be both longitudinally and laterally-dependent for severity estimation.

4. A multiple-run option should be included to allow users to name the parameters to be updated and multiple analyses conducted without intensive user input. Reducing the effort required to run multiple jobs will save time and money in the evaluation, and will reduce the number of user-caused errors in the evaluations.

- However, I do have to create user-defined features quite often.

SR.9 Do you find the RSAP default data tables appropriate?



Suggestions for improvements or comment:

- Cooper's data is the best data set. Not sure if the angle data for various different types of roadways is very useful (although there is a difference, the difference appears small). Recommend using results of the NCHRP "real world accident data base for severities.
- We used a different accident base rate table. Also, table associated with different hazards is sometime confussing and questionable as to how it is applied.
- need to be updated with current data - costs, vehicle trajectories, damages
- See bullet 8 below.
- You need to include a means for printing them out. They are critical to the cost/benefit analysis but there is no way of easily including them in a final report so managers and posterity have the details of what the decisions are based on. Plus, we use the severity index tables for other purposes and the only way we can refer to them is in an out-dated edition of the RDG (1995 I think).
- 1. Modeled severities of vertical drops are incorrect. Slope drop-off severities should be the same for the same height of drop-off for both intersecting slopes and foreslopes.

2. Some rigid object hazard rates are too low. The severities of some rigid object classes, from small size to large, were less than guardrail severities - analysis of treatments for those hazards will never recommend guardrail installation.

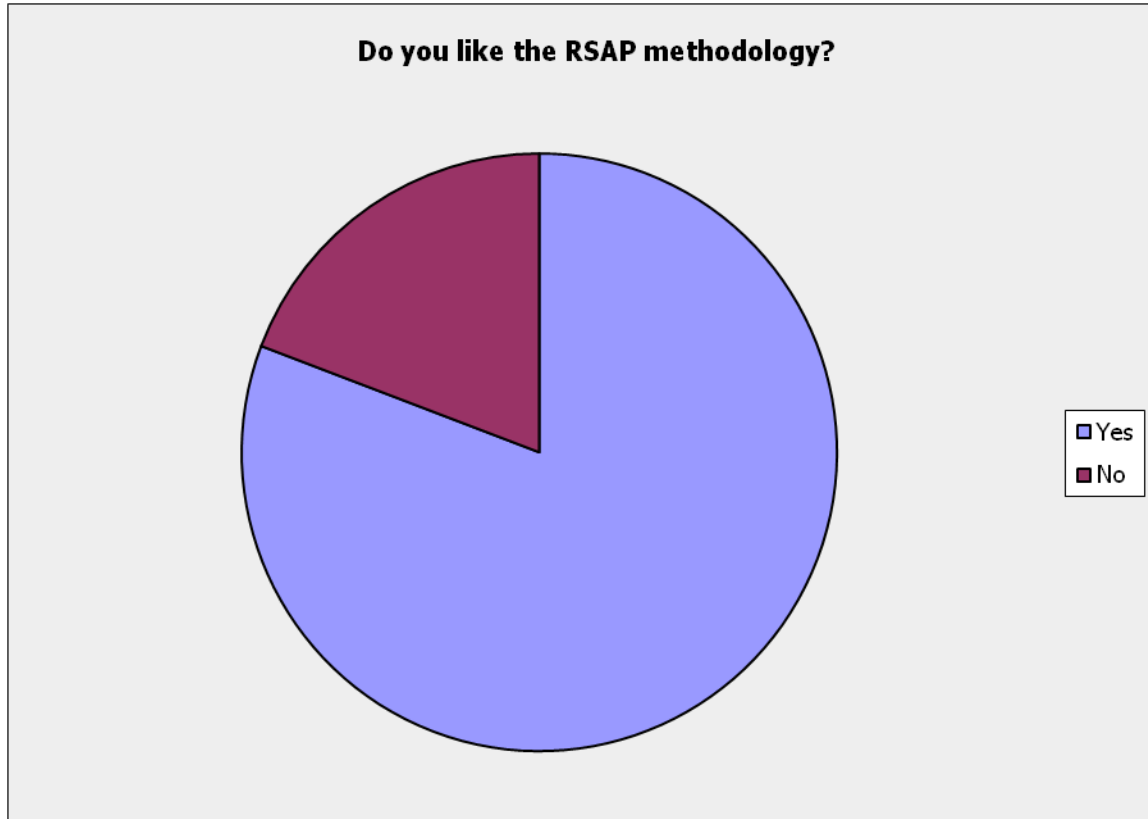
3. Rigid object sizes are very large; there should be some smaller rigid-object size classifications.

4. Tree severities are likely overstated. However, this does lead to a conservative analysis, and

since trees are one of the single most significant hazards for fixed-object ROR fatalities, overstatement of the severity of trees may lead to more trees being cut down than economics may currently indicate; however, this may save considerably more lives than the model would predict as well, with a lower resulting accident cost to the state.

9. Culvert grates ought to be investigated as an additional hazard class.
- In particular, the Severity Indices are incomplete and what is there needs updating.
 - Crash costs should reflect more recent data.
 - It would be nice to state the best alternative based on the B/C.
 - The injury and fatal crash costs need to be updated to reflect current FHWA crash costs.
 - Data on which it is based is flawed
 - Severity indices need work

SR.10 Do you like the RSAP methodology?



Suggestions for improvements or comment:

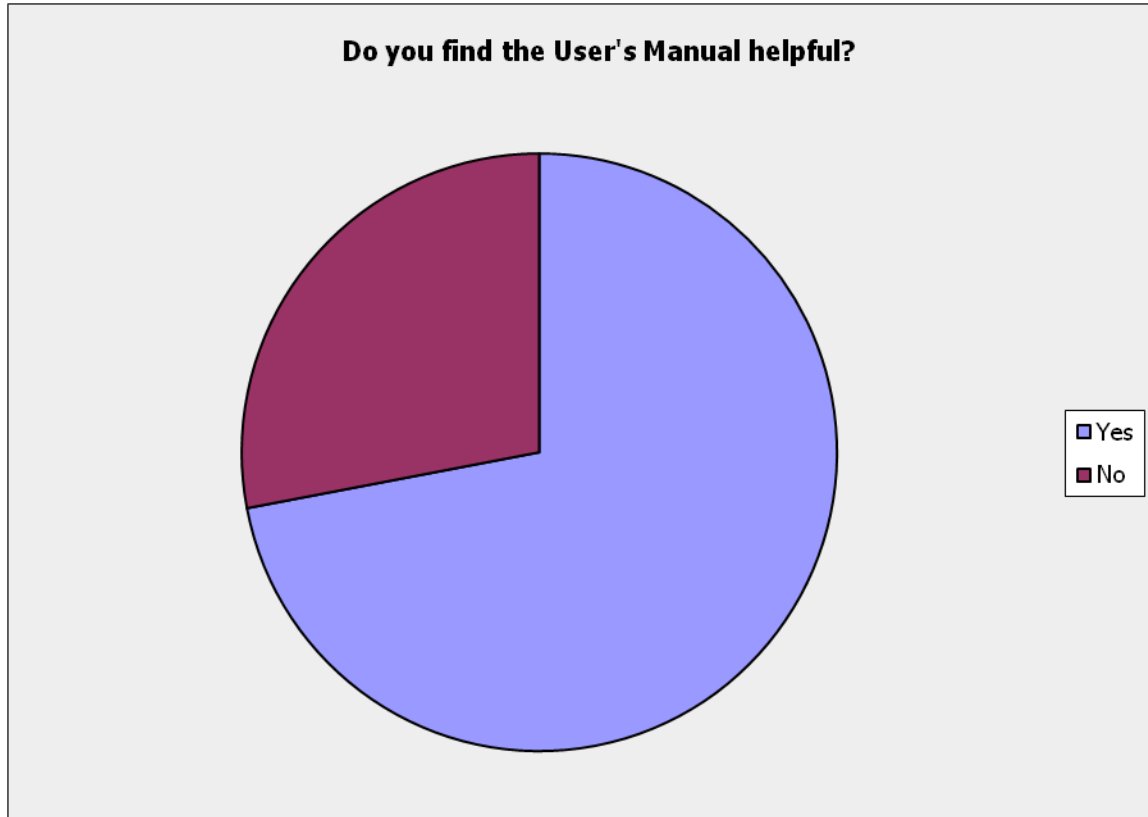
- Make it clearer in the reports section in the ranking of alternatives as they are compared to each other.
- You could do a better job explaining the methodology so that the results can be relayed to others.
- it's a bit of a secret, too black box. need to be more transparent to the user
- I think the bases of what RSAP is trying to accomplish and the methodology appropriate.
- See bullet 8 below.
- We were able to get the Monte Carlo simulation module to accurately model existing (known) conditions before we used it to predict future incidents.
- 1. Incorporation of scaling effects based yaw degree from impact should be incorporated. For example, scale severities of rigid objects when impacted in the side by a factor of 1.5; this may overrepresent the severity of side-impact crashes, but it will lead to possibly more accurate severity indices for most other object types through in-service evaluations and validation rather than a fixed severity regardless of yaw angle.

2. It may be more accurate to incorporate a secondary trajectory algorithm, permitting a vehicle to "slide" along the direction of an object after impact. For example: if the vehicle's kinetic energy is less than the energy required to rupture a guardrail, then the vehicle "slides" along the guardrail system in the direction that the guardrail system is defined (parallel to road unless there is a flare) except on interior curves. This may permit the vehicle to strike multiple objects if one object redirects the vehicle rather than stopping it. This algorithm should be dependent on the energy and sine of the impact angle (IS equivalent).
- The encroachment data is a very weak link in the chain. Given this fundamental weakness, I

would prefer a program that is probabilistic-oriented, as opposed to the current deterministic style.

- User manual needs to be rewritten for the beginner or infrequent user. Knowing when and why to use the seed number is not clear.
- Cannot get realistic output
- The data input seems logical, but I don't use this often enough to be familiar with the methodology.

SR.11 Do you find the User's Manual helpful?



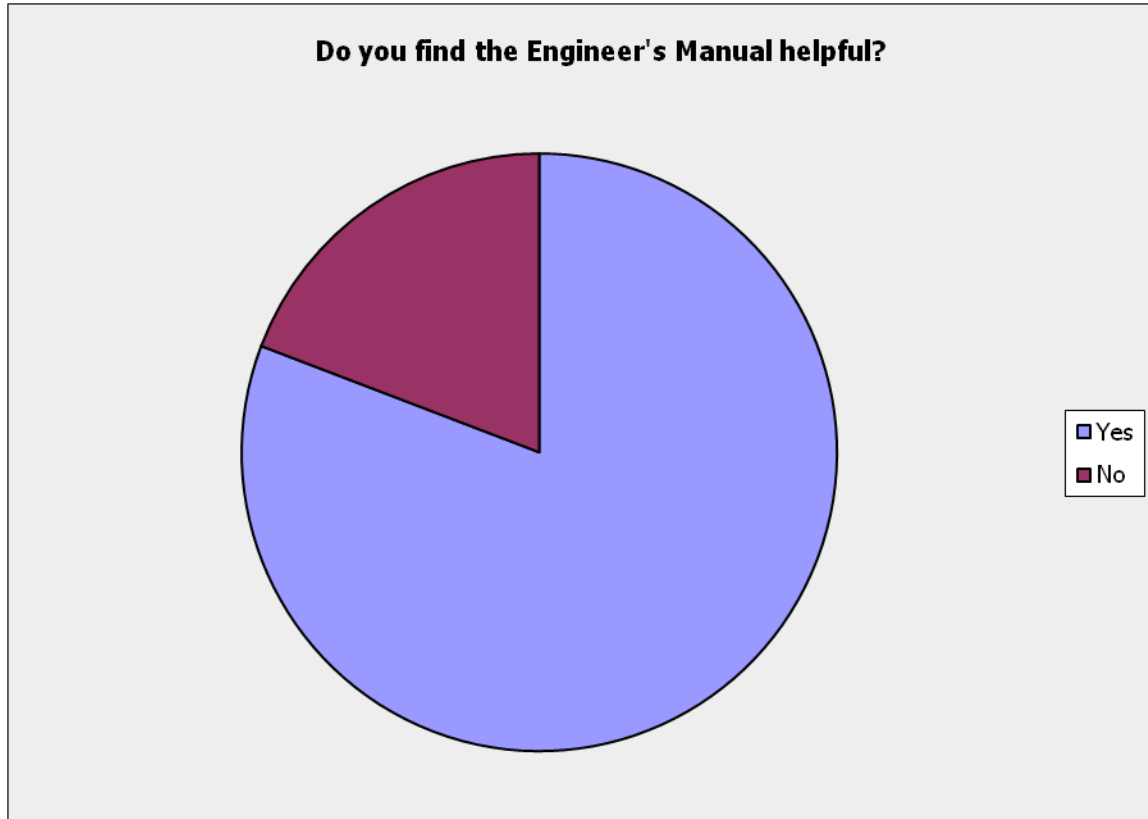
Suggestions for improvements or comment:

- More information as to how crash costs are determined would be helpful.
- Only marginally helpful. I have had to bug MwRSF to understand how to use the software.
- Pictures associated with different hazard/guardrail treatments would be helpful in the manual. Some confusion associated with how to key in distances related to alternatives and picking the right severity index.
- Needs more in-depth information.
- It was helpful, but it lacks a lot of information also. The best thing to do is after you make the modifications to the program and manual, sit down with several first time users and take copious notes as they work through the program using the manual. Then update the manual accordingly and repeat the process until the users can successfully accomplish the tasks with little or no help.
- More emphasis should be placed on the function of the RSAP code. It is difficult to understand exactly what is being computed at different times, and if the user's manual were more thorough in the computation of the different parameters, it would encourage more understanding and evaluation of the results. Furthermore, I believe the manual should discuss some of the limitations of RSAP and what is currently not incorporated or supported, so that researchers do not waste time and effort modeling a non-physical model that is not supported in RSAP; for example, it is difficult (if not impossible) to accurately model the placement of a fixed object on a slope. Accurate modeling of the slope requires incredible detail that the "average" person using RSAP, such as members of a DOT without extensive experience with the code, could never be expected to create with correct physical meaning and obtain meaningful results. While the intricacies of the code are not helpful for most users, the focus on the applications based on the hazards, as well as limitations and examples of "bypassing"

the limitaitons, would be helpful.

- Although it does not fully or completely explain all the bugs in the current software.
- See comment #6.
- Not enough detail
- Never used it

SR.12 Do you find the Engineer's Manual helpful?



Suggestions for improvements or comment:

- Only marginally helpful. I have had to bug MwRSF to understand how to use the software. I'm not sure when it is Ok to use foreslope and backslopes verses "parallel ditches".
When should/ how should a person decide to use "user defined features"
- Not aware of the Engineer's Manual -- just the User's Manual that is online.
- See my answer for 6 above.
- Have not read this.
- Add discussion on the use of RSAP for median applications for divided highway.
- Not enough detail
- Never used it
- I haven't used it.

SR.13 While using RSAP, have you encountered any incidents where your analysis results from RSAP were inconsistent with your experience/expectations/judgement?

- yes
- Analyzing bridge rails with different shoulder widths gives the rail with the narrowest shoulder as the lowest user cost because the narrow shoulder presumably does not allow a higher impact angle. Intuitively, a wider shoulder should be better.
- no
- RDG indicates 4:1 to 4:1 ditches are not desirable. I would guess that RSAP would have a larger SI.
- Yes, the B/C number elude me. The application at best is +/- 20% (i.e. it is based on probability of encroachment, estimates for cost and best guess for traffic voluments). People sometimes get hung up on the decimal for a decision. Most inconsistencies were tied to user error relating to not how to input things correctly. I am not sure of field experience to validate the numbers coming out of the application.
- no
- not really
- Problems with RSAP Roadside Safety Analysis Program

1) Whenever the user attempts to run a one way one lane roadway an error message occurs that states "Unexpected Termination of Analysis Module". This makes it impossible to run one lane ramps.

2) Problems have been reported when attempting to run user defined features. When a user inputs small increases to the severity values at 100 km/hour, sometimes the output does not show increases in average severity or annual crash cost.

3) When crash costs are changed from User-Defined Costs- KABCO (with the values WSDOT uses) to the Roadside Design Guide's values the annual crash cost does not change significantly. WSDOT uses Fatal= \$3,895,000, Severe Injury = \$325,000, Moderate Injury = \$70,000, Minor Injury = \$ 35,000, Property Damage Only = \$ 6,500.

4) In order to enter English units the user must use the pull down menu under view-options, then change into metric units and back to English units. If the user does not do this step, the input screens will request input in feet and require the user to use metric values. Even though the input is in metric units, the output is in English units.

- Yes, but we were able to work around that once we developed a better understanding of how the input data was used by the processors.
- No
- Several times. As noted above, the rigid-object hazards were at times less severe than guardrail; by definition this seems absurd. Further, without extensive input and incrementation of a slope (e.g. a 20-ft deep 2:1 slope adjacent to a drop-off by a bridge requires coding increments of the drop-offs adjacent to the bridge, since otherwise the bridge drop-offs are not accurately modeled. Placement of the slope immediately next to the bridge results in an odd recommendation. Slopes in general are difficult since they are often large rectangular hazards with constant severity, though this is not physically observed in the field. For the most part, however, I found it to be relatively in line with expectations.

1. Flat ground "severity" should be automatically incorporated into the model everywhere that there is no other hazard. Else, the "flat ground" hazard will affect the results if included, as there is some flat ground severity resulting from bumps, sticks, small trees, brush etc. The flat ground hazard should also be highly-dependent on the vehicle's yaw angle relative to the path

of travel.

- Not sure. Need more time to evaluate
- Yes
- have never been able to get one-way one-lane option to work.
- Yes, when analyzing front slopes on a recent comparison of AASHTO criteria to FDOT criteria, we had some questions compared to the results using the Highway Safety Manual.
- No.
- Yes, most of the time
- No
- No
- Yes - but I don't recall the circumstance.

SR.14 Are you aware of reports or papers about RSAP documenting its use? Please list them here.

- no
- no
- MwRSF is working on using RSAP for various Poolfund reports. However reports are not published as of yet
- recent TRB paper by MwRSF
- No
- Yes, I developed one based on our experience here but unfortunately our working copy was lost during the remodel of the fourth floor, our design section, and we had not made any copies at the point.
- No
- See report list for Midwest Roadside Safety Facility - there are many in the works.
- N/A
- no
- NO
- No.
- No
- No
- No
- Yes
- No

SR.15 What improvements would you like to see made to RSAP?

- Report functionality; ability to produce PDF's of reprot;
- More detail, its a very basic program, if you could model situations with more detail it would produce more accurate results.
- Make the inputing of cross section data more graphical
- Better examples with diagrams/pictures. A break down on the B/C. Intergration of Length of Need calculations into the RSAP -- tools to design the guardrail treatment with tables associated with different guardrail hardware options. If the design tool was intiutive such that people preferred to use, than more people would used the analysis comparison.
- Add a graphical interface so you are sure that you modeled what you wanted to.
- [1] Base the data input and reporting off of a control line (line of stationing), [2] add an option to print out the severity index table and the table of costs for fatals and injuries, [3] Make the user interface more intuitive, [4] Make the manuals more comprehensive (detailed) and based on actual user experience, [5] providing one or more additional tweak factors to normalize the output that are tied to specific logic would be helpful. Currently there is only one and although we were able to use it to normalize the output, but if we were ever questioned on our use of the factor we would not have answers other than that we changed the value until the program accurately modeled the historical data. [6] You should probably strive for Windows certification in order to provide users with a GUI and functionality they are familiar with.
- Specifically the visual interface. In addition, the algorithms used to calculate the trajectory (a cubic function, for example) and yaw-related severity scaling.
- ?
- Address methodology weaknesses (i.e. S.I. and encroachment rates) and update the user interface to make it web-based so that it does not have to be installed on a network or individual PC.
- reporting information should be more concise. Now you have to look at multiple pages to get all of the information. All info about features should be displayed together.
- Add infor for guardrail costs and maitneance and truss costs
- Undate RSAP to include cable barrier.

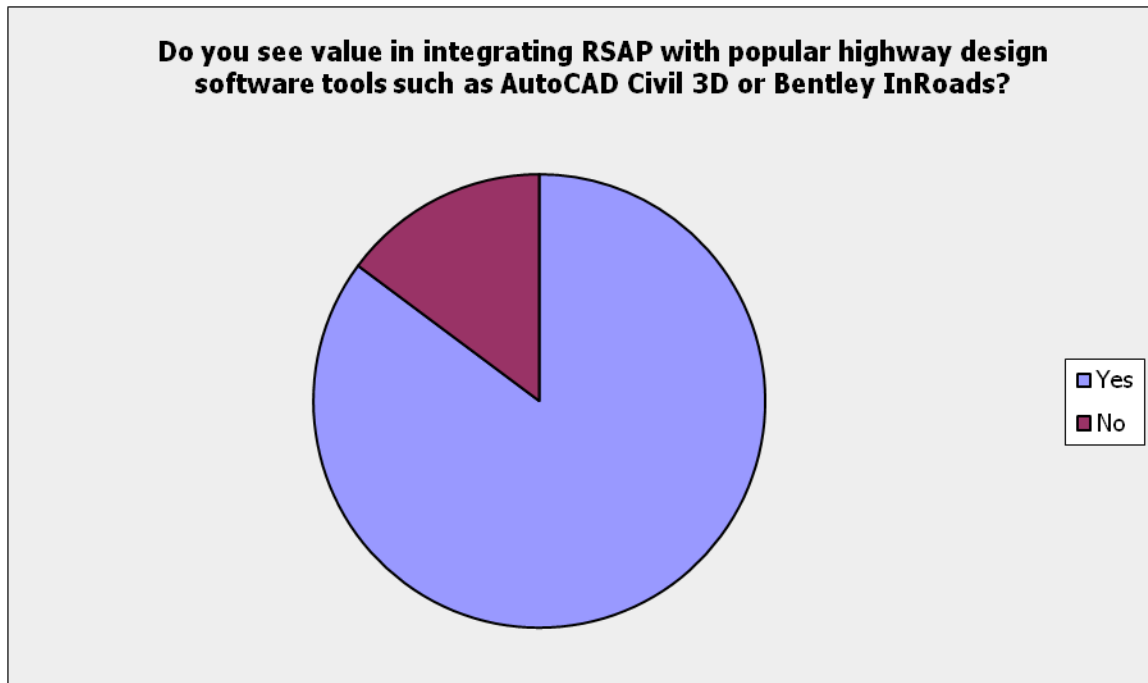
The output table shoulder be reformated. The incremental B/C is not easily explained to a beginner or the infrequent user.

- unsure
- Make it work properly and add a picture of Mac's scottish cow/steer
- I do not use it enough to have an opinion.
- No comments

SR.16 Which features of RSAP would you like to see remain unchanged in the next release?

- the basic data input screens.
- use of cooper data
- The probabilities methods are excellent and the Monte Carlo simulation seems appropriate.
The Window's style GUI is somewhat familiar.
- ?
- Ability to customize the crash values.
- unsure
- Its name
- none

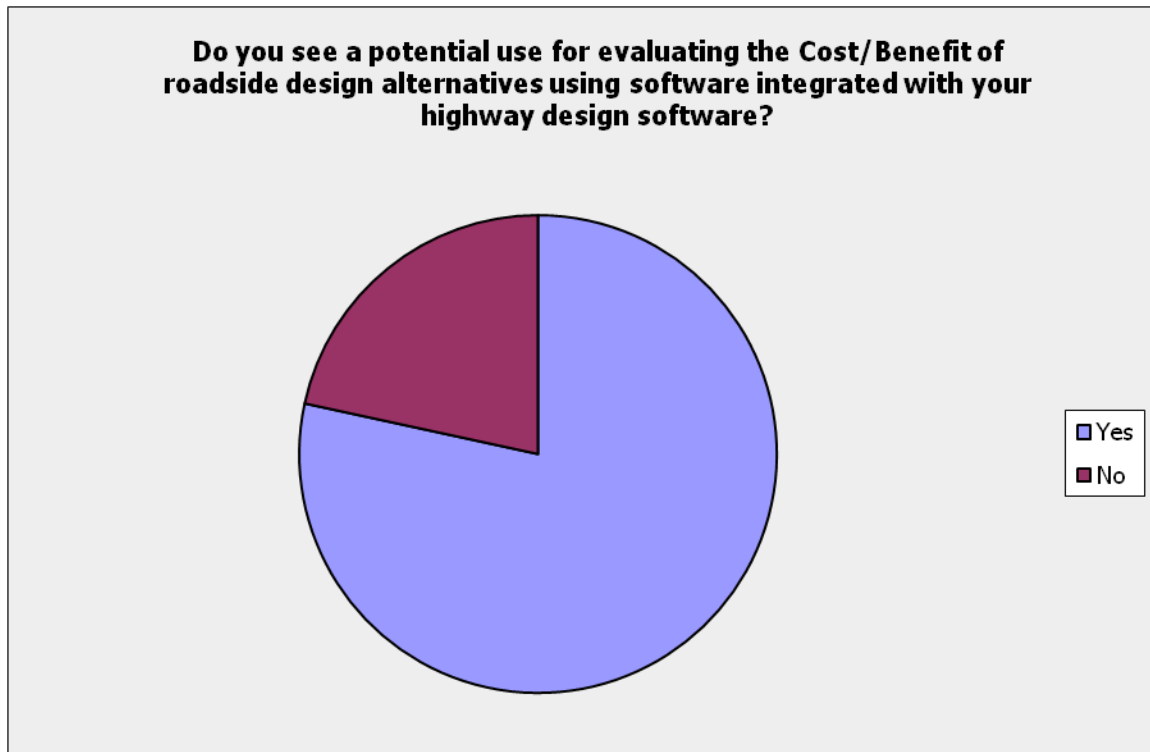
SR.17 Do you see value in integrating RSAP with popular highway design software tools such as AutoCAD Civil 3D or Bentley InRoads?



Comments:

- It would give RSAP the ability to evaluate specific design features.
- It may be "easier" just to get RSAP linked to a CADD drawing program verses a larger design software. Just having visual picture of the cross section within a segment of roadway would be help full
- Maybe, -- as a designer using Microstation/InRoads combination it may be helpful to integrate RSAP into the CADD application. As a design check person that may not have access Microstation/InRoads, this direction may be restrictive. Microstation/InRoads are complex application for people that do not use them regularly -- not sure if integration would add another level of complexity that may restrict use .
- Something with Solidworks would be valuable too.
- A separate RSAP application would best meet WSDOT's needs. Many of the individuals that might use this tool do not have access to highway design software.
- If you can do this you will be doing a great service to the traveling public; and I do mean great.
- That would certainly fix the visual aspect of the program; plus accurate geometries of the hazards could be obtained. I would see significant improvement in the meaning of the results with this update.
- Or, perhaps even better, integrating it into the FHWA's Interactive Highway Safety Design Model program.
- Think it should be a stand alone software.
- unsure
- Seems like two separate tasks to me
- This would enhance its usefulness to the practitioner.
- Absolutely.

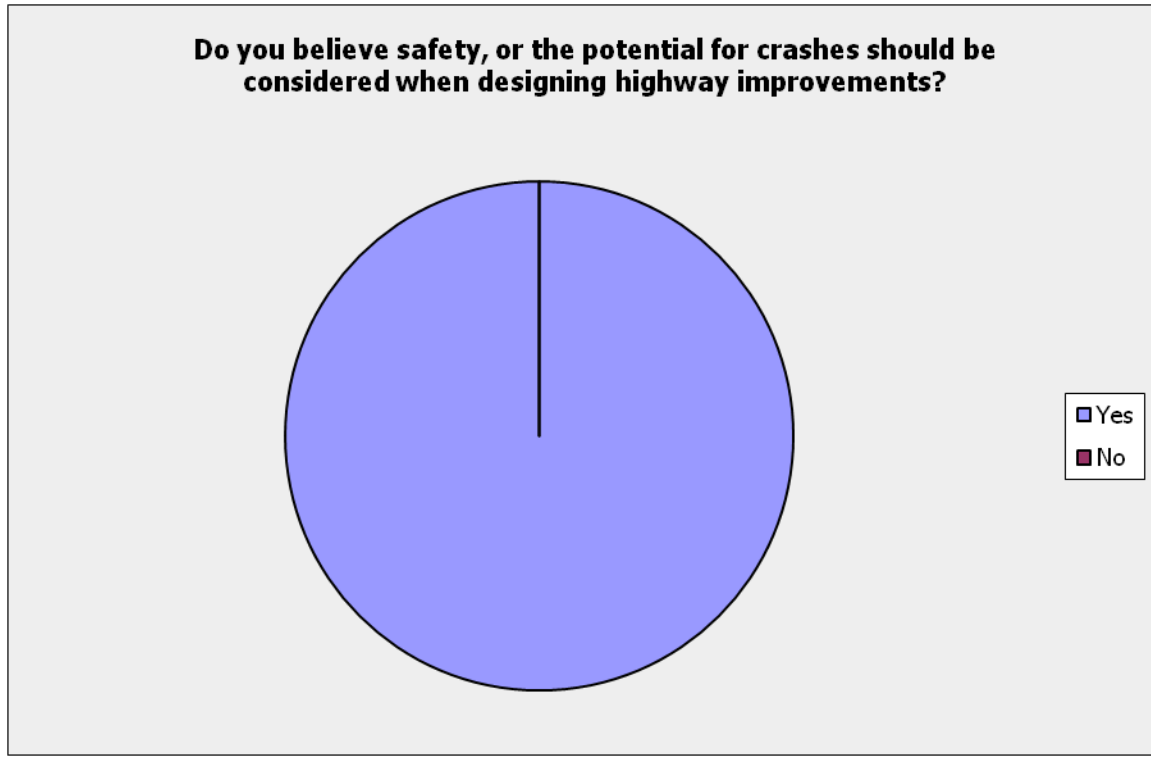
SR.18 Do you see a potential use for evaluating the Cost/Benefit of roadside design alternatives using software integrated with your highway design software?



Comments:

- I have only used RSAP during the development of the latest NHI training course on Roadside Design. I think it should be used by highway / roadside designers to develop roadside design policy and for individual hazard elimination scenarios.
- Need quick and simple tool for designers to get order of magnitude of B/C to compare roadside design options.
- KYTC tends to use the manual and justifies any judgments based on that information through required design documentation.
- Possibly
- Not sure how it applies to local streets.

SR.19 Do you believe safety, or the potential for crashes should be considered when designing highway improvements?



Comments:

- Need regular tools and processes to assist designers in making design decisions in the course of their work that explicitly include safety consequences.
- It should be "Considered" but not "Required".

APPENDIX B

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Introduction

This appendix serves as documentation for the software created to support this research. Extensive explanations, background information, explanation of existing software and literature and the potential implementation of this software are provided in the main document of this report. This appendix provides specific information regarding the program structure, which models are used in the program, how the models are used, and how to use the program.

Program Overview

This software has been created to support the performance-based highway design process. The analysis phase of this proposed process, includes a review of the cost-effectiveness of proposed alternatives. Cost-effectiveness is assessed using a benefit/cost (B/C) ratio. This process is demonstrated through highway safety. Any reduction in annualized crash costs is considered a benefit while direct costs (i.e., construction, Right-of-way, environmental, etc.) are considered the “cost,” that is, the denominator in the ratio. The B/C ratio is calculated as follows:

$$\text{B/C Ratio}_{2-1} = \frac{CC_1 - CC_2}{DC_2 - DC_1}$$

Where:

B/C Ratio 2-1 = Incremental B/C ratio of Alternative 2 to Alternative 1

CC₁, CC₂, = Annualized crash cost for Alternatives 1 and 2

DC₁, DC₂, = Annualized direct cost for Alternatives 1 and 2

Calculating the direct costs is relatively straight forward and has been part of publicly funded infrastructure projects since their inception. Calculating the crash costs can be complicated and relies on a good deal predictive models and data. This software was created to support the tasks necessary to calculate the crash costs using the encroachment probability model. This model includes a series of conditional probabilities as follows:

$$E(C) = V * P(E) * P(C/E) * P(I/C) * C(I)$$

Where:

$E(C)$ = Estimated crash cost

V = Traffic volume

$P(E)$ = Probability of encroachment (encroachment rate)

$P(C/E)$ = Probability of crash given encroachment

$P(I/C)$ = Probability of injury given crash

$C(I)$ = Cost of injury


The software has several distinct modules which support the end goal of estimating the crash costs. An overview of each module is presented below. These modules include:

- Data gathering and user entry,
- Encroachment module,
- Monte Carlo module,
- Crash prediction module, and
- Severity and cost prediction module.

Please note the software is programmed for imperial units, is currently limited to ten segments and six hazards, and 2-lane rural roads. This template, however, can be expanded to include a wide variety of highways.

Data Gathering and User Entry

The computational engine is programmed in Excel. This program uses a Monte Carlo simulation, therefore the user must change some of the default settings in Excel and manually calculate the workbook for the program to work properly. These steps are very simple and described here.

1. Click the Microsoft Office Button  , click Excel Options, and then click the Formulas category.
2. In the Calculation options section, select the Enable iterative calculation check box.
3. To set the maximum number of times that Excel will recalculate, type the number of iterations in the Maximum Iterations box. One thousand is a reasonable number for this workbook.
4. After changing these setting, the simulation can be run. Within the “UI1” tab, in cell I4, set the cell to false and hit the F9 key to reset the workbook.
5. After entering all of your data, enter true in cell I4 and hit the F9 key. 1,000 iterations will be calculated. In the event a circular reference error is thrown, repeat steps four and five until the error is resolved.

User entry of data can be accomplished through three methods, including the Windows form, Civil3D, and directly entering data into the worksheet. The manual data entry method is documented herein to allow for coverage of the most minor details and troubleshooting, if necessary in the future.

Data Entry

All data entry within the workbook occurs on the “UI1” tab, within the colored cells. This workbook has been created to allow for future expansion to include analysis of more

performance criteria. The colored cells are data entry cells. The yellow cells are the only cells in use at this time. The cyan cells have been added as placeholders. The first data entry section, shown in figure B-1, includes project specific information and the reset button described above.

Project Life (years)	20	Iterations=	6000
Traffic Growth (%)	1%	Reset =	TRUE

Figure B-1. Project Life Data Entry Fields.

Figure B-2 shows the hazard data entry field. Hazards are entered by baseline station and offset. The offset is measured from the baseline and the side of the baseline is specified as left of right (e.g., L or R). The user enters the segment data and hazards by Station and offset on the first sheet of the worksheet. The hazards are sorted automatically by segment in the “Enc Calc” sheet. The user does not sort hazards. Hazard types are entered by a hazard code equal to a value from one to ten. This is discussed more in the Severity and Cost Prediction Module section.

The only known exception to possible expansion of coding hazards by Station and Offset is the possible scenario of a station offset equal to zero, which results in an error. This may occur if median barrier is located along the construction baseline with zero offset. This scenario requires consideration for future efforts which define hazards by station and offset.

HAZARDS, BY STA & OFFSET					
Start STA	End STA	Offset (ft)	Offset LorR	Hazard	
369+09	388+80	43	L	10	
379+66	401+88	43	L	10	
401+88	422+83	43	L	10	
369+09	388+80	43	R	10	
379+66	401+88	43	R	10	
401+88	422+83	43	R	10	

Figure B-2. Hazard Data Entry Field.

Figure B-3 shows the segment data entry field. This data is entered in imperial units. Direct conversion from imperial to scientific units may be complicated due to the units used to established horizontal curvature. The degree of curvature measurement is defined

as degrees per one hundred feet. Such a definition does not exist for scientific units and a direct conversion to scientific units is not considered appropriate. Degree of curvature has been included here because it is a variable in the encroachment model. Future development efforts of the encroachment rate model, modifying factors and software should consider using radius of curvature for simplified expansion.

The lane width data entry field accepts lane widths of ten, eleven, or twelve feet. Again, this data is used in the encroachment model to modify the rate. The model is limited to these lane widths. Generally, urban and rural local and collector roads fall within that range, however, some arterials may have larger lane widths. More research is needed in this area.

A field for the directional distribution of traffic is provided. The use of this data is discussed further under the Monte Carlo-Encroachment Location section.

Figure B-4 shows the crash cost data entry field. The user may change the default values here. A discussion of how these values are used is below under the Severity and Cost Prediction Module section.

Seg #	Start STA	End STA	ADT	HC (degrees)	VG (percent)	# of Lanes Primary Direction	# of Lanes Opposing Direction	Lane Width (feet) for values of 10, 11, or 12	D (%) - Primary Direction
1	369+09	374+48	7000	0	5.31	1	1	12	50%
2	374+48	379+66	7000	20.1194	5.31	1	1	12	50%
3	379+66	382+60	7000	0	5.31	1	1	12	50%
4	382+60	388+80	7000	25.78	5.31	1	1	12	50%
5	388+80	398+33	7000	0	5.31	1	1	12	50%
6	398+33	401+88	7000	15.4927	4.6	1	1	12	50%
7	401+88	412+54	7000	0	4.6	1	1	12	50%
8	412+54	418+79	7000	36.3511	2.89	1	1	12	50%
9	418+79	422+83	7000	0	2.89	1	1	12	50%
10									

Figure B-3. Segment Data Entry Field.

	None	PDO1	PDO2	C	B	A	K
FHWA							
\$	\$ -	\$2,000	\$2,000	\$19,000	\$36,000	\$180,000	\$2,600,000

Figure B-4. Crash Cost Data Entry Field.

Encroachment Module

Miaou proposed an encroachment model which includes modifications for highway characteristics. This model has been incorporated and predicts the encroachment rate per mile per year. This rate is then adjusted within the worksheet the encroachment rate per segment length per year. Miaou's model, the highway characteristic adjustments, and model boundaries are presented here:

$$E = \left(\frac{365 * ADT}{1,000,000} \right) \exp^{\frac{\beta_{st} - 0.04 * ADT}{1,000} + L_{nf} + H_{azf} + 0.12HC + 0.05VG}$$

Where:

E = expected number of roadside encroachments per mile per year

ADT = average annual daily traffic between 1,000 to 12,000 vpd

β_{st} = State constant with a default value of -0.42. For those areas (or States) where rural two-lane road data are available, it is recommended that β_{st} be estimated as the natural log of the run-off-road accident rate for road segments with ADT < 2,000 vpd, that are relatively straight (e.g., horizontal curvature < 3 degrees) and level (e.g., vertical grade < 3%).

L_{nf} = 0, 0.20, and 0.44 respectively for lane widths of 12', 11', and 10'.

H_{azf} = 0.4 to 0.5 (0.45 is the default value)

HC = horizontal curvature in degrees per 100' arc from 0 to 30 degrees

VG = vertical grade in percent from 0 to 10 percent.

The software adjusts the ADT to the future year and predicts the encroachment rate using the future year. A better approach would be to average the traffic volumes over the life of the project to avoid over-predicting the encroachment rate.

Monte Carlo Simulation

The Monte Carlo simulation technique is used to simulate vehicle encroachments one at a time to determine, given an encroachment, if a crash would occur, the severity of the crash, and the resulting crash cost. The conditions of each simulated encroachment are determined by random numbers whose values are weighted to account for distributions within each scenario. The following conditions of the encroachment are determined by random number and discussed below:

- Encroachment location within the segment, including the Station, direction of travel, and direction of departure (left or right);
- Encroachment speed and angle; and
- Vehicle type.

Encroachment Location

First the direction of travel is determined by a random number between zero and one, with the probability of a vehicle traveling in either direction equal to 0.5. Therefore, the directional distribution of traffic is assumed to be 50%. The exception to this is when the user enters a directional distribution equal to 100%, in which case only one direction of travel (e.g., the primary direction) will result. Further development of this software should include an adjustment for the distribution of traffic volumes.

Second an encroachment location within the segment is determined by a random number between zero and one. The random number is multiplied by the segment length and the value is added to the start Station of the segment for vehicles determined to be traveling in the primary direction or subtracted from the end Station of the segment for vehicles traveling in the opposing direction.

Third, a random number between zero and one is generated to determine whether the vehicle encroaches to the left or right. For values of 0.5 or below, the vehicle encroaches to the right.

Future development efforts may consider combining all of the possible scenarios and generating one random number which would determine the location, direction of travel, and which side the vehicle encroaches to.

Encroachment Speed and Angle

There is believed to be a strong relationship between encroachment speed and angle and the functional classification of the road. Previous software to predict encroachments has presented this data in a seven by seven matrix. This software provides a data table for each functional classification of road on the “Speed&Angle” tab. The first column is the probability of a certain combination of speed and angle, the second column is the speed and the third is the angle. A single random number between zero and one is generated this data table is referenced twice with the same random number. First the random number is used to determine the speed of the encroachment and second to ascertain the angle. Using the same random number ensures the relationship between speed and angle is maintained.

Vehicle Type

RSAP currently recognizes twelve vehicles classes and adjusts for the population. This software generates a random number between one and thirteen, adding motorcycles. Vehicle type information is ultimately used to determine vehicle swath. While there are thirteen different vehicle classes, many classes have the same length (e.g., swath). Future development efforts should consider reducing the number and focusing perhaps on larger categories such as passenger vehicles, box trucks, etc. with the same swaths.

Crash Prediction Module

The crash prediction module determines if an encroachment would result in a crash. For every hazard, the software determines if the vehicle leaving the road in that simulation, will have a swath that will impact the hazard. Currently, a straight line vehicle path is assumed and both sides of the vehicle swath are calculated and checked. A better approach, which could include curved vehicle paths, may be to program the centerline path of the vehicle and use a circle with a diameter equal to the vehicle length to represent the vehicle swath. If a hazard is within the circle, then a crash would be predicted.

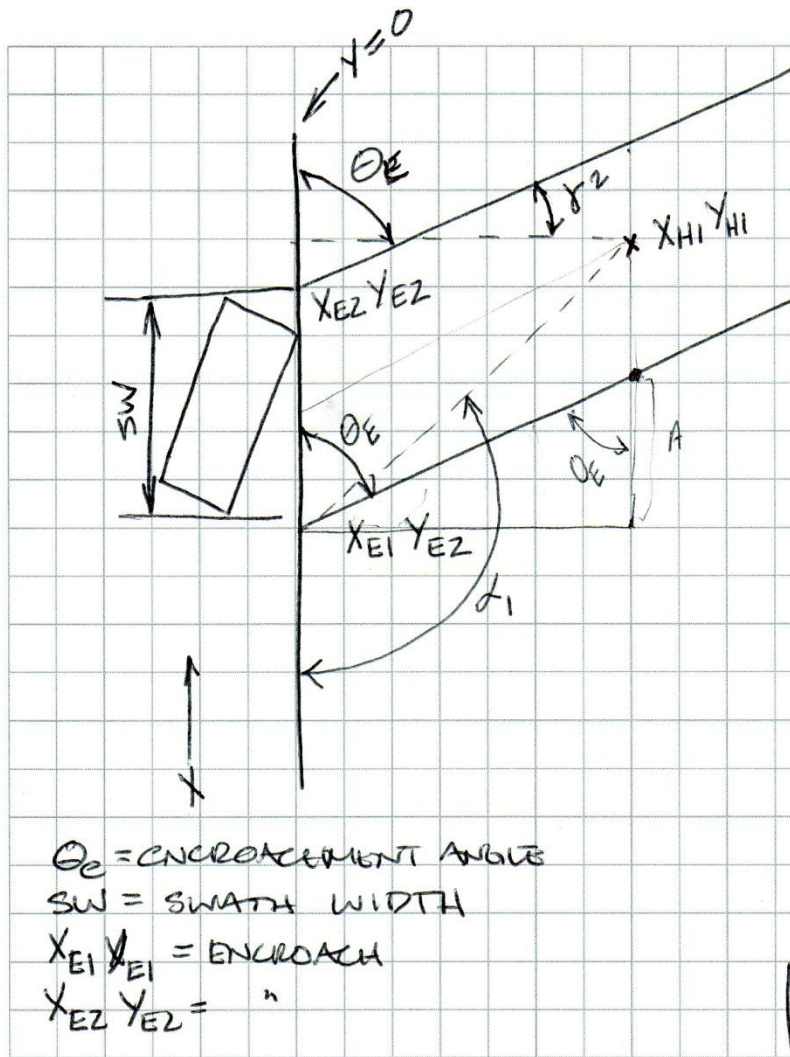


Figure B-5. Crash Predictions.

Severity and Cost Prediction Module

Given a crash, the severity of the crash is determined using a Severity Index (SI). There are a wide variety of published SIs for hazards which relate the vehicle speed and angle of impact to the severity of the crash.

RSAP uses an SI/unit of speed with speed in kilometers per hour. This software is coded in Imperial units, therefore miles per hour (MPH) was used. To convert the SIs used in the RSAP code to SI/MPH, the SI values were divided by 0.6213881.

In the “SI-Injury-Cost” tab, the programmed SI values are shown with the corresponding hazard and a numeric code from 1-10. If the user chooses to change the ten provided SIs, the Hazard Name and SI value should be changed here. From the user entry tab the user can view the hazard name and corresponding numeric code for convenience. The user should enter the numeric code in the yellow box which best represents the hazard.

After determining the severity of the crash, the equivalent crash cost can be evaluated. The spreadsheet also asks the user for input as to which crash cost scale should be used. The user supplies this information in the user input worksheet. The default values are the FHWA willingness-to-pay values. This information is transferred to the “SI-Injury-Cost” tab and adjusted for the over-reporting of higher severity crashes and used to predict crash cost. The data is referenced by means of a look-up table. Using table B-1 as an example of the adjusted FHWA costs, an SI between four and five would yield a crash cost equal to \$20,964.

Table B-1. Crash Costs Related to Severity Index.

Cost	SI
\$0	0
\$2,000	0.5
\$1,006	1
\$2,707	2
\$8,536	3
\$20,964	4
\$49,336	5
\$104,244	6
\$169,204	7
\$339,050	8
\$661,640	9
\$2,600,000	10

These crash costs are summed for the positive crashed modeled within the segment during the Monte Carlo analysis. The cumulative crash cost is then divided by the number of iterations to determine the average crash cost of any crash on the segment.

Upon determining the average crash cost, the probability of encroaching far enough to impact the hazard has to be considered. This extra step reduces the average crash cost based on the offset of the hazard as follows:

$$y = \frac{e^{5.768-0.262x}}{3.19}$$

where:

y=percent exceeding lateral distance x

x=lateral distance to hazard in meters

This model is appropriate for two-lane undivided roads.

After modifying the average single crash cost per segment by the lateral extent of encroachment, next the encroachment rate, discussed above, in units of encroachments per segment is multiplied to determine the average crash cost per segment per year. These results are presented alongside the segment data in the “results” tab.

Benefit-Cost Analysis for Highways

After the segment average crash costs per year and the direct costs are determined for each improvement alternative, the concept of incremental benefit/cost (*B/C*), discussed above, is used to determine the cost-effectiveness of the design and choose the preferred alternative.

Summary and Conclusions

This appendix describes the software which accompanies the performance-based highway design process proposed by this research. This software supports the proposed analysis phase of the performance-based process, analyzing highway safety as the outcome. Results are currently presented in the “results” tab. This workbook can be expanded to include a broader range of measurable outcomes. Additions to the workbook can be made in subsequent tabs and results added to the “results” tab, allowing for a more complete performance-based analysis of highway design.

This workbook incorporates some AMFs used in the HSM, introduces the use of the industry standard of Station and Offset to describe segments and location hazards and automatically sorts hazards for the user. Observations and suggestions have been made

throughout this document could be considered during future research efforts. Particular attention should be paid to three general areas which include the segment and hazard identification by Station and Offset; the use of scientific verses imperial units; and the data derived from random numbers. Additional attention should also be paid to the vehicle path during an encroachment.

Identification of segments and hazards by Station and Offset would allow users to enter data directly from a printed plan set or similar set of construction documents. Meticulous attention should be given to scenarios where hazards are located along the baseline or segments/hazards have negative stations to ensure this does not create an error.

The encroachment probability model includes a series of conditional probabilities. Each conditional probability has a model which supports the outcome. Some of these models are dependent on variables which include units of measure. Every effort should be made to remove conversions between various units to reduce the possibility of error. One possible solution may include two sets of lookup tables, one for imperial units and one for scientific units, with only the mathematics hard coded.

The generation of random numbers and the calculations resulting from each generated number requires computation time. One possible way to reduce computation time is to reduce the number of random numbers required. This would have to be accomplished without obstructing the intent of the Monte Carlo simulation. Two possible areas to consider this reduction are the vehicle class generation and the direction of travel/side of the road generation.

There are thirteen recognized vehicle classes, but many of these classes have some overlap between the vehicle sizes. Future development efforts may consider reducing these classes into categories of vehicles such as passenger vehicles, box trucks, etc. with the same swaths.

The direction of travel and the side of the road the vehicle encroaches toward could possibly be combined into one random number generation per simulated encroachment. Future development efforts could consider combining all of the possible scenarios and generating one random number per combined scenario to reduce computation time.

In summary, this workbook can be used to calculate annual crash costs. This workbook demonstrates the use of AMFs, automatic hazard sorting and the use of Station and Offset. Using Excel has exposed all of the calculations and allows the user to calibrate individual calculations, as necessary, with field collected crash data. The resulting annual crash costs can be used in a performance-based analysis of highway design alternatives.