National Cooperative Highway Research Program
(NCHRP)

Project 22-27

ROADSIDE SAFETY ANALYSIS PROGRAM (RSAP) UPDATE

DRAFT INTERIM REPORT

Malcolm H. Ray
Shaw-Pin Miaou
Christine E. Conron

Malcolm H. Ray, P.E., Ph.D.
186 Staples Hill Road
Canton, Maine 04221

26 January 2010

Table of Contents

LIST OF TABLES vi
LIST OF FIGURES vi
CHAPTER 1 1
INTRODUCTION 1
CHAPTER 2 3
LITERATURE REVIEW 3
INTRODUCTION 3
Background 3
Crash-Data Approach 5
Encroachment Approach 13
Comparison of the Crash-Based and Encroachment-Based Approaches 23
RSAP 30
Background 30
Roadside and RSAP 33
Methodology 33
Modeling Encroachments 36
Modeling Crashes 48
Modeling Crash Severity 49
Severity Measures 60
RSAP Severity Indices 62
Severity Index Calibration 67
Limitations 68
Bugs, Errors and Discrepancies 69
HIGHWAY AND ROADSIDE DESIGN SOFTWARE 85
Highway Design Software Suites 85
AutoCAD Civil3D by Autodesk 86
Highway Design Suites by Bentley 86
Roadside Design Programs 87
Data Exchange 92
Software Platform and Programming Issues 93
Summary 95
CHAPTER 3 97
RESULTS OF SURVEY OF PRACTICE 97
Question 1: Please provide the following optional information about yourself. 97

Question 2: What type of work do you do? ... 97
Question 3: Which highway design software tools does your company/organization use for design and plan production? ... 98
Question 4: Please list other software tools you use to assist with design decisions and cost analysis. ... 98
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? ... 99
Question 6: What have you used RSAP to evaluate? ... 99
Question 7: Do you like the RSAP user interface? ... 100
Question 8: Do you like RSAP functionalities? ... 100
Question 9: Do you find the RSAP default data tables appropriate? ... 101
Question 10: Do you like the RSAP methodology? ... 102
Question 11: Do you find the RSAP User's Manual helpful? ... 102
Question 12: Do you find the Engineer's Manual helpful? ... 102
Question 13: While using RSAP, have you encountered any incidents where your analysis results from RSAP were inconsistent with your experience/expectations/judgment? ... 103
Question 14: Are you aware of reports or papers about RSAP documenting its use? Please list them here. ... 103
Question 15: What improvements would you like to see made to RSAP? ... 103
Question 16: Which features of RSAP would you like to see remain unchanged in the next release? ... 104
Question 17: Do you see value in integrating RSAP with popular highway design software tools such as AutoCAD Civil3D or Bentley InRoads? ... 104
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? ... 104
Question 19: Do you believe safety, or the potential for crashes should be considered when designing highway improvements? ... 104
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. ... 104
Conclusions ... 105
CHAPTER 4 ... 107
RESEARCH PLAN ... 107
Revised Work Plan ... 107
TASK6 A: Programming, Software and Algorithms ... 110
Task 6A1: Program Architecture ... 110
Task 6A2: Develop Data Table Specifications ... 111
Task 6A3: Pseudo-code documentation ... 112

Task 6A4: Re-write the Software ... 113
Task 6A5: Verification ... 115
TASK 6B: Data Representation ... 116
Task 6B1: Convert Existing Data to Conforming Data Tables ... 116
Task 6B2: Encroachment Model Updates ... 117
Task 6B3: Multilane Adjustment Factor ... 120
Task 6B4: Updated Severity Indices ... 121
Task 6B5: Penetration of Features ... 123
Task 6B6: Driver Input and Curvilinear Paths ... 125
TASK 6C: Validation ... 126
Task 6C1: Benchmark Cases ... 126
Task 6C2: Validation ... 126
Task 6C3: Compare RSAP and HSM ... 128
TASK 7: Alpha and Beta Testing ... 128
TASK 8: Final Report ... 130
REFERENCES ... 133
APPENDIX A ... 141
SEVERITY INDICES – VEHICLE SPEED RELATIONSHIPS FOR EIGHT TYPES OF ROADSIDE FEATURES IN THE RSAP 2.0.3 ... 141
APPENDIX B ... 157
SURVEY FORM AND RESPONSE DATA ... 157

LIST OF TABLES

Table 1. Default Distribution for Accident Severity Level on Rural Two-Lane Highways.......... 8
Table 2. Default distribution for Accident Type and Manner of Collision on Rural Two-Lanes . 8
Table 3. Definitions of Roadside Hazard Ratings Used in Crash Prediction Models 10
Table 4. Safety Prediction Worksheet for a Roadway Segment.. 12
Table 5. Input data for sample applications. 25
Table 6. Differences between the RSAP and IHSDM CPM Input Data. 27
Table 7. Results of Alternatives Analysis Using RSAP and IHSDM CPM. 29
Table 8. Comparison of RSAP and ROADSIDE. [after Mak03] 34
Table 9. Twelve built-in v-ditch configurations in the current RSAP program. 58
Table 10. Thirty-four built-in fixed objects in the current RSAP program. 58
Table 11. Top five most harmful events when entering ditches and striking guardrail face........ 59
Table 12. Severity Index to Severity Distribution Conversion Table used in RSAP program.... 63
Table 13. Maximum test impact severity under six test levels as specified in Report 350. 83
Table 15. PLANSAFE Regression Models. 91

LIST OF FIGURES

Figure 1. Photographic Representation of Roadside Hazard Ratings (RHR)............................. 11
Figure 2. ROR Crash Predictions Using RSAP and IHSDM CPM.. 29
Figure 3. RSAP computational flow chart.. 32
Figure 4. RSAP Base Roadside Encroachment Rate. [Mak03].. 37
Figure 5. Cooper Base Encroachment Rate.. 37
Figure 6. Roadside Encroachment Rates for 6 and 8-Lane Divided Highways with 12-ft lanes. 40
Figure 7. Horizontal Curvature Adjustment Factor.. 42
Figure 8. Grade Adjustment Factor. 44
Figure 9. Example of Relationship Between SI and Impact Speed. 50
Figure 10. Seat belt usage rates in the US from 1983 to 2009... 53
Figure 11. NCHRP 22-12(2) severity index calibration procedure. 68
Figure 12. Base Roadside Encroachment Rate Curve for Divided Highways. 71
Figure 13. Roadside Encroachment Rates for 6 and 8-Lane Divided Highways. 71
Figure 14. Exceedance Probability: Code vs. Engineer’s Manual.. 73
Figure 15. Base Encroachment Rates Using Under-Reporting Ratios in EM. 74
Figure 16. LandXML Data Diagram. 92
Figure 17. Example LandXML Data Export. 93
Figure 18. Distribution of Respondents’ Work Categories. 98
Figure 19. Distribution of CAD Software Use. 99
Figure 20. Distribution of RSAP Use Frequency. 100
Figure 21 Flow Chart of NCHRP 22-27 Phase II Tasks.. 109
Figure 22. Revised Project Budget 131
Figure 23. Revised Project Schedule 132

CHAPTER 1
INTRODUCTION

The Roadside Safety Analysis Program (RSAP) is a computer program for performing cost benefit analyses on roadside designs [Mak03]. The original version of RSAP was developed under NCHRP Project 22-9(1) [Mak03]. Subsequently, some improvements were made, bugs corrected and patches installed under NCHRP Project 22-9(2) [Mak03]. Finally, a third NCHRP project, 22-9(3) was initiated but never completed. RSAP has been distributed with the AASHTO Roadside Design Guide (RDG) since the 2002 edition [AASHTO02].

A key step in performing such analyses is to estimate the frequency and severity of roadside crashes for a particular roadside design where the design encompasses highway geometric features like the horizontal curvature and grade as well as the roadside features like the location and type of guardrails, the shoulder widths and the slope of the roadside. Once the frequency and severity of crashes has been estimated, the cost can be found by mapping the frequency and severity into units of dollars given the average societal cost of each expected crash. A roadside design that results in a smaller societal cost is, therefore, a safer and better design. If the reduction in crash costs over the design life of the improvement are greater than the construction and maintenance costs of the improvement the design is cost-beneficial and should be constructed. On the other hand, if the reductions in crash costs are less than the construction/maintenance cost of the improvement the project probably is not worth pursuing.

Estimating the frequency and severity of crashes for a given roadside design can be very challenging since a good deal of data is required. Some of this existing data is currently hardcoded into RSAP and some is entered by the designer. For example, crash costs and roadside objects are hardcoded, but the analyst enters the roadway geometry for each project. Advances in computers and design support software has made the possibility of automating project specific data entry possible and left users expecting more from computer software and their user interfaces. Progress in roadside hardware and roadside research has made the hardcoded data tables outdated.

The objectives of this research are to rewrite the software, update the manuals, improve the user interface, and update the embedded default data tables of RSAP. A new version of the RSAP software will be produced in this project. For convenience the updated program is called RSAP2010 in this report.

Chapter 2 provides a literature review of the history of both the crash-data and encroachment approach to modeling crashes, the software support available for both approaches, and other software used for highway design purposes. A summary of the results of a survey of design, research, and construction practitioners about their use and experiences with RSAP is included in Chapter 2. Concerns and suggestions for improvements for RSAP have been identified through the survey and are summarized. Gaps in the literature are identified to permit these issues to be addressed during the second phase of this research. Finally, recommendations for the improvement of RSAP are presented in a work plan (Chapter 4) which aims to address concerns identified in the survey and gaps identified in the literature review.

CHAPTER 2
LITERATURE REVIEW

INTRODUCTION
Background

Motor vehicles crashes cost society more than $230 billion annually [FHWA08b]. On an average day, 117 fatal crashes occur on U.S. roadways, 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.

Run-off-road (ROR) traffic crashes account for almost one-third of the deaths and serious injuries each year on the Nation's highways. There were 41,059 people killed in motor vehicle crashes in 2007, of which 15,506 people (i.e., more than 37percent) were killed in single-vehicle run-off-road crashes [NHTSA07]. Collisions with fixed objects and non-collisions (e.g., rollovers which mainly occurred off the road) accounted for about 19 percent of all crashes but they were responsible for 46 percent of fatal crashes.

Inattentive driving, including distracted driving, drowsy driving, or fatigued driving, has been identified as a significant causal factor in crashes of all types.[FHWA01] While inattentive driving is not always identifiable during crash investigations, such behavior is considered by many to be prevalent among a large number of drivers involved in crashes. With the recent trend in “cell phone driving” and “texting while driving,” it has been suggested that inattentive driving is as serious a problem as impaired driving under the influence of alcohol and drugs. [HO08] Inattentive driving and impaired driving have been, and will continue to be, responsible for the majority of inadvertent roadside encroachments and thus run-off-the-road (ROR) crashes.

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 below:

- 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 [HSA66].
- 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 [HSA73].
- 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 the Hazard Elimination Program [FHWA08d].
- The *Intermodal Surface Transportation Efficiency Act of 1991:* This legislation was responsible for funding the two programs enacted under the 1978 legislations [FHWA08d].
- The *Transportation Equity Act for the 21st Century:* This legislation added a provision that States must consider bicycle safety [FHWA08d].

Much of this legislation, including the most recent, also was a means to provide funding for the operation of the U. S. National Highway System (NHS). Many different factors contribute to the cost of operating a transportation system such as the network of roads that comprise the NHS. Costs are realized from the planning of the network through the design, construction and maintenance of the network. Many of these costs are obvious: the design cost, the construction costs and the costs to maintain the infrastructure. Some costs, however, 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 during a Value Engineering (VE) review. When the potential for vehicles striking the guardrail is considered, however, the societal cost of crashes and increased guardrail repair costs throughout the design life of that section of road may result in costs not considered in the traditional design or VE process. 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, for example, moving the culvert intake farther from the road such that a guardrail is no longer necessary. While the construction cost for moving the culvert out of the clearzone would be greater, if this construction cost results in fewer crashes and the corresponding smaller societal costs of crashes, this may be the better alternative.

The *National Highway System (NHS) Designation Act*, passed by Congress in 1995, included a provision that required States to conduct a VE analysis for all NHS projected with an estimated construction cost of $25 million or more [NHS95]. In 1997, VE regulations were published by the Federal Highway Administration (FHWA), establishing the program [VE08] The FHWA's website devoted to VE analysis suggests that "Federal, State and local highway agencies are responsible for getting the best overall project value for the taxpayer. …VE is an organized application of common sense and technical knowledge directed at finding and eliminating unnecessary costs in a project." [VE08] The FHWA suggests that design, right-of-way and construction costs shall be included in a VE analysis. Unfortunately, this 1995 *NHS Designation Act* requiring VE analysis and the *Transportation Equity Act for the 21st Century* with a focus on highway safety, do not share the same goal of increasing highway safety throughout the United States, as the foregoing definition of VE does not specifically address safety. A VE analysis of the design, right-of-way and construction costs is limited in scope and has the potential to overlook or eliminate design features which have the potential to improve safety therefore increasing the potential for crashes and the resulting societal costs.

Safety or the potential for crashes is not often directly considered during the planning and design phases of a project but highway designers often rely on established design standards as a means for producing a "safe" design. These established design standards, including the American Association of State Highway and Transportation Officials' (AASHTO) *A Policy on Geometric Design of Highways and Streets* (i.e., the Green Book) and the *Roadside Design Guide* (RDG), also published by AASHTO, provide the designer with criteria for designing a roadway [AASHTO01; AASHTO06]. While these guidelines are simple to follow, they may not result in the safest designs. For example, the Green Book suggests in Exhibit3-26 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) should be used when there is no super-elevation [AASHTO01]. This criterion does not consider the interaction of the horizontal curvature with other highway characteristics like the vertical alignment, the clear zone, the number of lanes, the side slopes or the expected traffic. The horizontal alignment is considered independent of the other characteristics of the road even though common sense would suggest that all the highway alignment characteristics are interrelated.

Mathematical models have been developed to predict where crashes might occur along the road and the roadside as a function of traffic and geometric characteristics. These complex statistical models often consider the vertical and or horizontal alignment of the highway, the placement of roadside objects, the speed of the traffic and 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 included as 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.

Highway engineers are constantly designing and building, and redesigning and rebuilding roadways to meet higher standards to provide ever safer highways with increased mobility. This includes designing and building roadways that are more forgiving when a driver inadvertently encroaches onto the roadside. There are, however, impediments that keep highway engineers from achieving the desired design and operational goals of safety and mobility including the need to operate, maintain, and improve a vast highway system with limited resources. Consequently, highway engineers are often required to make incremental improvements over time and make difficult trade-offs between cost, safety and mobility. Modeling tools that enable highway engineers to evaluate the costs and benefits of highway design decisions are essential in making these trade-offs.

Historically, models of the relationships between ROR crashes and roadside features, such as utility poles, traffic sign posts, trees, guardrail, median barriers and side-slopes, have been categorized as either crash-based or encroachment-based approaches. The following sections describe, compare and contrast each of these basic analysis approaches.

Crash-Data Approach

Background

Crash-data based approaches generally take advantage of police-level crash reports that are collected by all the States. The main strength of using the crash-based approach is the sheer size of the available crash and road inventory data which are collected and maintained routinely by state Departments of Transportation (DOTs), Departments of Public Safety, and the National Highway Traffic and Safety Administration (NHTSA). The limitation of using this real-world crash data is its lack of detail regarding the roadside, vehicle, and collision conditions. In addition, minor crashes tend to be underreported and/or under-coded in the state traffic crash database so lower severity crashes are usually not included.

Since the 1980s crash-based roadside studies, including many conducted as part of the Federal Highway Administration's (FHWA) Interactive Highway Safety Design Model (IHSDM) program discussed in a later section, have largely been limited to a small number of roadside features or some sort of roadside hazard indexes on rural two-lane roads and intersections. The crash-based approach relies mainly on statistical regression models to develop macro-level relationships between reported ROR crashes and associated traffic, highway geometric and roadside characteristics. Typically the regression models are formulated to predict reported ROR crash frequencies by severity for a selected set of sites (e.g., typically intersections or road segments). The crash severity predictions are the dependent or outcome variables and traffic, highway geometrics, and roadside characteristics associated with these sites are the independent or explanatory variables. The predictive values from these regression models, together with estimated uncertainties, are then used in risk and benefit-cost analysis.

In the last four decades there have been dramatic developments in the statistical and biomedical sciences on specialized statistical regression methods for handling discrete/categorical types of response data, such as event frequency or event count data like highway crashes. These developments "reflect the increasing methodological sophistication of scientists and applied statisticians, most of whom now realize that it is unnecessary and often inappropriate to use methods for continuous data with categorical responses." [Agresti96] Many textbooks have been published to introduce these new techniques under such titles as categorical data analysis, generalized linear models, models for discrete data, models for limited-dependent variables, and, recently, generalized linear mixed models. In addition, statistical procedures for carrying out these regressions are now available or programmable in many popular statistical software packages like SAS and SPSS.

The advent of statistical techniques for treating discrete response data has triggered an explosive number of crash-based studies with more appropriate statistical regression models and associated goodness of fit measures in the last 20 years [Miaou92; Miaou93; Miaou94]. In these newer crash-based studies, the focus has largely been on traffic volume and highway design characteristics, such as AADT, lane width, horizontal curvature, grade, and different lane and intersection configurations. The promising results from many of these studies over the past several years have led to three recently completed and one pending NCHRP projects under an extensive initiative by the Transportation Research Board (TRB), FHWA, and AASHTO aimed at developing a Highway Safety Manual (HSM).

Highway Safety Manual

The development of the Highway Safety Manual is both the synthesis and culmination of the crash-data based approach to highway and roadside safety [AASHTO09]. Development of the HSM was initiated by a Transportation Research Task Force and, so far, supported by six NCHRP projects totaling more than $3 million with additional projects still being planned. The HSM focuses on knowledge and tools relevant to the safety profession and will quantify the safety effects of decisions in planning, design, operations, and maintenance. It is intended to serve a role for safety analysis similar to that which the Highway Capacity Manual (HCM) serves for traffic operational analysis.

The HSM targets practitioners in the daily decision making process within state highway agencies, as well as local organizations such as municipal agencies and Metropolitan Planning Organizations. The following projects, three of which are completed and one which is still underway, focus on the development of statistical accident or crash predictive models using a crash-data based approach, quantifying relationships between roadway characteristics and crash experience for various roadway classes:

- NCHRP Project 17-18(4): Developed a prototype chapter of the HSM on rural two-lane highways. [Bellomo02]
- NCHRP Project 17-26: Developed a quantitative safety prediction methodology on urban and suburban arterials. [Harwood07]
- NCHRP Project 17-29: Developed a quantitative safety prediction methodology on rural multilane highways. [Lord08]
- NCHRP Project 17-45: Developing an enhanced safety prediction methodology and analysis tool for Freeways and Interchanges. [NCHRP 17-45]

Crash prediction models and associated accident modification factors (AMF) in the HSM are currently separated into two model categories: road segment models and intersection models.

Intersection and intersection related crashes are defined as those that have occurred within 250 ft from the geometric center of an intersection. All other crashes are considered road segment crashes. The physical coverage of intersections and segments are accordingly defined. In all modeling projects conducted for the HSM, efforts were made to follow this definition of intersections and segments and associated crashes to the greatest extent possible and to ensure that no overlapping or double counting occurred in assigning crashes to these two types of roadway entities.

The following is a summary of crash prediction models and associated AMF developed for HSM from various projects focusing on models for road segments.

NCHRP Project 17-18(4): Rural Two-Lane Highways

- Types of models: Segment and intersection models.
- Base segment model: Total crashes using Washington State and Minnesota crash data.
- AMF: lane width, shoulder width and type, horizontal curves, super-elevation, vertical grades, driveway density, passing lanes, two-way left-turn lanes, roadside hazard rating (RHR).
- Calibration factor for local conditions: Calibration methods described in the manual for a particular geographical area or highway agency.
- Ability to estimate ROR crashes by severity: It is possible but extremely limited based on predictions of total number of crashes from the model and the raw distribution of crashes and severity types as shown in Tables 1 and 2 taken from the HSM.

NCHRP Project 17-29: Rural Multilane Highways

- Types of models: Segment and intersection models. The project had problems separating crashes by the segment-intersection definition described earlier (i.e., the 250 ft rule).
- Models for segments: Divided highways and undivided highways:
    - California models (Total Crashes and Injury Crashes): AADT, lane width, shoulder width, number of intersection on the segment
    - Texas model (Total Crashes and KAB, or Fatal and Injury, Crashes): AADT, lane width, shoulder width, number of curves on segment
    - Minnesota model (Total Crashes and Injury Crashes): AADT, lane width, shoulder width
- AMF: Divided versus undivided highways, horizontal curves, side-slopes, median barrier, median width, lane width and paved shoulder width.
- Calibration factor for local conditions: Used the same calibration methods described for two-lane highways in the manual.
- Ability to estimate ROR crashes by severity: No, crashes were grouped into single-vehicle and multi-vehicle crashes. The project did not subdivide single-vehicle crashes into finer categories, such as collisions with animals, fixed objects, other objects, etc.

Table 1. Default Distribution for Accident Severity Level on Rural Two-Lane Highways. [AASHTO09]

EXHIBIT 2. DEFAULT DISTRIBUTION FOR ACCIDENT SEVERITY LEVEL ON RURAL TWO-LANE HIGHWAYS

Accident severity level	Percentage of total accidents: Roadway segments[a]	Three-leg STOP-controlled intersections[b]	Four-leg STOP-controlled intersections[b]	Four-leg signalized intersections[b]
Fatal	1.3	1.1	1.9	0.4
Incapacitating Injury	5.4	5.0	6.3	4.1
Nonincapacitating injury	10.9	15.2	12.8	12.0
Possible injury	14.5	18.5	20.7	21.2
Total fatal plus injury	32.1	39.8	41.7	37.7
Property damage only	67.9	60.2	58.3	62.3
TOTAL	100.0	100.0	100.0	100.0

[a] Based on HSIS data for Illinois (1992), Michigan (1995), Minnesota (1996), and North Carolina (1995).
[b] Based on HSIS data for Michigan (1995) and Minnesota (1996).

Accident severity distributions are estimated with Exhibit 2.

Table 2. Default distribution for Accident Type and Manner of Collision on Rural Two-Lane Highways [AASHTO09]

Highway Safety Manual

Accident type and manner of collision distributions are estimated with Exhibit 3.

EXHIBIT 3. DEFAULT DISTRIBUTION FOR ACCIDENT TYPE AND MANNER OF COLLISION ON RURAL TWO-LANE HIGHWAYS.

Accident type and manner of collision	Percentage of total accidents: Roadway segments[a]	Three-leg STOP-controlled intersections[b]	Four-leg STOP-controlled intersections[b]	Four-leg signalized intersections[b]
SINGLE-VEHICLE ACCIDENTS				
Collision with animal	30.9	2.1	0.6	0.3
Collision with bicycle	0.3	0.7	0.3	1.0
Collision with parked vehicle	0.7	0.1	0.1	0.1
Collision with pedestrian	0.5	0.4	0.2	1.3
Overturned	2.3	2.1	0.6	0.4
Ran off road	28.1	10.4	4.5	1.9
Other single-vehicle accident	3.6	3.9	1.4	1.6
Total single-vehicle accidents	66.3	19.7	7.7	6.6
MULTIPLE-VEHICLE ACCIDENTS				
Angle collision	3.9	29.8	51.4	28.5
Head-on collision	1.9	2.0	1.4	1.8
Left-turn collision	4.2	6.4	5.9	9.0
Right-turn collision	0.6	0.4	0.2	0.4
Rear-end collision	13.9	26.2	17.2	36.2
Sideswipe opposite-direction collision	2.4	2.9	1.7	2.0
Sideswipe same-direction collision	2.6	4.5	4.4	5.5
Other multiple-vehicle collision	4.1	8.1	10.1	10.0
Total multiple-vehicle accidents	33.7	80.3	92.3	93.4
TOTAL ACCIDENTS	100.0	100.0	100.0	100.0

[a] Based on HSIS data for Illinois (1992), Michigan (1995), Minnesota (1996), and North Carolina (1995).
[b] Based on HSIS data for Michigan (1995) and Minnesota (1996).

NCHRP Project 17-26: Urban and Suburban Arterials

- Types of Models: Segment and intersection models
- Models for Segments:
    - Two-lane undivided arterials (2U),
    - Three-lane arterials including a center TWLTL (3T),
    - Four-lane undivided arterials (4U),
    - Four-lane divided arterials (i.e., including a raised or depressed median) (4D) and
    - Five-lane arterials including a center TWLTL (5T).
- Base Segment Models**:** Single-vehicle crashes; total, fatal, injury and property-damage-only (PDO) crashes using the Minnesota and Michigan data.

- Minnesota data: ADT, On-street parking, and roadside hazard rating (RHR).
  - Michigan: ADT and shoulder width for a few highway types.
- <u>AMF:</u> On-street parking, roadside fixed objects (i.e., fixed objects density), roadside hazard rating and lighting.
- <u>Calibration factor for local conditions:</u> Used the same calibration methods described for two-lane highways in the manual.
- <u>Ability to Estimate ROR crashes by Severity:</u> Yes, but limited. Used single-vehicle prediction models together with distributions of single-vehicle collisions for roadway segments by collision type. Collision types included: collision with parked vehicle, collision with animal, collision with fixed object, collision with other object, other single-vehicle collision and non-collision.

The HSM attempts to predict all types of crashes on the highway segments or intersections. Roadside features are largely accounted for using a roadside hazard rating (RHR) as an explanatory variable to represent roadside conditions in crash prediction models. RHR is a qualitative index that is very subjective and visual. The visual comparison relies mainly on side-slope and clear zone impressions from video-logs or visual inspections to determine roadside conditions. Table 3 lists the characteristics that are meant to be indicative of each RHR score. The RHR has a scale of 1 to 7; 1 for very good to 7 for very poor roadside conditions, respectively.

Using the text descriptions or the original photos (i.e., see Figure 1), 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 (see Figure 1) is under consideration, the RHR would likely still equal four, even after the unprotected hazard at the start of the guardrail has been removed. The RHR, then, is a very course representation of the roadside.

After determining the RHR, the AMF developed by Zegeer *et al.* and adopted by the HSM to account for the affect of roadside design can be calculated. [Zegeer81] The base model 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 for each 250 foot segment, which represents both sides of the road, is calculated as follows [AASHTO09]:

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

where:

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

The roadside AMF is only one of many AMFs. Table 4 is a worksheet from the HSM that leads the user step-by-step to compute the expected number of crashes for a two-lane road segment using a variety of AMFs to modify the base model. All the crash models by crash type and severity developed for HSM can be used in a similar manner. Worksheets guiding users to make predictions for intersection models are also available in the HSM. Since these models were developed using crash data from a small number of states, calibration methods have been developed for users to adjust crash prediction models for a particular geographical area.

Table 3. Definitions of Roadside Hazard Ratings Used in Crash Prediction Models [AASHTO09;Zegeer88]

Roadside Hazard Rating (RHR)	**Roadside Design Characteristics**
1	• Wide clear zone greater than or equal to 30 ft from the pavement edge-line • Side-slope flatter than 1:4 • Recoverable
2	• Clear zone between 20 to 25 ft from pavement edge-line • Side-slope about 1:4 • Recoverable
3	• Clear zone about 10 ft from pavement edge-line • Side-slope about 1:3 or 1:4 • Rough roadside surface • Marginally recoverable
4	• Clear zone between 5 to 10 ft from pavement edge-line • Side-slope about 1:3 or 1:4 • May have guardrail 5 to 6.5 ft from pavement edge-line • May have exposed trees, poles, or other objects (about 10 ft from pavement edge-line) • Marginally forgiving, but increased chance of a reportable roadside collision
5	• Clear zone between 5 to 10 ft from pavement edge-line • Side-slope about 1:3 • May have guardrail 0 to 5 ft from pavement edge-line • May have rigid obstacles or embankment within 6.5 to 10 ft of pavement edge-line • Virtually non-recoverable
6	• Clear zone less than or equal to 5 ft (from pavement edge-line)* • Side-slope about 1:2 • No guardrail • May have guardrail 0 to 5 ft from pavement edge-line • Exposed rigid obstacles within 0 to 6.5 ft of the pavement edge-line • Non-recoverable
7	• Clear zone less than or equal to 5 ft (from pavement edge-line)* • Side-slope 1:2 or steeper • Cliff or vertical rock cut • No guardrail • Non-recoverable with high likelihood of severe injuries from roadside collision

*The clear zone condition "(from pavement edge-line)" was added for clarity.

The crash-data based approach, then, has been used to develop statistical regression models based on police-level reported crashes. The HSM has collected many of the different statistical models and created a systematic approach to estimating the number of highway segment and intersection crashes. The roadside component of the HSM prediction, however, is very course since it depends almost entirely on the RHR. The RHR is simply not precise enough to detect subtle differences in roadside feature design or placement.

Figure 1. Photographic Representation of Roadside Hazard Ratings (RHR). [Harwood00]

Table 4. Safety Prediction Worksheet for a Roadway Segment. [AASHTO09]

EXHIBIT 12. SAFETY PREDICTION WORKSHEET FOR A ROADWAY SEGMENT

ROADWAY SEGMENT SAFETY PREDICTION WORKSHEET	
General Information	***Site Information***
Analyst ______	Highway ______
Agency or Company ______	Roadway Section ______
Date Performed ______	Jurisdiction ______
Analysis Time Period ______	Analysis Year ______
Input Data	
Length of segment (mi) – L	
ADT (veh/day)	
Lane width (ft)	
Shoulder width (ft)	
Shoulder type (paved/gravel/composite/turf)	
Presence or absence of horizontal curve (curve/tangent)	
Length of horizontal curve	
Radius of horizontal curve (ft)	
Presence or absence of spiral transition curve	
Superelevation of horizontal curve	
Grade (percent), straight grade from PVI to PVI	
Driveway density (driveway per mi)	
Presence or absence of passing lane	
Presence or absence of a short four-lane section	
Presence or absence of a two-way left-turn lane	
Roadside hazard rating	
Base Model	
From Equation (5): $N_{br} = (ADT)(L)(365)(10^{-6})\exp(-0.4865)$	
Accident Modification Factors	
Lane width (if lane widths differ for two directions, determine the AMFs separately)	
AMF_{ra} - AMF for Related Accident (Exhibit 4)	
$AMF = (AMF_{ra} - 1)0.35+1.0$	
Shoulder width and type AMF (if widths and or type differ for two directions, determine the AMFs separately)	
AMF_{wra} - AMF for related accidents based on shoulder width (Exhibit 5) AMF_{tra} - AMF for related accidents based on shoulder type (Exhibit 6)	
$AMF = (AMF_{wra}\ AMF_{tra} - 1.0)\ 0.35 + 1.0$	
Horizontal Curve	
Length, Radius and Presence or Absence of Spiral Transition	
$AMF_{LRS} = \dfrac{1.55L_c + \dfrac{80.2}{R} - 0.012S}{1.55L_c}$ (Equation [8])	
Superelevation	
SD - Super elevation (Exhibit 7)	
If $SD < 0.01$, $AMF_S = 1.00$ If $0.01 \leq SD < 0.02$, $AMF_S = 1.00 + 6(SD-0.01)$ If $SD \geq 0.02$, $AMF_S = 1.6 + 3\ (SD-0.02)$	
$AMF = AMF_{LRS}\ .\ AMF_S$	
Grades	
AMF (Exhibit 9)	
Driveway Density	
$AMF = \dfrac{0.2+[0.05-0.05\ln(ADT)]DD}{0.2+[0.05-0.05\ln(ADT)](5)}$ (Equation [13])	
Passing Lanes	
For conventional passing lane added in one direction of travel on the two-lane highway - AMF = 0.75 For short four-lane sections - AMF = 0.65	
Two-Way Left-Turn Lanes	
$P_D = \dfrac{0.0047DD + 0.0024DD^2}{1.199 + 0.0047DD + 0.0024DD^2}$ (Equation [15]) $P_{LT/D} = 0.5$	
$AMF = 1-0.7\ P_D\ P_{LT/D}$ (Equation [14])	
Roadside Design	
Determine appropriate roadside hazard rating RHR from Appendix C	
$AMF = \dfrac{\exp(-0.6869 + 0.0668RHR)}{\exp(-0.4865)}$ (Equation [16])	
Calibration Factor	
C_r (Appendix A)	
Safety Prediction Model	
From Equation (1): $N_{rs} = N_{br}\ C_r\ (AMF_{1r}\ AMF_{2r} \ldots AMF_{nr})$	

Exhibit 12 presents the safety prediction worksheet for roadway segments.

Encroachment Approach

Background

The other alternative available for making decisions about roadside design is the encroachment approach. There is a long history of the use of the encroachment approach for cost-benefit and probabilistic methods in roadside safety dating back to at least 1974. Not surprisingly, the literature devoted to cost-benefit methods in roadside safety, crash prediction modeling, encroachment modeling, severity modeling is extensive going back as far as Hutchinson in 1962 and proceeding right up to present-day on-going NCHRP projects like Projects17-11 and 17-22.[Hutchinson62, Bligh08] In his Ph.D. dissertation, Ray provided an extensive review of the research related to probabilistic modeling of roadside crashes as of 1993.[Ray93] Turner wrote an NCHRP Synthesis report in 1994 collecting the latest research on severity indices of roadside features. [Turner94] In addition there are several on-going NCHRP projects that either are using RSAP or are directly working on improved methods that could be integrated into a new version of RSAP in the future.

Probably the first researcher to suggest the use of risk-based cost-effectiveness analysis for roadside safety was Glennon in 1974.[Glennon74] Glennon noted that the warranting approach, the approach where a set of guidelines about the selection, location and placement of roadside hardware, failed to provide an assessment of priorities or effectiveness. If there were unlimited funding, then all roadside safety problems could be treated using the warranting approach. Of course, there is never sufficient funding so an approach was needed to prioritize possible alternatives in order to select the roadside design alternative that would make the greatest improvement in safety at the least cost. This would allow designers and highway agencies to maximize the benefit of scarce construction and maintenance funding. Ross included Glennon's basic risk-based cost-benefit procedure for roadside safety in Chapter VII and Appendix E of the 1977 Barrier Guide, the first document promoted by the American Association of State Highway and Transportation Officials (AASHTO) that provides guidance on designing the roadside. [BarrierGuide77]

The method as presented in the 1977 Barrier Guide was not particularly practical for roadside design practitioners since there was a lot of tedious hand calculation required. In 1988, AASHTO revised the 1977 Barrier Guide transforming it into the Roadside Design Guide. [AASHTO88] Appendix A of the Roadside Design Guide included a revision of the cost-effectiveness procedures and provided a computer program called ROADSIDE to ease the calculation burden on designers and policy makers. The ROADSIDE program was essentially a direct computer implementation of the procedure in the 1977 Barrier Guide as proposed by Glennon. A similar cost-effectiveness procedure called BCAP was included in the 1989 AASHTO Bridge Specification for designing bridge railings.[AASHTO89] In their day, ROADSIDE and BCAP were innovative implementations of encroachment-based risk-based probabilistic roadside cost-benefit design. Of course, as computer applications became more sophisticated and additional research was performed to refine and improve encroachment models, severity indices and other aspects of the procedures, it became apparent that a new computer program was needed. The resulting program, RSAP, was completed in 2003 and documented in NCHRP Report 492 by Mak and Sicking. [Mak03] The basic RSAP procedure was included in the 2002 revision of the AASHTO Roadside Design Guide and has remained a feature of subsequent editions of the Roadside Design Guide ever since. [AASHTO02] The methodology, implementation and limitations of RSAP will be discussed at length in a following section but the basic approach will be discussed in general in the remainder of this section.

Rationale

The encroachment-based approach divides the encroachment event into a series of sub-events; from vehicle departure to collision, to the severity of the crash and the determination of expected benefit-cost ratios for various alternatives. The approach uses a conditional probability model consisting of a series of conditionally independent probabilities which quantify possible consequences of inadvertent encroachments onto specific roadside design conditions at various stages of the encroachments.

In terms of evaluating the benefit-cost of alternative roadside designs, there are basically two salient arguments favoring the use of encroachment-based approach over the crash-based approach. The first argument is that not all roadside encroachments result in crashes and, for those that do become crashes, they do not necessarily get reported; and for those that do get reported, they do not necessarily get recorded into the traffic crash database. Thus, examining the reported traffic crash records alone may not allow the full benefits of good roadside designs/features to be realized. This argument can be better understood when encroachments are classified by possible outcomes and crash reporting requirements as follows.

- No Crash: The encroaching vehicle safely returns to the travelled-way without serious vehicle damage and without occupant and non-occupant (i.e., pedestrians and cyclists) injury or death and without striking anything; or, putting it differently, the driver is able to either successfully stop the vehicle or regain control of the vehicle without striking a roadside object, incurring serious vehicle damage or causing injury or death to vehicle occupants and non-occupants after encroaching into the roadside. Often, the driver simply drives the vehicle away and no one knows that a potential crash has occurred.
- Unreportable Crashes: The encroaching vehicle experiences only minor damage and the collision does not result in an injury or death and the damages do not exceed the lawful reporting threshold in the jurisdiction (e.g., drivers must report crashes if $1,000 or more damage results from the crash in states like Michigan and Wyoming). An example of this type of crash is a vehicle that leaves the roadway, strikes a cable median barrier but is so lightly damaged that it is able to drive away.
- Unreported Crashes: Some encroachments result in what should be a reportable crash (i.e., the damage exceeds the legal threshold) but the crash is not reported for a variety of reasons (e.g., vehicle leaves the scene or is towed without notifying the police). Previous studies have found that many reportable crashes involve hitting safety features, especially more forgiving breakaway devices such as sign posts. For example, a vehicle may leave the roadway and strike a luminaire support. The luminaire may activate and cause damage to the vehicle, but the driver may be able to have the vehicle towed from the scene and may elect not to report the crash to the police even though the damage to the vehicle and luminaire exceed the reporting threshold. This is particularly common for single-vehicle run-off-road crashes since there is only one vehicle involved and the driver may see no need to notify the police.
- Reported Crashes Not Recorded into Database: Depending on the particular state, some reported crashes, especially minor single-vehicle crashes, may not be entered into the state computerized traffic crash database. Generally states do this to minimize the cost of maintaining the database. As an example, a single vehicle may run off the road and strike a guardrail. Even if the police are notified, if the damage to the guardrail is minor, the

police report may not be entered into the State-wide database so a record of the crash is lost.

- Reported Crashes Recorded into Database: When the encroaching vehicle leaves the roadway and strikes an object such that the vehicle is damaged and/or vehicle occupants or non-occupants are injured, the crash is generally reported to the police. Oftentimes, this is the only data that is available to the researchers in studying traffic safety.

Setting aside how states maintain their crash databases, it should be clear that the first argument centers on the potential benefits of good roadside designs. Good roadside design provides a better chance of resulting in the first three types of encroachments: no crash, an unreportable crash, or an unreported crash. It is a fairly reasonable assumption that crashes resulting in injuries will be reported. Relying only on reported crashes can distort the effectiveness of roadside hardware since injury and larger amounts of property damage will be over-represented in the data. For example, say that before a crash cushion was used in front of a particular bridge pier, there were 10 reportable crashes in a five year period, five of which caused injuries. After a crash cushion is installed, only two crashes are reported, one of which involves injury but eight additional crashes occurred but were never reported to the police because the crash cushion was effective in preventing occupant injuries or serious vehicle damage. Based on the reported data, the crash severity for the treated and untreated site are the same (i.e., 50 percent injury rate) when, in fact, the crash cushion reduced the severity of eight of the crashes to a level where they were no longer reported at all. The crash cushion really had a 10 percent injury rate, five times less than the untreated site. Crash-based data analysis would by definition miss the unreported low severity crashes that represent successful roadside hardware design.

The second salient argument embodied in the encroachment-based approach is that the crash-based approach has not been able to provide the kind of detailed relationships required to conduct the necessary benefit-cost evaluation. Roadside conditions can be complex and variable along the roadway and thus their safety effects can be difficult to quantify. In evaluating roadside safety improvements, many roadside safety features and their natures and configurations need to be considered for different classes of roadways which have different traffic volumes and posted speed limits. Typical roadside features include foreslope, backslope, parallel ditches, intersecting slopes, fixed objects, breakaway sign posts, culvert ends, longitudinal barriers, terminals and crash cushions, shoulder rumble strips and pavement markers, to name just a few. The encroachment-based approach provides a probabilistic framework that allows for more detailed modeling of vehicle-roadside interactions (e.g., various driver input, including braking and steering, behaviors), manner of collision with roadside objects (e.g., a combination of impact positions, speeds, and angles), and consequence of collisions (e.g., damage/injury severity distributions for striking different types of objects). This probabilistic modeling framework is more sensitive to the safety design parameters associated with complex roadside features and configurations and the needs of roadside safety evaluations. The price that must be paid for this increased analysis capability is that the detail required by the encroachment-based approach demands more detailed data which may be difficult to obtain, or, require more assumptions about the way crashes occur which may be difficult to validate.

Encroachment Modeling Methods

One of the more difficult aspects of the encroachment approach is developing encroachment probability models. There are basically three approaches that have been used to estimate encroachment rates:

(1) Direct observations of vehicle roadside encroachments based on wheel tracks, skid marks, etc., from field inspections or electronic/video monitoring.
(2) Estimation of unreported crashes, including unrecorded and some un-reportable crashes, by inspecting damage, scratches and scuff on roadside safety devices in the field and/or checking maintenance and repair records and then comparing the results with reported crashes.
(3) Estimation of encroachment rates using crash-data based crash prediction models developed typically from the state-maintained traffic crash databases.

Direct Observation Method

The strength of the direct observation approach is its ability to observe all five types of encroachments discussed earlier, especially those encroachments that safely return to the travelled-way without resulting in reportable crashes.

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 and effectiveness of medians. [Hutchinson62] Highway segments included the Edens, Calumet, and Kingery expressways in Chicago, Illinois and data was collected 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 (i.e., the day it opened) to April 6, 1961 and along US Route 66. Encroachment locations and the lateral extent of encroachment (i.e., distance from the edge of the lane perpendicular to the road) where identified through direct observation of the snow covered medians. 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 partially access controlled roads with intersections at grade. Traffic volumes varied from 3,700 to 6,200 vpd, relatively light traffic by today's standards. 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." [Hutchinson62] Hutchinson concluded that the frequency of encroachments can be related to traffic volume below practical capacity as follows:

$$E = (705)10^{-0.0000466\ ADT}$$

where:

E = frequency, encroachments per 100 million vehicles miles of travel
ADT = average daily traffic volume below practical capacity

Furthermore, as traffic reaches capacity, Hutchinson concluded that the rate of encroachment becomes constant. [Hutchinson62]

The so-called Cooper data was the next attempt at direct observation of encroachments. [Cooper80] According to De Leuw Cather in association with ADI Ltd, the company responsible for collecting the Cooper data, twelve data collection teams were recruited and trained in June of 1978. [DeLeuw78] Field data collection took place during a four-month period from July to October in 1978. The data were collected on 59 road sections, each between 60 and 100 km in length. These road sections were selected from five geographically dispersed Canadian provinces. The 59 sections surveyed were not homogeneous in terms of the posted speed limit, AADT, paved shoulder width and other key attributes. Out of these sections, about 20 percent were four-lane divided highways having a posted speed limit of about 100 km/hr (i.e., 60 mph) and the other 80 percent were two-lane undivided highways with a posted speed limit of about 80 km/hr (i.e., 50 mph). These road sections appear to cover a wide range of traffic volumes: from about 6,000 to 45,000 vehicles per day for the four-lane divided highways and from about 1,000 to 13,000 vehicles per day for the two-lane undivided highways. These traffic volumes were seasonally adjusted using traffic count data to reflect the higher traffic volume during the four summer months when data was collected. Each road section was surveyed within a one-day period at one week intervals for the duration of the study period. Only those encroachments that occurred to the right of the edge-line of the through traveled lane were collected (i.e., encroachments that occurred in the median area were not collected for four-lane divided highways). For each detected encroachment, the survey teams measured three features:

1. The maximum extent of lateral encroachment (i.e., the perpendicular distance from the edge-line of the rightmost through traveled lane to the farthest point of departure or the point when the first fixed object was struck).
2. The longitudinal encroachment length (i.e., the parallel distance along the roadway from the first point where the vehicle leaves the edge of the through traveled lane to the point where the maximum extent of lateral encroachment occurs).
3. The encroachment angle (i.e., the angle of departure at the first point where the vehicle leaves the edge-line of the through traveled lane).

Before carrying out any statistical analyses, Cooper subdivided the 59 road sections into 756 smaller segments using an exploratory statistical technique called "clustering." In his report (i.e., Section 2.2), he provided two main reasons for further subdividing sections into shorter segments: (a) to increase the number of data points (i.e., the sample size), which would be beneficial statistically and (b) to reduce the diluted effects of mixing various geometric features in these relatively long sections. Cooper stated that "it was thus considered necessary to subdivide the sections, and the means in which this is done is perhaps the most critical stage in the data reduction process." [Cooper80] The clustering technique basically grouped similar sites within a section to form segments based on a subjective user-defined similarity measure. Cooper adopted a similarity measure that was based primarily on the spacing of encroachment locations and secondarily on traffic volume.

Cooper's first reason for the delineation is a misguided one and the second reason is a valid one. If the sample size is increased by simply cutting sections into smaller segments then each section can be cut into, say, 100 segments to obtain a really large sample of segments, each of which will be relatively homogeneous since each segment will be rather short. The statistical reality is that the number of segments (i.e., the sample size) and the expected number of encroachments per segment go hand in hand. Cutting sections into shorter segments also reduces proportionally the expected number of encroachments per segment and ends up with no statistical benefit. Cooper's second reason is typically adopted in the crash-based approach, in which the goal of dividing highway sections into similar segments has always been on achieving some degree of homogeneity in terms of key traffic and highway geometric characteristics for each segment.

Unfortunately, this so-called data reduction procedure performed by Cooper using the clustering technique created a statistically flawed segment data set. The reason is that this procedure made the determination of analysis units (i.e., the segments) dependent on the outcome variable (i.e., the encroachments). This dependency introduced bias into the data or, more specifically, it artificially inflated the highs and lows of encroachment frequencies into the delineated road segments. The consequence is that whatever relationships were developed from the segment data regarding the encroachment frequency will be overstated. For example, if a particular factor, say, access density, has a positive influence on encroachment rates, the size of this influence would be exaggerated when estimated from the Cooper data.

The way that Cooper delineated road sections into shorter segments violated the basic principle of statistical design. He devised a statistical design that is dependent on the outcomes of the process or phenomenon under study. This kind of dependency introduces bias into the sampled data and is usually avoided at all possible cost in statistical design. Unfortunately, the exact effects of this bias introduced by Cooper when the data is used to develop statistical relationships are not known and probably can never be fully examined after all these years. Even if the occurrence of a stochastic event is totally random on a line (i.e., roadway), the outcome observed will be clustered in some way. The sanctity of statistical theories are their ability to distinguish between clusters that are due to pure random phenomena from those that are not. In other words, some crash clusters are clustered merely as a function of random chance whereas others are related to the characteristics of the highway; the difficulty is recognizing which is which. Second, designing statistical studies that are dependent on outcomes or possible outcomes of the process or phenomenon is done in nationwide large-scale government surveys, such as those conducted by the Census Bureau or NHTSA. These designs are often clustered and staged sampling design. They are designed in this way to contain costs. The survey would be prohibitively costly if a pure random sampling design were used. To adjust the bias introduced in these designs, statisticians take great pains to devise "sampling weights" (or probability weights") to correct the bias introduced into the design and have developed specialized statistical analysis methods to analyze these kind of data. Unfortunately, none of this was done in the Cooper study.

Other than the age issue, the Cooper data suffer from two other problems that are common to all data collection efforts that took the direct observation approach: both the tire track and video monitoring methods. The first and most fundamental problem of the direct observation approach is its inability to distinguish between intentional (or controlled) and unintentional (or uncontrolled) encroachments. Drivers may pull the vehicle off the roadway intentionally for various reasons. For example, a driver may want to allow faster traffic to pass, the driver may need time to read a map, to check on the vehicle condition, to switch drivers, to make U-turns, or nowadays to answer or make phone calls. In addition, road maintenance crews routinely drive on the roadside to do maintenance work. In the past, both routine inspection of wheel tracks/skid marks and video monitoring have failed to come up with effective ways to distinguish these intentional encroachments from the unintentional encroachments of interest (note: intentional and unintentional encroachments and controlled and uncontrolled encroachments are used in this report and most of the rest of the literature interchangeably). One could argue that more elaborate classification schemes might be needed. For example, in analyzing the field vehicle trajectory data, Cooper (1981) classified a selected number of encroachments in three types: (1) intentional and controlled, (2) unintentional but partially controlled, and (3) unintentional and uncontrolled. Divining driver intent, however, from tire tracks or even video monitoring is very subjective.

The second problem is the effort and thus cost required to collect a representative and large enough sample. This problem has limited the previous efforts to collect data from a small number of road sections and/or for a short period of time. Besides the performance problems at nighttime, a video camera can only monitor a relatively short section of roadway. Thus, except in a small number of large urban areas where video surveillance systems are already widely deployed on major freeways, one can only expect to obtain a limited amount of data in space and time with this method. For routine collection and recording of wheel tracks and skid marks, the final report by DeLeuw Cather (1978) gives a good account of their experience throughout the process of collecting the Cooper data. The report includes some details about the recruiting and training of field personnel, selection criteria of road sections, field crew safety, the logistics involved in their field work, the effect of adverse weather conditions, ensuring consistency among data collection teams and other personnel and technical issues. Overall, the report provides a good glimpse of the nuances and potential difficulties involved in such a field data collection effort. The cost issue has limited previous data collection efforts to just a few summer or winter months. As a result, weather effects were either under-represented, as in Cooper, or over-represented, as in Hutchinson and Kennedy, in the collected data.[Cooper80; Hutchinson66]

The percentage of intentional or controlled encroachments is assumed to be 40 percent in RSAP based on a study of unreported versus reported crashes involving barriers. [Moskowitz61] Thus, in RSAP, the encroachment rate is multiplied by a factor of 0.6 to remove these intentional or controlled encroachments. It can be logically deduced that the overwhelming majority of the intentional or controlled encroachments do not involve any type of crash event. Based on this logic, using barrier crashes, reported or not, in RSAP to infer about non-crashes seems to be stretching the data beyond the proper limit. Other authors have provided opinions on this subject. McGinnis, for example, interviewed Professors Hutchinson and Kennedy for their well-known freeway median encroachment data collected in the 1960s in Illinois.[McGinnis04] Professor Hutchinson indicated that he "is confident that there were very few controlled encroachments in their data." Professor Hutchinson's recollection may well be reasonable given that his data involved median encroachments primarily in the winter months. A driver wishing to fix a flat tire, read a map or perform some other activity would be unlikely to choose the median shoulder especially in the winter. In reviewing a video study of encroachments, Mak and Sicking state that "by restricting the definition of uncontrolled encroachments to sudden changes in vehicle trajectory or hard braking, only 14 of the approximately 7,000 (video) recorded encroachments were considered to be uncontrolled, which gives a ratio of about 500 controlled encroachments for every uncontrolled encroachment." [Mak03] Cooper selected 394 out of about 2300 encroachments which occurred on tangent or long radius curve sections where the vehicle did not reach the ditch bottom and where no objects were struck. [Cooper80] He then classified these encroachments into three types:

1. <u>Intentional and controlled</u> (167 cases or 42 percent): Cases where the vehicle track formed a continuous arc from point of departure to point of re-crossing shoulder and where there were no apparent discontinuities in the path or its shape such as might indicate a stop at any point.
2. <u>Unintentional but partially controlled</u> (184 cases or 47percent): Cases where the vehicle tracks exhibited a steer-back response but where either recovery was not completed or there was evidence to suggest that the vehicle came to a stop before continuing (or being towed) back to the roadway.
3. <u>Unintentional and uncontrolled</u> (43 cases or 11percent): Cases where the vehicle tracks indicated a down-slope variance from the straight line run-off and where no recovery was made; such conditions indicate wheel lock-up.

One could argue that, out of those 1900 cases that Cooper did <u>not</u> select for analysis, most of them are unintentional except, perhaps, for those cases where data are missing regarding the trajectory of the encroachments. Clearly, making judgments about the intent of the driver based on tire marks is at best a hap-hazard business.

The impression from all these studies is that no one has any idea about what percentage of the encroachments are intentional or controlled and which are not. Some may even question the measurability of controlled encroachments. Is it really possible to distinguish between intentional and unintentional encroachments? If a driver suddenly approaches stopped traffic on a divided highway and steers to the right entering the roadside to avoid striking vehicle, is this a controlled or uncontrolled encroachment? The driver intends to enter the roadside and may well be in control but they may also strike, for example, a guardrail terminal on the shoulder. For the direct observation method to be technically viable in the future, this fundamental problem of distinguishing between intentional and unintentional encroachments need to be resolved.

Another problem specific to the wheel tracks/skid marks method used by Cooper is the presence of paved shoulders or even well-compacted graveled shoulders on the surveyed sections. Vehicle encroachments within or just slightly beyond the shoulder area are very difficult to detect. Mak and Sicking believed that the Cooper encroachment data are underreported for encroachments with lateral extent of 4 m or less for this reason.[Mak03] They reanalyzed the Cooper encroachment data by excluding encroachments of 4 m or less in lateral extent. More detailed descriptions of the reanalysis are discussed later with respect to RSAP but based on results of the re-analysis, Mak and Sicking estimated that encroachments were under-reported by a ratio of 2.466 for two-lane undivided highways and 1.878 for multilane divided highways. Thus, the encroachment frequency was adjusted upward by these ratios to account for under-reporting of encroachments because of paved shoulders.

In summary, the Cooper data suffers from several serious problems:

1. At this point the data is very old and may not reflect modern traffic or highway designs,
2. The data analysis technique was seriously flawed,
3. The impact of intentional and/or controlled encroachments cannot be satisfactorily accounted for and
4. The method for addressing under-reporting of encroachments due to paved and compacted gravel shoulders is questionable.

McGinnis conducted a comparative review of both data sets where he reviewed the collection procedures, roadway characteristics and traffic conditions in an effort to determine why independent research efforts reached different conclusions about encroachment length [McGinnis99]. 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 more current information is needed than either of these two decades-old studies can provide. [McGinnis99]

Indirect Observation Method

Indirect observation has not, to the author's knowledge, been used to estimate encroachments *per se*, but it has been used to estimate the proportion of report and unreported crashes. In NCHRP Report 490, Ray *et al* developed procedures for studying the in-service performance of roadside devices like guardrails and guardrail terminals. [Ray03] The procedures involved collecting data on crashes involving particular roadside features. Data collectors made measurements and observations about barrier performance and site conditions after being notified of a crash in one of three particular ways: (1) a police-report crash, (2) a crash where damaged roadside hardware was reported to the local DOT maintenance garage and (3) direct observation of the roadside hardware for evidence of vehicle barrier interaction. In this last category, for example, data collectors would periodically (e.g., generally once a month) scan each section of studied barrier to record any scraps, rubs, paint transfers or other evidence of a crash. This allowed the research team to compare the numbers of crashes reported to the police to the number of crashes where some physical evidence was left behind on the barrier.

For example, Fitzpatrick *et al* studied the performance of concrete median barriers on a 1.68 km-long section of I-84 in East Hartford, Connecticut over a seven month (i.e., April to October) period in 1999. [Fitzpatrick99] I-84 in this area has an ADT of about 128,000 vpd and the median shoulder is only 0.78-m wide. The team used a photo-log truck with a side-mount camera to videotape the face of the concrete median barrier. A baseline videotape was made at the beginning of the study and four subsequent videos were made. Each video was compared to the previous video in the series and any tire marks, concrete spalling or other indications of damage were noted. The team also obtained all police reports for crashes in the highway segment and attempted to match damage evidence with police report locations. Over the study period, there was physical evidence of 62 crashes but only nine crashes were reported to the police. Thus, on this study segment only 14.5 percent of the crashes resulted in reported collisions. Using the traffic volume, segment length and crash data, Fitzpatrick estimated that the concrete median barrier collision rate on this section of I-84 was about 0.0007 collision/km/vehicle/day. Since the median shoulder is very narrow, the encroachment rate would likely be just a little about this value since it would be difficult for a driver to avoid striking a barrier with less than one meter to recover.

Interestingly, the highway segments studied by Fitzpatrick included two, three and four-lane cross sections on one side of the divided highway (i.e., four, six and eight lane highways). The observed crash rate for the six-lane segments was 1.125 higher and for eight-lanes was 2.25 times higher than the four-lane section. If viewed as HSM-style AMFs where a four-lane highway (i.e., two lanes in each direction) is the base conditions, this would indicate that the AMF for a six-lane highway is 1.125 and an eight-lane highway is 2.25. Fitzpatrick also calculated the expected crash frequencies from RSAP and found that the effective AMF for a six-lane highway based on the RSAP predictions was about 8 and the AMF for an eight-lane highway was about 14. At least for these data, RSAP seemed to greatly over-predict the number of encroachments and collisions as compared to the collected field data.

Similarly, Ray *et al* looked at collisions with the BCT and MELT guardrail terminals in portions of Iowa and North Carolina.[Ray00] Ray found that of the 51 BCT and MELT collisions that occurred in Iowa, 26 (51 percent) were reported to the police and 25 (49 percent) were reported only to the DOT maintenance garage. Obviously, these numbers do not included very minor collisions that required no repair but it is still interesting that only about half of damage-causing crashes were reported to the police.

Ray performed a sub-study of the Iowa data were data collectors closely monitored a 35.8-km long section of I-80 in Johnson County, Iowa for 12 months. This highway section had 24 BCT terminals and no MELT terminals and the ADT of the highway was about 32,000 vpd. In addition to monitoring police and maintenance crash reports, data collectors physically inspected each BCT terminal installation each month to record any evidence of collisions. In the 12-month data collection period, four police report crashes (6 percent) occurred, three collisions were reported to the DOT maintenance garage but not the police (4 percent) and data collectors found evidence of 62 minor collision (90 percent) events that were report to neither the police or DOT maintenance garage. Generally, the BCTs were all installed about 12 feet from the travelled way (i.e., eight foot shoulders and a four-foot flare for the BCT). Ray found that there was one collision for every million vehicles passing the BCT installation (i.e., both reported and unreported collisions) whereas there was one police reported collision for every 34 million vehicles passing a particular BCT installation. Ray and Weir used the same technique to study reported and unreported collisions with W-beam guardrails in Iowa, North Carolina and Connecticut.[Ray01]

What these studies show is that if the total number of crashes (i.e., reported and unreported) are known and the traffic characteristics and placement details are likewise known, an estimate of the encroachment rate can be back-calculated to estimate an encroachment rate, especially for devices that are placed close to the road and are, therefore, more likely to be struck. Also, these studies show there is a wide variation in maintenance reporting from State to State that depends on police reporting thresholds and maintenance repair thresholds.

Crash Data Based Method

Among vehicle roadside encroachment characteristics, roadside encroachment rates and lateral extent of encroachment distributions are two key parameters that drive the encroachment-based probability models. The collection of encroachment data in the field is, however, challenging and expensive and estimating encroachment rates from the field-collected encroachment data can be technically difficult. This has motivated researchers to develop alternative methods to estimate these two parameters. One such method was to use the crash data to estimate encroachment rates and lateral extent of encroachment through the development of crash-based statistical regression models. For example, in a series of small-scaled demonstration studies conducted for FHWA, Miaou has shown that the crash-based predictive models of reported single-vehicle ROR (SVROR) crashes could be used to estimate roadside encroachment rates and possibly the lateral extent of encroachment distributions. [Miaou96; Miaou97; Miaou01] These studies exploited the probabilistic relationship between roadside encroachment events and ROR crash events and tried to combine the strengths of both crash-based and encroachment-based approaches. These demonstrations have only been conducted for rural two-lane roads but extending the method to other types of roadways is relatively straightforward.

The following is an example of using the crash-based approach to model different types of ROR crashes and then applying the prediction from the estimated models to conduct benefit-cost analyses of installing certain safety features. In a recent study to develop improved guidelines for the use of median barriers on high-speed, multilane, divided highways in Texas, statistical relationships between ROR crashes and traffic flow and geometric variables for road sections were developed. [Miaou05] Statistical regression models, specifically built to model discrete and categorical types of response data such as event frequency or event count data (e.g., crash events), were developed for four crash and barrier combinations:

- Cross-median crashes on road sections with no barrier,
- Other median-related crashes on road sections with no barrier,
- All median-related crashes on road sections with barrier and
- Hit-median-barrier only crashes on road sections with barrier.

Both crash frequency and crash severity were modeled. Crash frequencies were modeled using the so-called Poisson-Gamma or negative binomial regression models while crash severities were modeled with ordered multinomial logit models. These models are variants of popular statistical regression models that have been commonly used in traffic crash studies using crash-based approach since early 1990s. The development of these types of regression models in traffic crash studies has followed the development in statistical and biomedical sciences closely.

In this median barrier guideline study, explanatory variables considered in the models included vehicle miles traveled, number of lanes, median width, and posted speed limit. Predictive values, including high, mean, and low predictions, from these models were used to compute benefit and cost ratios of adding a median barrier to existing or planned highways at different AADT and median width. Based on these benefit-cost ratios, guidelines for the installation of median barriers were developed. The benefit-cost ratio in this study is the ratio of expected benefits accrued from crash and/or severity reduction to expected costs of implementing, operating, and maintaining a median barrier project.

Comparison of the Crash-Based and Encroachment-Based Approaches

The HSM crash-based method is the culmination of the crash-data approach since it synthesizes and organizes decades of research using this method. Unfortunately, it is not an easy matter to compare the predictions from an encroachment-based method (i.e., RSAP) with those from a crash-data based method (i.e., the HSM or its computer implementation, the CPM of the IHSDM) for several reasons.

Run-off-road (ROR) crashes were not modeled specifically in any of the three projects discussed previously above for the HSM. Roadside crashes are just a small portion of the crashes of interest in all the HSM projects. For example, for two-lane highways in Project NCHRP 17-18(4) Project, only total crashes were modeled. Although one could in theory multiply the predicted number of total crashes from the model by a percentage of ROR crashes (and rollover crashes) in the population to approximate an estimate for ROR crashes, the estimate would likely be poor. One of the reasons is the so-called aggregation effect where the estimation for effects of some covariates will be diluted and not good for any sub-population (i.e., ROR crashes). For example, shoulder width has effects on both on-road and off-road crashes. But if shoulder width affects off-road crashes more than on-road crashes, the aggregation effect would seriously understate the shoulder width effect on ROR crashes. Another example is the roadside hazard rating (RHR) which in principal should affect ROR crashes only. This effect could be lost in the model using total crashes as the dependent variable in several ways. When RHR is correlated with mainline features such as horizontal curvature and vertical grade, the effects of RHR will be undercut and taken away by these mainline features.

- The roadside hazard rating (i.e., Table 3) was used in developing some of the models in the 17-18(4) and 17-26 projects. For comparison, an equivalency table needs to be developed for RSAP to mimic the roadside conditions represented for each RHR values. The development of such an equivalency table will not be straightforward.
- Some of the developed models do not include any roadside variables at all.

These two different approaches, the encroachment method and the crash-data based method, use different techniques to estimate the frequency of crashes such that benefit-cost analyses can be performed to aid in highway design decisions. The crash-data based approach is in essence a macro approach where an estimate is developed based on a broad and general overview of the highway characteristics. The encroachment approach, on the other hand, is a micro approach where the detailed interactions of each roadside feature are accounted for. In the end, both approaches ought to produce compatible measures of crash frequency and crash severity but it should be recognized that they are approaching the problem from fundamentally different perspectives.

In order to better understand the predictions of the crash-based (i.e., HSM) and encroachment based (i.e., RSAP) methods, an example problem is presented below. Appendix A of the RDG provides a summary of RSAP and provides several example problems to demonstrate the cost-effectiveness analysis procedure. The particular example problem discussed here 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 5.

An analysis of this example problem was conducted using the version of RSAP currently available in the RDG (i.e., version 2.0.3) and the Beta version of the IHSDM CPM. These results were compared with the results published in Appendix A of the RDG, presumably the results of RSAP 1.0. All roadside features were considered to be on the right side of the road as documented in the RDG example problem. The user input differences in the software and the differences in the predicted number of crashes are presented below.

A direct comparison between RSAP and the IHSDM CPM is difficult because of the inherent differences in the methods used to model ROR crashes, although the resulting predictions of total ROR crashes within a road segment for a given study period should be similar. Table 6 provides a summary of the similarities and differences between the data used by both RSAP and the IHSDM CPM. Where discrepancies exist in the available data entry fields, assumptions were made and are discussed here.

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 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. 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 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 [AASHTO09], 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 then is reflective of reality.

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 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.

Table 5. Input data for sample applications. [AASHTO06]

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

Table 5. (continued)

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		116m [380 ft]	
of first segment	N/A	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		101m [331 ft]	
of first segment		upstrm	
		186m [610 ft]	
	N/A	dnstrm	N/A

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 systems for the regions the data was collected from.

Table 6. Differences between the RSAP and IHSDM CPM Input Data.

Data Element	RDG App A Example	Recalc using RSAP	IHSDM CPM
Cost Data			
Project Life	Yes	Yes	No
Discount Rate	Yes	Yes	No
Installation Cost	Yes	Yes	No
Annual Maintenance Cost	Yes	Yes	No
General Highway Data			
Functional Class	Yes	Yes	Yes
Highway Type	Yes	Yes	Yes
Pavement Material	No	No	Yes
Shoulder Material	No	No	Yes
Speed Limit	Yes	Yes	No
Design Speed	No	No	Yes
Desired Speed	No	No	Yes
85th Percentile Speed	No	No	Yes
Current Year ADT	Yes	Yes	No
Future Year ADT	No	No	Yes
Traffic Growth Factor	Yes	Yes	No
Percent Truck	Yes	No	No
User-Defined Adjustment Factor	Yes	No	No
Highway Geometrics			
Segment Length	Yes	Yes	Yes
Vertical Alignment	Yes	Yes	Yes
Horizontal Alignment	Yes	Yes	Yes
Lane Width	Yes	Yes	Yes
Shoulder Width	Yes	Yes	Yes
Roadside Elements			
Culvert Headwall, Type C	Yes	Yes	RHR
Intersection Slopes,			
Slope	Yes	Yes	Yes
Lateral Offset	Yes	Yes	No
W-Beam Strong Post:	Yes	Yes	RHR
Crashworthy End Terminals	Yes	Yes	RHR

While the total number of differences in software inputs is small between RSAP and IHSDM CPM, the potential impact of even a small change in the roadside environment can dramatically influence roadside safety. Carefully modeling the roadside, therefore, is paramount to improving overall road safety. Limiting the roadside design consideration section of the HSM and the IHSDM CPM to the Roadside Hazard Rating (RHR) scale to reflect the entire potential of everything outside of the edge of travelled-way results in a linear relationship, proportional to the scale, for the roadside if no other roadway safety upgrades are considered. In other words, one could consider a whole range of options which fall within a RHR equal to three and the IHSDM CPM and HSM crash predictions would always result in the same crash prediction.

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).

This problem has been reanalyzed using the currently available version of RSAP [RSAP09] and the current version of the IHSDM CPM [IHSDM09] and compared with the results published in the RDG Appendix A. [AASHTO06] The results of the analysis are presented in Table 7. The results are presented using the terminology used by the respective programs. The terms incident, crash, and accident are used interchangeably to describe crashes in an effort to remain consistent with the original literature. RSAP conducts a cost-benefit analysis and presents results of the expected crash costs for ROR crashes for each alternative, whereas the IHSDM CPM predicts total crashes for a segment of road and does not distinguish between the ROR crash severities, therefore, cannot accurately estimate the crash cost. The RDG Example Problem results for Incidents/Year are plotted in Figure 2 versus the RSAP recalculation of Accidents/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 2 for a direct comparison of magnitude with the RDG and RSAP values.

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. This was an extremely surprising result. On the other hand, the comparison between RSAP 1.0 (i.e., what is published in the RDG) and the IHSDM/CPM were surprisingly similar.

The example problem shown in Appendix A of the RDG is dated May 1, 2001 and lists the version of RSAP as 1.0. [AASHTO06] 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/yr [AASHTO06] while the RSAP Engineering Manual uses an encroachment rate of about 1.5 enc/km/yr [Mak03] which would explain some discrepancies in RSAP values, however, there is not any documentation to accompany the RSAP update from version 1.0 to 2.0.3 to determine which encroachment rate is used in the code. Clearly there were changes made in RSAP between versions 1.0 and 2.0.3 that have made drastic changes in the predictions.

The IHSDM CPM comes generally closer in predicting the number of crashes for Alternatives one and three over this 350 meter section of road to those predicted by the RDG, however, 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.

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. A factor of ten difference is not acceptable; at the very least the difference needs to be understood and explained.

Table 7. Results of Alternatives Analysis Using RSAP and IHSDM CPM.

Results	Baseline Conditions Alternative 1	Install Guardrail Alternative 2	Extend Culvert Alternative 3
2006 RDG (1):			
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
RSAP 2.0.3 (5) in SI units:			
Expected Crash Frequency (Acc./Year)	0.029	0.050	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
IHSDM CPM (6) in SI units:			
	RHR 5	**RHR 4**	**RHR 3**
Total ROR Crashes	7.56	7.07	6.61
Crashes/Year	0.302	0.283	0.264

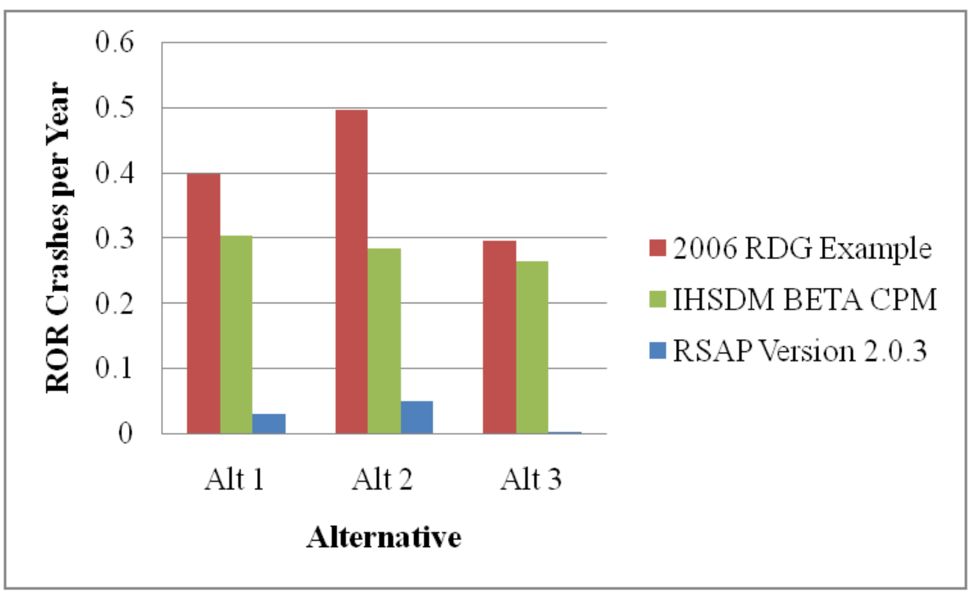


Figure 2. ROR Crash Predictions Using RSAP and IHSDM CPM.

Additional attention should be given to coordinating efforts between the development of the HSM and the continued development of the RDG and RSAP. The data gathered in the study and development of the HSM can be used to further refine the encroachment-based benefit-cost models. Focusing on single-vehicle ROR crashes will allow for improved modeling of roadside design alternatives, thereby allowing modelers to model features such as the addition of guardrail (Alterative 2). As discussed above, a slight change in the roadside environment can dramatically improve the roadside safety. Including all roadside crashes into one subjective scale ranging from one through seven is a disservice to the practitioners using these two manuals. The improved modeling of ROR crashes or the possible incorporation of the encroachment modeling portions of RSAP as a module in the IHSDM should be evaluated.

In order to truly compare the encroachment method used in RSAP with the crash-based model used by the HSM an equivalency table needs to be developed for RSAP to mimic the roadside conditions represented by each RHR value and, likewise, specific roadside features and geometries need to be clearly mapped to RHR. The mapping between RSAP configurations and RHR values are many. For example, the descriptions of RHR values are rather vague and contain much "may have ..." language in the descriptions such as "may have guardrail 5 to 6.5 ft from pavement edge". Different people will come up with different interpretations so a more systematic guidance for developing RHRs based on a wider variety of roadside conditions is needed. Gaining a consensus for this table to be accepted by the roadside and highway safety communities may be challenging. Development of this equivalency table should also consider whether the left and right sides of the roads are allowed to have different RHR values, especially for divided roads.

RSAP

Background

While the encroachment method is conceptually straight forward, estimating the three conditional probabilities at the heart of the method can be very difficult and computationally tedious. Each of these conditional probabilities must be developed based on some type of statistical model which in turn is either based on observed encroachment and crash data or assumptions about the way crashes happen in the field. Since the computations can be complicated, a computer program has seemed to be the most useful way to implement the encroachment-based approach in roadside safety analysis.

While a designer could have used the methods presented by Glennon in NCHRP Report 148 or by Ross in the 1977 Barrier Guide, performing the calculations by hand would be very time consuming and tedious. The various parts of equation have, over the years, been referred to by particular names. For example, the term $P(E|X_1)$ has become known as the "encroachment model" and $P(RORA_s|Collision, X_4)$ has, as one of its main constituents, a term called the severity index or SI. In the 1997 Barrier Guide procedure, the severity indices were determined subjectively by an expert panel that ranked different hazards on a scale of 0 to 10 with 10 being the most severe type of crash. A crash with a typical guardrail, for example, might be assigned a severity of 2 or 3 whereas a collision with a large tree might be an 8 or 9. Mak performed a study in 1984 to develop a more consistent and broader range of severity indices based, at least in part, on crash reports from the field. [Mak86] Refining and redefining severity indices has continued up until the present time with reports by Mak and Sicking as well as a report by Tuner to name a few. [Mak86; Turner94] Similarly, the 1977 Barrier Guide used an encroachment model based on data initially reported by Hutchinson and Kennedy in 1962 whereas RSAP relied on data from Cooper collected in the 1970's. [Hutchinson62; Hutchinson66; Copper80] As will be described in detail in the following sections, improving and validating encroachment models has likewise continued up until the present with the most recent effort involving the on-going NCHRP Project 17-11(2). [Bligh08]

RSAP is an encroachment-based computer software tool for cost-effectiveness evaluation of roadside safety improvements originally developed under NCHRP Project 22-9(1) [Mak03]. Subsequently, some improvements were made, bugs corrected and patches installed under NCHRP Project 22-9(2) [Mak03]. Finally, a third NCHRP project, 22-9(3) was initiated but never completed. RSAP has been distributed with the AASHTO Roadside Design Guide (RDG) since the 2002 edition [AASHTO02].

The current version of the software consists of two relatively independent, but interoperable, programs: the Main Analysis Program and User Interface Program. The Main Analysis Program is written in the FORTRAN programming language and it contains the procedures, models, formulas, and data for cost-effectiveness analysis. The User Interface Program is written in the C++ programming language and provides a sequence of simple menus for users to specify input data and review analysis results in a Microsoft Windows environment. A flow chart that describes the basic portions of the analysis and information flow in RSAP was deduced from the Engineer's Manual and the actual code and is shown in Figure 3.

As described in the RSAP Engineer's Manual (i.e., section 3.3.1), RSAP can currently perform evaluations of projects with a maximum of 20 different safety improvement alternatives, 20 consecutive roadway segments for roadways of up to 16 lanes and 1,000 roadside features. In addition, the program is capable of analyzing hazards on either or both sides of the roadway as well as in the median for a divided roadway simultaneously. RSAP computes the crash cost for a mixture of 12 vehicle types. RSAP includes the following types of built-in roadside features that users can use to model their roadway: fore-slope, back-slope, parallel ditches, intersecting slopes, fixed objects, culvert ends, longitudinal barriers, and terminals and crash cushions. Users can also create user-defined roadside features.

The two most significant documents related to the RSAP are:

- Mak, K. K. and Sicking, D. L., "Roadside Safety Analysis Program (RSAP) – Engineer's Manual," NCHRP Report No. 492, National Cooperative Highway Research Program, Transportation Research Board, Washington, D. C., 2003.[Mak03]
- Mak, K.K. and Sicking, D.L. "Roadside Safety Analysis Program (RSAP)— User's Manual." Prepared for NCHRP Project 22-9, National Cooperative Highway Research Program, Transportation Research Board, National Research Council, 2002.[Mak02]

The RSAP Engineer's Manual describes the inner workings of the cost-effectiveness analysis procedure and the various formulas, algorithms and data built into the procedure. The separate User's Manual describes the User Interface Program, including the data input process and the output from the program.

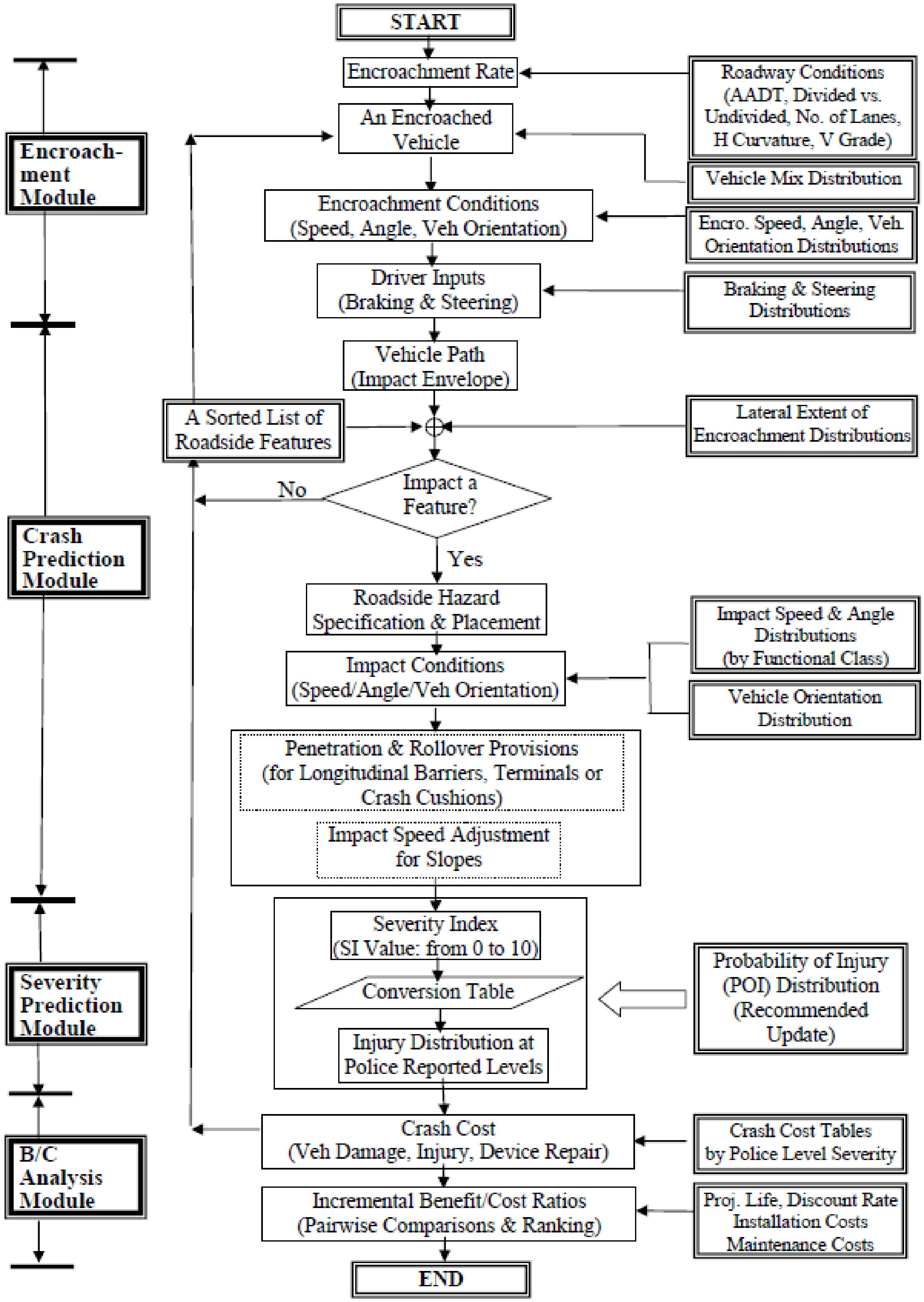


Figure 3. RSAP computational flow chart.

It should be made clear at the outset that, limited by its data and built-in analytical procedures, RSAP is currently intended for evaluating high speed highways where additional right-of-way can be acquired. It is not intended for use in low-speed roads, such as urban multi-lane and two-lane undivided roadways, where either curb-and-gutter roadside conditions prevail or where roadsides are typically cluttered with fixed objects with little or no clear zone and frequent intersections. RSAP contains an implicit assumption that intersections, access points and ramps are few and far between. This may be a reasonable assumption in designing a multi-lane access-controlled highway or even a rural two-lane highway but it is clearly not a reasonable assumption for designing urban streets or suburban collectors where clearzones are limited and intersections and access points are numerous. RSAP is, therefore, better suited to the analysis of some types of roadways than others.

The analytical model behind RSAP is an encroachment-based approach using a series of conditionally independent probabilities representing vehicle roadside encroachment events, the conditional probability of a crash given a roadside encroachment has occurred, the probable severity of crashes that are likely to occur and the expected benefit-cost ratios of various roadside design alternatives. Based on the sequential nature of these conditional probabilities and the assumption that they are independent, the Main Analysis Program is basically structured into the following four modules which are likewise indicated on the left side of Figure 3:

- Encroachment module,
- Crash prediction module,
- Severity prediction module and
- Benefit-cost module.

Roadside and RSAP

Prior to the introduction of RSAP, the ROADSIDE program, included in the 1989 and 1996 versions of the AASHTO *Roadside Design Guide*, was the most commonly used cost-effectiveness analysis procedure for roadside design. RSAP was intended to replace and improve upon the ROADSIDE program. [AASHTO89; AASHTO96] RSAP provided many procedural and algorithmic improvements over its predecessor, ROADSIDE as summarized in Table 8. RSAP also provides a more user-friendly graphical interface making it much easier to use than the ROADSIDE program. In the roadside safety community, RSAP is widely considered as the state-of-the-art safety evaluation software tool. In order to address the more complex encroachment relationships adopted by RSAP, the Monte Carlo simulation approach is used to generate the solution, as opposed to the deterministic approach used in the ROADSIDE program.

Methodology

For a particular roadside hazard (e.g., a utility pole or guardrail) and a particular type of vehicle (e.g., a passenger car), a basic roadside encroachment model of a road segment of unit length can be conceptually represented by the following equation:

$$E(Cost) = V \times \ell \times P(Enc \mid X_1) \times P(\text{in Envelope} \mid Enc, X_2) \times P(Collision \mid \text{in Envelope}, X_3) \times \left\{ \sum_{s=1}^{S} P(RORA_s \mid Collision, X_4) \times C_s \right\}$$

Table 8. Comparison of RSAP and ROADSIDE. [after Mak03]

Parameter	ROADSIDE	RSAP
Encroachment Rate	A constant of 0.0003 encroachments per km per year per vehicle per day	Cooper encroachment data, adjusted for encroachments with lateral extent of encroachment less than or equal to 4m
Vehicle Type	Single vehicle type	12 vehicle types based on nominal percent truck
Encroachment Speed	Function of design speed	Same as impact speed
Encroachment Angle	Average angle based on point-mass model	Same as impact angle
Vehicle Orientation	No	Based on "real-world" crash data
Lateral Extent of Encroachment	Assumes 3.7 m/sec/sec (0.4 *g*) deceleration rate and sine curve density function for steer back	Cooper encroachment data, adjusted for encroachments with lateral extent of encroachment less than or equal to 4m
Shielding of One Hazard by Another	No	Yes
Multiple Hazards	Each hazard has to be analyzed individually and the crash costs summed manually	Yes
Effect of Barrier Protection	All impacts with hazard shielded by barrier eliminated, regardless of barrier length	Vehicles encroaching upstream of barrier could impact hazard shielded by barrier
Rollover Crashes	No	Rollovers initiated by hitting fixed-objects
Cross Median Crashes	No	Not Really (Can potentially "trick" the program to emulate the event, but not recommended)
Impact Speed	= Encroachment speed - speed loss with 3.7 m/sec/sec (0.4 *g*) deceleration rate	Based on "real-world" crash data
Impact Angle	Same as encroachment angle	Based on "real-world" crash data
Severity (SI)	Average values only	Function of impact speed
Incremental *B*/*C* Ratios for Multiple Alternatives	Have to be calculated manually	Yes
Solution Method	Deterministic	Stochastic, using the Monte Carlo simulation technique

where :

$E(Cost)$	=	Expected crash cost;
V	=	Number of vehicles per year passing through the road segment ;
l	=	Segment length;
$P(Enc \mid X_1)$	=	Probability a vehicle encroaching the roadside while travelling a unit length of such a road segment which has traffic and geometric attributes X_1;
$P(\text{in Envelope} \mid Enc, X_2)$	=	Conditional probability that, given a roadside encroachment and a hazard on the segment with attributes X_2, the location of the encroachment is such that an impact with the hazard is possible (i.e., the vehicle is the "impact envelope";
$P(Collisiion \mid \text{in Envelope}, X_3)$	=	Conditional probability that, given an encroachment in the potential impact envelope and vehicle swath characteristics X_3, a collision between vehicle and hazard will occur;
$P(\text{ROR Crash} \mid Collisiion, X_4)$	=	Conditional probability that, given a collision occurs and attributes of the impact and objects X_4, a run-off-road accident (RORA) of severity level s will occur;
S=1,2, …S		Crash severity level ranging from 1 to S; and
C_s	=	Crash cost of severity level s.

A detailed review and analytical study of this encroachment-based probability model, together with a list of major assumptions of the model, can be found in two FHWA reports.[Miaou96; Miaou01]. Because of the model assumptions underlying RSAP, the RDG Guide advises that the analysis results from RSAP should be treated as general in nature, not all inclusive or absolute. [AASHTO02] When applied in conjunction with sound engineering judgment, however, the analysis results obtained from such a benefit-cost analysis approach can provide useful information for engineers to make a cost-effective choice of alternative roadside designs.

An underlying assumption of the encroachment probability model above is that the four conditional probabilities in the model are conditionally independent. This assumption allows these conditional probabilities to be multiplied directly to obtain the unconditional probability. This assumption is valid if all the necessary covariates, X_1, X_2, X_3 and X_4, are included in the model. If all the necessary covariates are not included, then the validity of this assumption is questionable. For example, intersections play an important role in generating vehicle to vehicle conflicts and thus generate more roadside encroachments and more encroachments with relatively higher encroachment angles. Ignoring the presence of intersections on road segments that, in fact, have intersections may compromise this conditional independence assumption required by RSAP. In practice, only a limited number of covariates are considered because of data limitations and thus this assumption is certainly challengeable. At present, this conditional independence assumption of RSAP is treated as a tacit assumption that is largely left uncontested.

Modeling Encroachments

The encroachment module in RSAP deals with the first key question in assessing the benefit-cost of a roadside safety design. Namely, how often do roadside encroachments occur by highway type or functional class, traffic volume, and highway geometric characteristics such as the number of lanes, horizontal curvature and grade? This question is addressed in RSAP through the incorporation of base encroachment rates which quantify how often vehicles leave the travelled way (i.e., the marked lanes) and inadvertently or unintentionally enter the roadside. The base encroachment rate is the encroachment rate for a relatively straight, flat standard cross-section of highway. Base encroachment rates are expressed as the number of vehicle roadside encroachments per unit length per year as a function of traffic volume. Adjustment factors are used to include the effects of horizontal curvature, grade and future traffic growth. Calculating the encroachments on a particular segment, therefore, is a two-step process. The first step is to calculate the base encroachment rate and the second step is the application of the modification factors.

RSAP relies on the so-called Cooper data which were collected using the direct observation approach in the 1970's as described in an earlier section. [Cooper80] Section 3.3.3 of the RSAP Engineer's Manual states that "the Cooper encroachment data, collected in the late 1970s, are more than [30] years old. Many changes have occurred in the interim (e.g., improved highway and roadside designs, higher speed limits, higher traffic volumes, and better vehicle safety equipment). Unfortunately, no newer or better encroachment data are available. Efforts to collect encroachment data with videotape surveillance and electronic monitoring system in the 1980s were not successful. There have also been exploratory efforts to estimate encroachment rates from police-level crash data and statistical modeling, some of which are still ongoing. The encroachment probability model can greatly benefit from better encroachment data. " [Mak03] So, while the developers of RSAP recognized some of the limitations of the Cooper data they simply had no better alternative at the time for modeling encroachments.

Base Encroachment Rate

The Cooper encroachment data were collected on mostly straight and level roadway sections. These data were used by the developers of RSAP to estimate roadside encroachment rates as a function of AADT. These encroachment rates are then multiplied by 0.6 to remove 40 percent of the estimated intentional encroachments. Then, according the RSAP Engineer's Manual, these encroachment rates are further multiplied by 2.466 and 1.878, respectively, for two-lane divided highways and multilane divided highway, to adjust for underreporting due to paved shoulders as described earlier. The roadside encroachment rates thus obtained are called base roadside encroachment rates. The base roadside encroachment rate curves, after adjusting for under-reporting and intentional encroachments, are a function of AADT and shown in Figure 4.

The exact models and methods used to obtain these encroachment rate curves are not clearly documented in the RSAP Engineer's Manual. As far as Dr. Zimmerman could recall (Dr. Zimmerman was one of the developers involved in the original development of RSAP), the curves were re-fit from the Cooper data, mainly by Mr. Wolford for a different project. The fit was so poor that the team decided to follow what Cooper came up with in his 1980 report and that is what is shown in Figure 5 below.

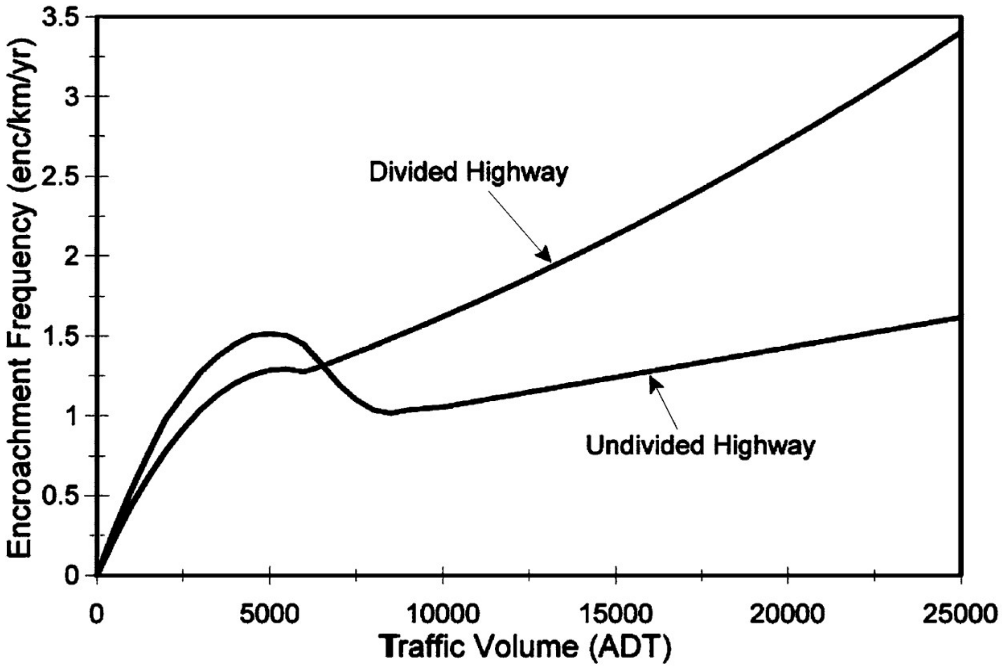


Figure 4. RSAP Base Roadside Encroachment Rate. [Mak03]

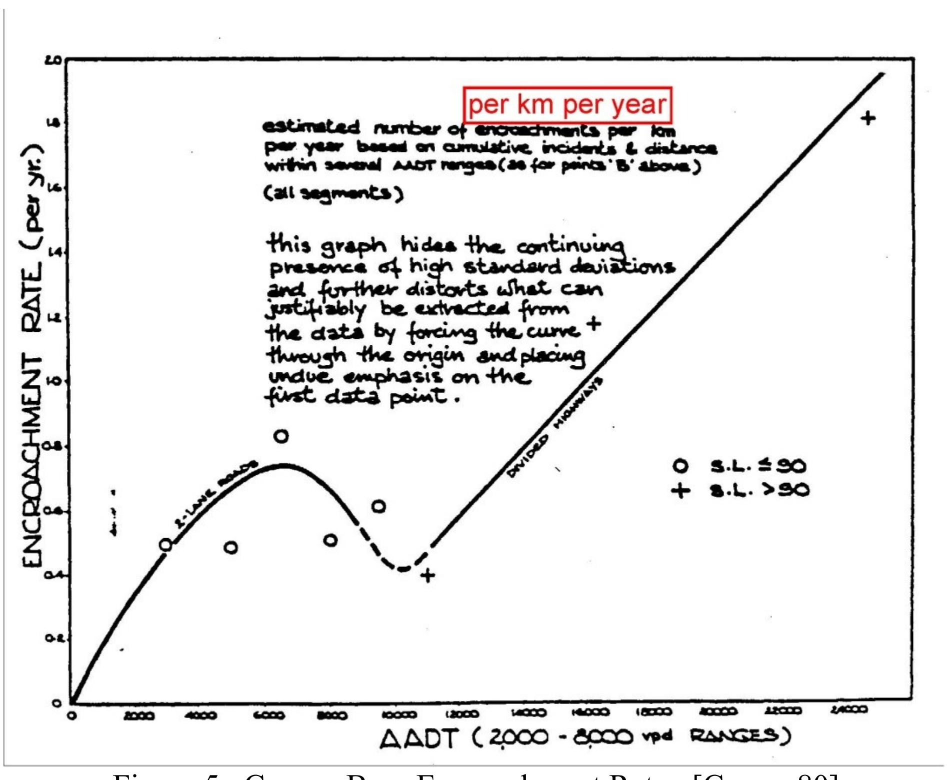


Figure 5. Cooper Base Encroachment Rate. [Cooper80]

Given that the RSAP rates were meant to follow those in Cooper and that the Cooper data did not include encroachments on medians for divided highways, it might be expected that the RSAP rates should be about twice those of the Cooper rates for divided highways since RSAP assumes the same encroachment rate for right- and left-hand encroachments. By comparing the

Cooper curves and the RSAP curves, we can see that this is indeed the case: the RSAP rates are about twice those of Cooper's rates for four-lane divided highways. One might also expect that the RSAP rates for two-lane undivided highways would be essentially the same as those in Cooper but this, however, is not the case. The RSAP rates are about two to three times higher than those in Cooper for AADTs below about 12,500 vpd, which is the maximum AADT for the two-lane undivided highways in the Cooper data. It is not clear why the RSAP rates and Cooper rates are so different.

As pointed out earlier, Cooper was unable to establish any useful statistical relationship between encroachment rates and AADT and a large number of other explanatory variables that he included in his attempts to build regression models. Cooper ended up using an *ad hoc* method to obtain this encroachment rate curve. His failure to establish good statistical relationships was largely because of his use of inappropriate statistical models and associated goodness of fit measures as discussed earlier.

Lane Encroachment Rate

RSAP currently uses road segments as basic analysis units. A road segment is meant to be a generally homogenous section of roadway in terms of highway characteristics and it, by definition, does not include intersections, access points (i.e., driveways) or on/off ramps. RSAP does not make any provision for intersections, access points or ramps to be considered so there is an implicit assumption in RSAP that the road segments are either free of intersections, access points and ramps or there are few of them and they do not affect the overall encroachment rate. RSAP does not even allow the access density along a highway segment to be specified. In general, high-speed highways with higher access densities are known to be related to more vehicle to vehicle conflicts and, thus, more roadside encroachments and more run-off-road (ROR) crashes.

Even though the focus of RSAP is on the roadside, it actually simulates vehicle encroachments (or excursions) lane by lane. For the purpose of this discussion, vehicles inadvertently leaving the edge-lines of their intended travel lane are referred to as lane encroachments as opposed to the roadside encroachments referred to elsewhere in this report. Since not all lane encroachments become roadside encroachments, an analytical procedure was devised in RSAP to decide the appropriate level of encroachment rates for each lane so that the roadside encroachments originating from all lanes would sum to the base roadside encroachment rate estimated from the Cooper data for every possible AADT for two-lane undivided and four-lane divided highways.

The lane encroachment does not enter the general formulation for the encroachment probability model presented as Equation (7) in Section 3.1 of the RSAP Engineer's Manual (page 20). In fact, this lane-based analytical and simulation procedure receives little coverage in Engineer's Manual. A short and rather vague description is given in Subsection 4.2.1.4 (page 31). It is not really possible to understand the technical side of the procedure from the Engineer's Manual, such as the rationale, analytical methods and assumptions behind the procedure. The role of this procedure in RSAP, both in code development and its analytical implications, is, however, substantial. When inspecting the code, it is apparent that a large portion of the RSAP code and a large amount of the system memory are devoted to this lane-based procedure which appears to involve intensive bookkeeping operations. Thus, in any attempt to re-code RSAP, this procedure will require a lot of programming attention.

In terms of the analytical procedure involved, the first step is to estimate lane encroachment rates from the base roadside encroachment rate curves obtained for two-lane undivided and four-lane divided highways from the Cooper data. The second step is to estimate lane encroachment rates for highways that are not two-lane or four-lane highways, especially for those that have more than four lanes (e.g., the maximum number of lanes RSAP is designed to accommodate is 16).

The first step of the analytical procedure is not described in the RSAP Engineer's Manual but inspection of the code shows that for a given AADT, the formulas to compute lane encroachment rates from the base roadside encroachment rates are as follows:

- Two-Lane Undivided: Lane Encroachment Rate=Base Roadside Encroachment Rate/2.9226
- Four-lane Divided: Lane Encroachment Rate=Base Roadside Encroachment Rate/3.1826

That is, lane encroachment rates for a given AADT are obtained by dividing the base rates with a constant depending on highway type. Although it is not reported in Engineer's Manual, Dr. Zimmerman has explained the derivations of the two constants (i.e., 2.9226 and 3.1826) and the derivations will be given in a later section where program bugs are discussed. These are important technical data which the Engineer's Manual should have discussed. In a later section it will be shown that the derivation to obtain the constant 2.9226 for two-lane undivided highways was incorrect and the correct value is half of this value.

The derivations of these two constants require an assumption of a four-meter travel lane and that each lane is equally likely to generate a lane encroachment ignoring possible differences in lane traffic volumes. Other implicit assumptions are also required to derive these constants. For example, it needs to use the off-road lateral extent of encroachment distributions derived from the Cooper data to simulate on-road lane encroachments. Basically, this requires the assumption that driver's maneuvering behaviors, road surface conditions, collision opportunities, etc., are the same for both on- and off road encroachments. These assumptions are certainly questionable.

The second step of the analytical procedure is to estimate lane encroachment rates for highways that are not two-lane undivided or four-lane divided highways. This is vaguely described in Section 4.2.1.4 of the Engineer's Manual as "the encroachment rate is assumed to be the same for all lanes." Inspection of the code shows that for divided highways, RSAP assigns the same lane encroachment rate to each lane as the four-lane highway. That is, the lane encroachment rate is based on the value for a four-lane divided highway using the formula presented above regardless of the number of lanes involved. As an example, for a given segment AADT, the RSAP procedure will give twice as many lane encroachments to an eight-lane highway as that given to a four-lane highway (assuming same geometrics and traffic growth). Note that there are some problems with the way that RSAP is handling divided highways with an odd number of lanes, which will be discussed in a later section. Here we will only discuss highways with an even number of lanes.

To get a sense of the analytical implication of this constant lane encroachment rate assumption for multilane divided highways, the roadside encroachment rates for six-lane and eight-lane highways with 12-ft wide lanes were computed following the procedure used in the RSAP code. The rates computed are shown in Figure 6. For a given AADT, the roadside encroachment rates are obtained as follows: (1) the lane encroachment rate is first computed from the base roadside encroachment rate using the formula presented above for four-lane divided highways, (2) the computed lane encroachment rate is then assigned to each lane, (3) the proportion of lane encroachments that becomes roadside encroachments is computed lane-by-lane using the lateral extent of encroachment distribution curve obtained for the four-lane divided highways from Cooper, and (4) roadside encroachment rates are calculated as the sum of the roadside encroachment rates originated from all lanes. Note that these roadside encroachment rates include those encroachments onto the median. Also, there is a discrepancy on the lateral extent of encroachment distribution curves between those described in Engineer's Manual and those actually used in the RSAP code. The detail of this discrepancy will be given in a later section. The calculations here follow those used in the code.

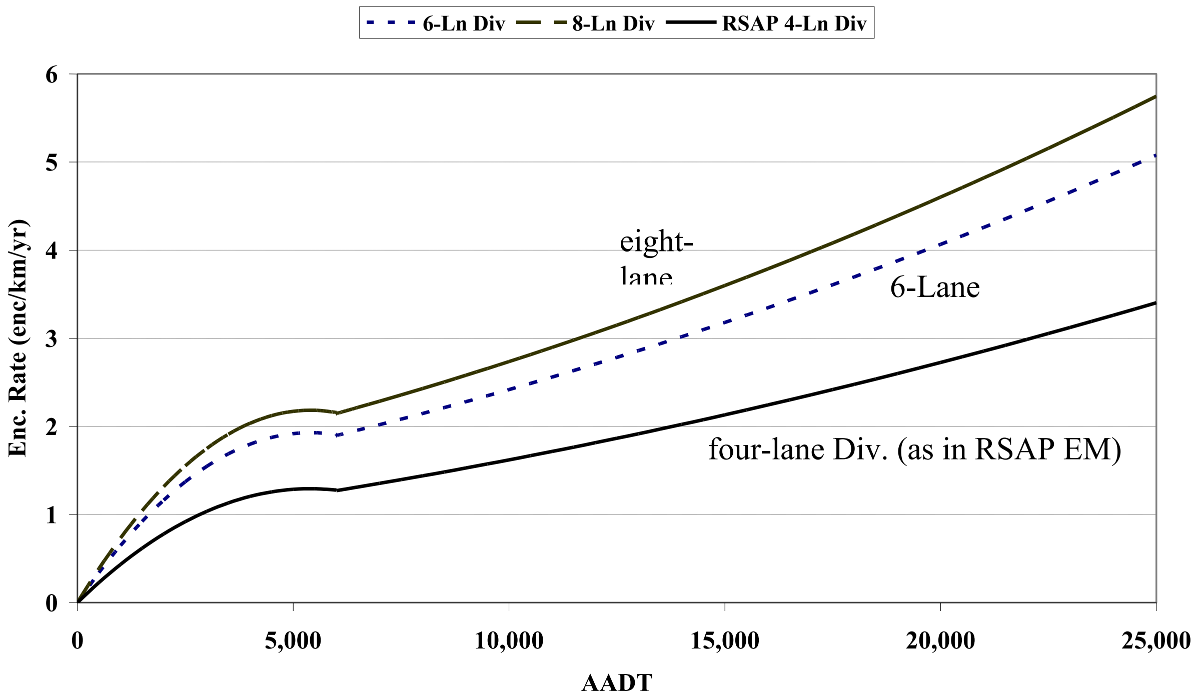


Figure 6. Roadside Encroachment Rates for six and eight-Lane Divided Highways with 12-ft lanes.

For comparison purpose, Figure 6 also shows the base roadside encroachment rate for four-lane divided highways as shown in Engineer's Manual (solid line). The roadside encroachment rates for six-lane and eight-lane highways are higher than those for the four-lane highways with the same AADT. This is a counterintuitive result since with the same AADT, more lanes should result in fewer roadside and median encroachments because vehicles have more space to recover on the roadway. Note that there is a limit of about 22 m for the maximum extent of lateral encroachments in the RSAP code. So, at some point the increase in the roadside encroachment rate as the number of lanes increases would stop.

For a given AADT, assigning the same lane encroachment rate calculated from the four-lane divided highways to each lane of a multilane divided highway regardless of the number of lanes involved does not make good logical or driver behavioral sense. Recall that, by "lane encroachments, unintentional or inadvertent lane encroachments are supposed. Using the eight-lane versus four-lane example presented earlier, for a given AADT, the RSAP procedure will give twice as many lane encroachments to an eight-lane highway as that given to a four-lane highway assuming the same geometrics and traffic growth. Why would so many more drivers suddenly become inattentive or fatigued when driving on an eight-lane highway compared to a four-lane highway? What are the causes for the lapse of driver attention and physical condition as they drive on highways with different numbers of lanes? There is no real convincing explanation for this to occur so there is simply no good basis for making such an assumption.

This lane by lane on-road lane encroachment simulation procedure should be abandoned in updating RSAP. Abandoning this procedure would allow the RSAP to focus on the roadside as it should. It would also allow a much leaner, cleaner and efficient RSAP code to be produced. Here are two arguments for removing the lane encroachment simulation procedure from RSAP:

- Data for estimating lane encroachment rates, on-road lateral extent of encroachment distributions, and on-road vehicle trajectories will likely never be available. Thus, on-road lane encroachment characteristics needed to implement this procedure will always need to be assumed in RSAP and, whatever assumptions are made, they can never be validated. Besides the data collection cost issue, whether unintentional on-road lane encroachments can really be observed is a serious question. In addition, all the problems undermining the collected roadside encroachment data discussed earlier, especially on driver intent and vehicle controllability, apply equally or more so to the lane encroachment data.
- RSAP's purpose is to help make decisions about roadside safety and should, therefore, focus its data collection, modeling, and parameter estimation efforts on this part of the roadway. Those effects associated with mainline characteristics have been handled in RSAP using adjustment factors, such as horizontal curvature adjustment factor, vertical grade adjustment factor, and other adjustment factors discussed earlier. The same adjustment factor concept can be adopted to handle roadside encroachments for highways with more than four lanes.

One way to estimate the proposed multilane adjustment factor would be to compare the run-off-road crash rates for highways that have four-lane, six-lane, eight-lane or even larger numbers of lanes. Preferably, the highways selected for collecting data for this compassion would be relatively straight and leveled. In addition, it can be expected that most multilane highways would have 12-ft wide lanes. A lot of data that are up to date data are readily available for conducting such comparisons. One such example (i.e., the Fitzpatrick study in Connecticut) was discussed earlier where the lane AMF for an eight-lane highway was 2.25. Other ways to estimate this adjustment factor are possible and can be researched if deemed necessary.

Most multilane highways are expected to have 12-ft or 13-ft wide lanes. If RSAP is to allow significantly different highway lane-width scenarios, then devising and adding a "lane-width adjustment factor" could be considered in a similar manner. The lane-width AMF already calculated and used in the HSM could well provide a basis for such a modification factor in the update of RSAP.

Adjustment Factors

As mentioned previously, the encroachment module uses a two-step process to estimate encroachment frequency. After the base encroachment rate is obtained, the next step is to adjust the base encroachment frequency to account for specific highway characteristics that affect encroachment rates. Four adjustment factors are included in RSAP:

- A horizontal curve adjustment factor,
- A vertical grade adjustment factor,
- A traffic growth adjustment factor and
- A user-defined adjustment factor.

The adjusted encroachment rates are determined by simply multiplying the base encroachment rates times all the applicable adjustment factors. Each of these adjustment factors are briefly described next.

<u>*Horizontal Curvature Adjustment Factor*</u>

RSAP incorporates adjustment factors to increase encroachment rates on horizontal curves as shown in Figure 7 taken from the RSAP Engineer's Manual. The adjustment factor for horizontal curves is determined in relation to the roadway segment and the direction of travel.

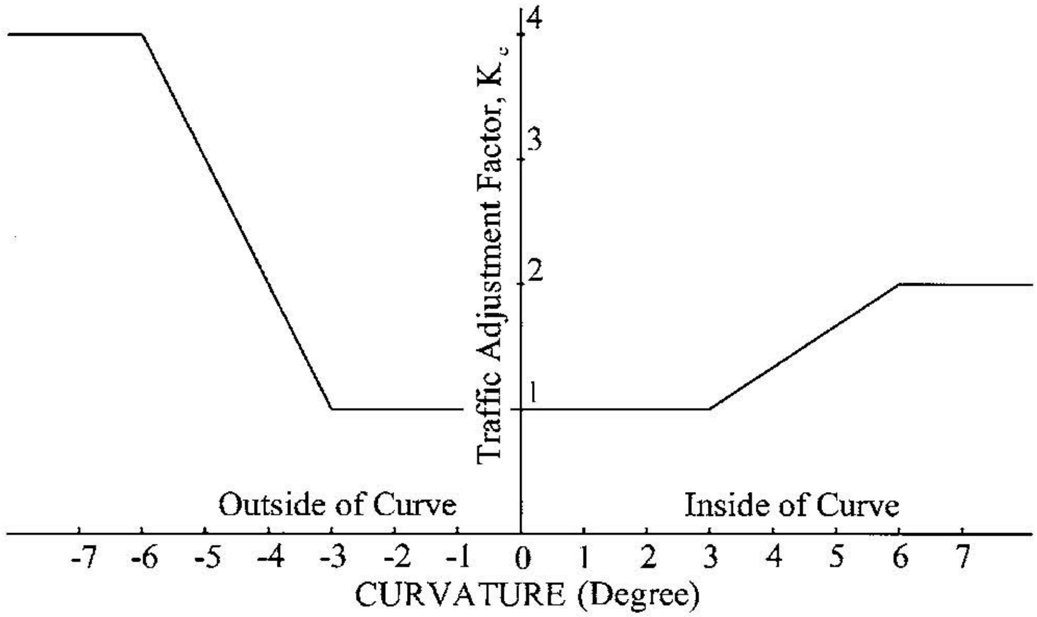


Figure 7. Horizontal Curvature Adjustment Factor. [Mak03]

The horizontal curve adjustment factor is based on a research study conducted in 1976 on 300 single-vehicle, fixed-object fatal crashes in Georgia. [Wright76] The study compared the roadway characteristics (e.g., cross-sectional data elements, geometrics, and roadside conditions) at fatal single-vehicle, ran-off-road crash sites with those at comparison sites that were 1.6 km upstream of the fatal crash sites. The underlying assumption is that differences in roadway characteristics between the fatal crash sites and the comparison sites are correlated with the occurrence of these fatal crashes. Horizontal curves were significantly over-represented at the fatal crash sites, with the outside of the curve accounting for 70 percent of the fatal crashes on curves. The drawbacks of the study, as described in the RSAP Engineer's Manual, include:

- The sample size was relatively small with only 300 fatal crashes investigated,
- There was no control for some variables that are likely to be significant (e.g., highway type, terrain, and traffic volume. For example, some of the crashes occurred on un-surfaced rural roads) and
- Only fatal crashes were included in the sample and the results might not be applicable to crashes with lesser severity.

In light of these drawbacks, the horizontal curve adjustment factor probably overstates the effects of horizontal curvature on encroachment rates although there is no better source of information on the effects of horizontal curvature on encroachment rates available at this time.

According to the RSAP Engineer's Manual, the horizontal curve adjustment factor is a function of horizontal curvature (in degrees) as shown in Figure 7. This is, however, not how the adjustment factor is determined in the code. In Subroutine INPUT1, which is where the adjustment factor is defined, it uses curve radius instead. The relevant part of the code is shown below:

```
IF (CURLORR(K,J).EQ.2.0) THEN
  IF (CURRAD(K,J).LT.300.0) THEN
    CURADJ(J,1) = 4.0
    CURADJ(J,2) = 2.0
    CURADJ(J,3) = 2.0
    CURADJ(J,4) = 4.0
  ELSE
    CURADJ(J,1) = 1.0+(6.0-CURRAD(K,J)/100)
    CURADJ(J,2) = 1.0+(6.0-CURRAD(K,J)/100)/3
    CURADJ(J,3) = CURADJ(J,2)
    CURADJ(J,4) = CURADJ(J,1)
  ENDIF
ELSE
  IF (CURRAD(K,J).LT.300.0) THEN
    CURADJ(J,1) = 2.0
    CURADJ(J,2) = 4.0
    CURADJ(J,3) = 4.0
    CURADJ(J,4) = 2.0
  ELSE
    CURADJ(J,1) = 1.0+(6.0-CURRAD(K,J)/100)/3
    CURADJ(J,2) = 1.0+(6.0-CURRAD(K,J)/100)
    CURADJ(J,3) = CURADJ(J,2)
    CURADJ(J,4) = CURADJ(J,1)
  ENDIF
ENDIF
```

In the code, 300 and 600 meters are used as the break points, instead of the 3 and 6 degrees per 100-ft station as shown in the Engineer's Manual. So, the code really provides an approximation to what is explained in Engineer's Manual. Fortunately, the approximation is reasonably close (i.e., corresponding to about 2.9 and 5.8 degrees per 100-ft station). Unlike other discrepancies found between the code and the Engineer's Manual, this discrepancy really does not make much difference. But since the horizontal curvature is calculated in the program in the subroutine INPUT1, it should have been used in the code and it would have been consistent with what is shown in the Engineer's Manual.

Grade Adjustment Factor

RSAP also incorporates an adjustment factor to increase encroachment rates on grades as shown in Figure 8 taken from the RSAP Engineer's Manual. The same study used to develop the horizontal curve adjustment factor was used to develop the grade adjustment factor so the same limitations listed in the last section apply to the grade factor as well. The RSAP grade adjustment factor probably overstates the effects of vertical grade on encroachment rates. As stated in the RSAP Engineer's Manual, however, there is still no better source of information on the effects of vertical grade on encroachment rates.

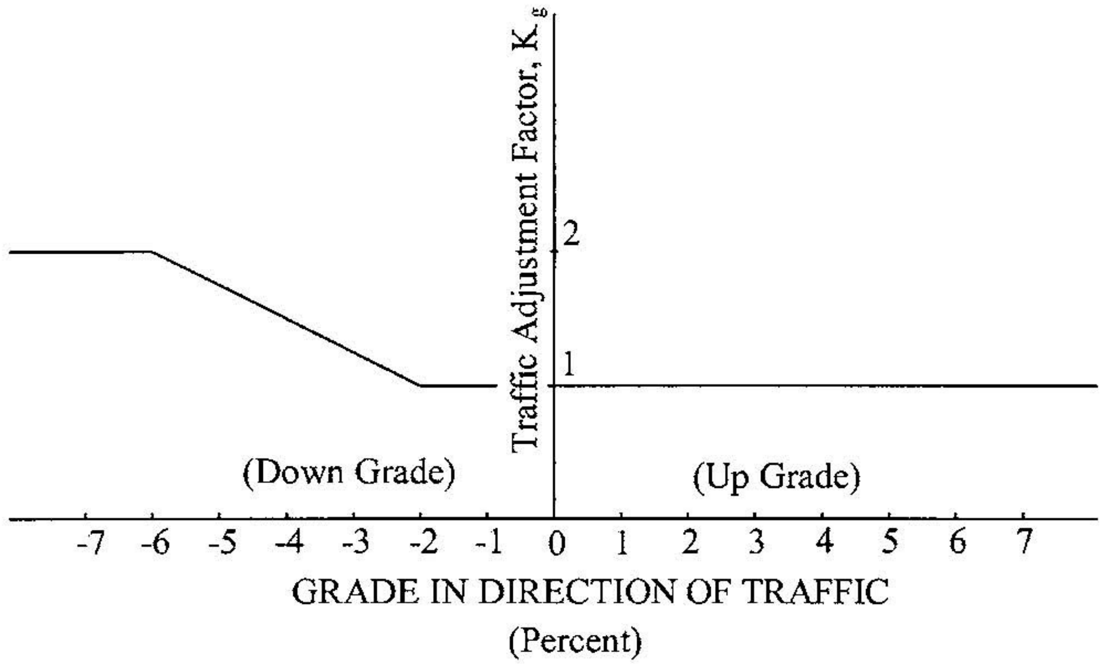


Figure 8. Grade Adjustment Factor. [Mak03]

Traffic-Growth Adjustment Factor

On page 36 in the RSAP Engineer's Manual, the growth adjustment factor is described as a factor that averages the traffic volume over the life of the project and is calculated as follows:

$$\text{Traffic growth adjustment factor} = \sum_{n=1}^{N} (1+i)^n / N$$

Where:

i	=	The annual percent traffic growth and
N	=	The project life in years.

With this formula, the traffic growth factor can be pre-computed without involving AADT values at all.

User-Defined Adjustment Factor

The purpose of the user-defined adjustment factor, whose default value is unity, is to allow users to adjust the encroachment rate to local circumstances. For example, say that after using RSAP and comparing the results to local crash data, an agency determines RSAP over predicts encroachments by 10 percent. The reason for the discrepancy may or may not be apparent. For example, perhaps the topography, land-use or climate of the particular area are substantially different than the areas used to develop the adjustment factors in RSAP. In any case, the agency could adjust for this local affect by using a user-defined encroachment adjustment factor of 0.9 to bring RSAP's predictions into line with what is observed in that particular area. Some qualitative advice is given in the Engineer's Manual on when to set the user-defined factor to a value greater than less than unity.

Need for Other Adjustment Factors

Roadway improvements intended to decrease run-off-road crashes include better geometric design, increased skid resistant roadway surfaces, more durable pavement markings and more visible roadside signs. In recent years, several State transportation agencies and toll road authorities have also installed and evaluated the effects of shoulder rumble strips on run-off-road crashes, particularly on rural high-speed highways and toll facilities. The results of these evaluations have consistently shown significant decreases in single-vehicle run-off-road crashes. Thus, encroachment characteristics, including encroachment rates and lateral extent of encroachment distribution, on these highways with shoulder rumble strips should be quite different from those without shoulder rumble strips. The HSM crash-based approach has the potential of generating different encroachment parameters for highways with and without shoulder rumble strips where crashes and related roadway and roadside data are available. There is probably a need to add more adjustment factors to RSAP to include the effect on encroachments of more modern treatments like rumble strips.

It may be possible to take some of the AMFs from the HSM or perhaps the data used to generate the AMFs and calculate modification factors for characteristics like lane widths, shoulder widths, shoulder types, rumble strips, etc. that can be used in RSAP.

Encroachment Conditions

Once the probability of a vehicle leaving the roadway has been calculated and adjusted, the next step shown in Figure 3 is the calculation of the encroachment conditions, that is, the speed, angle, orientation, location that a vehicle is likely to leave the travelled way. RSAP uses a Monte Carlo simulation technique to estimate the likely encroachment conditions as described in the Chapter 4 of the RSAP Engineer's Manual. The technique involves probability distributions for the following conditions:

1. Encroachment location along the segment (i.e., longitudinally from the start of the segment),
2. The direction of travel,
3. The lane where the encroachment originates,
4. The direction of encroachment (i.e., left or right),
5. The encroachment speed and angle,
6. The vehicle type and
7. The vehicle orientation.

Some of the encroachment or departure conditions like the speed and angle are combined since the angle and speed are statistically dependent on each other (e.g., higher speeds are associated with smaller impact angles). Thus, there are seven presumably independent probability distributions involved in the simulation of one encroachment.

The essence of the Monte Carlo method is to generate a random number and use that random number to select from a probability distribution. In the case of RSAP, this is done for each of the seven probability distributions listed above. For example, first the location on the segment is determined so a random number is generated, say, 0.52. In this case a location 52 percent of the way along the segment is selected and the longitudinal coordinate is chosen. Next, the direction of travel is selected by generating another random number, say, 0.32. For numbers less than 0.5 the direction of travel is assumed to be the "primary" direction (i.e., the direction corresponding to the stationing) and for numbers greater than 0.5 the opposite direction is assumed. In this example, the primary direction would be selected for a random number of 0.32. The encroachment is assumed to be equally likely for all lanes and a range is set up for each possible lane although the Engineer's Manual does not explicitly define how this is done. For the example's sake, say that this is a two-lane undivided highway so the encroachment must come from the one lane that is in the primary direction. Next, the direction of encroachment must be chosen so another random number is generated, say 0.67. RSAP assumes left and right encroachments are equally likely and those with random numbers less than 0.5 are right encroachments and those greater than 0.5 are left encroachments. In this example, then, the encroachment would be to the left or across the opposing lane. The speed and angle are found from one of five lookup tables where each table corresponds to a functional class (see Table 6-1 in the RSAP Engineer's Manual). For our example, assume the roadway is a rural collector and the random number generated indicates the cell specifying a 27.5 degree encroachment angle and a 88 km/hr speed. Next, a vehicle type must be selected from the 12 types of vehicles defined in RSAP. The selection is based on the percent of trucks on the segment as shown in Table 6-2 of the Engineer's Manual. Assume for this example that a small pickup truck is randomly chosen. Lastly, the vehicle orientation or side-slip angle is chosen based on the probability distribution shown in Figure 6-10 of the Engineer's Manual. For this example, assume a value of 15 degrees of side-slip is randomly selected. Thus, after generating this series of random numbers and selecting the encroachment conditions, this example would indicate that a small pickup truck leaves the left side of the roadway at a location 52 percent of the way down the primary direction of travel. The vehicle is travelling at 88 km/hr and leaves the road at a 27.5 degree angle with a side-slip of 15 degrees. This process is repeated for each modeled encroachment.

In fact, the technique used in RSAP is a little more complicated than what is described above. In choosing the speed/angle and vehicle distributions RSAP uses a uniform selection technique where any speed/angle or vehicle type is equally likely. Weights are pre-computed for each speed/angle and vehicle type combination and applied to the resulting severity estimate. In a simplified sense, assume for example, that a heavy truck is chosen and according to the traffic mix data this type of heavy truck represents three percent of the traffic. The severity costs for trucks are therefore multiplied by a weight that correctly proportions the truck crash with the much more likely and common passenger vehicle crashes. Likewise, high encroachment speeds and high angles are sampled as often as more typical speeds and angles so each cell in the 49 speed and angle combinations is weighted to reflect the probability of that particular cell. Choosing the appropriate weights is an important feature of the RSAP algorithm and depends on the programmer knowing a prior how many combinations must be accounted for and how to properly choose the weights.

The Monte Carlo technique is an appropriate tool when the outcome is dependent on a number of stochastic processes and the relationships between those processes is unknown or presumed to be non-linear. If all the distributions were normal (i.e., bell shaped), the mean value of each of the distributions could be taken to find the encroachment conditions eliminating the need for repeated calculations – a so-called, deterministic solution technique as was used in the Roadside program. Unfortunately, many of these distributions are not normal so a very unlikely extreme impact condition could have a disproportionate affect on the overall cost. For example, while a tractor-trailer truck striking a cable median barrier at high speed and high angle is unlikely, the crash consequences are likely very severe since the vehicle will probably enter opposing lanes of traffic and collide with other vehicles. This is the reason the Monte Carlo technique is used in RSAP, to account for the possible disproportionate contribution to the overall crash cost of infrequent but very costly crash occurrences.

The RSAP Engineer's Manual notes both the advantages and disadvantages of the Monte Carlo simulation technique in Chapter 3. Most of the advantages listed in the Engineer's Manual suggest that the Monte Carlo method lends itself better to modular software design and, hence, easier updates. There is, however, no inherent advantage for modularity of either the deterministic approach or the Monte Carlo approach. Perhaps the RSAP developers meant to suggest that since the Monte Carlo approach breaks the process down into many more or less independent processes it would be easier to update one piece of the process without necessarily having to change the rest of the process. This is certainly true since with the deterministic approach used, for example, in Roadside, all the various probability distributions that go into the prediction of a crash are lumped together and cannot be easily separated. For example, the crash rate for a cable median barrier placed at the center of a flat 48-ft wide median that experiences 50,000 vpd of traffic could be determined assuming there was sufficient data. In fact, this has been done by, for example, Ray in assessing crashes in Arizona. If the user wants to determine the crash rate for the same barrier (i.e., cable median barrier) with the same traffic (i.e., 50,000 vpd) but on a 24-ft wide median, the entire data collection and analysis would have to be repeated for the new location because the affect of the lateral offset is "hidden" inside the crash rate. On the other hand, with the Monte Carlo technique used by RSAP, the final crash rate (which is not actually calculated in RSAP since it is not needed) is the product of many independent probabilities so it is possible to change just one (e.g., the lateral offset in this example) and extrapolate to a new situation for which there may not be data.

Of course, RSAP only actually uses the Monte Carlo technique to estimate the encroachment conditions (i.e., the characteristics of the vehicle as it leaves the roadway) and uses a simple straight-line assumption to model the vehicle's off-road trajectory as described in the next section.

An open discussion of the pros and cons of the Monte Carlo method versus a deterministic method or some mixed method should be undertaken. On the one hand, the way the Monte Carlo breaks complex events down into their individual components is clearly an advantage in understanding and updating the probability of a crash event occurring. If the underlying probability distributions cannot be obtained or validated, though, the method becomes a series of guesses based on very limited data. Essentially the Monte Carlo method is very precise but may never be accurate if the underlying probability distributions cannot be developed with confidence. On the other hand, a deterministic approach can be rooted in observable data and calibrated even if all the individual pieces cannot be separately measured. A deterministic method can be very accurate without necessarily being very precise. The advantage is that the resulting distribution is based on observable data that can be checked and validated but the disadvantage is that there can be no understanding of how the vehicle behaved prior to the collision and it may be difficult to extend the probability distributions to new situations.

A simple example of using deterministic collision rates is provided in a series of studies done in the State of Washington regarding cable median barriers.[MacDonald07] Fortunately, the State of Washington has very detailed cable guardrail inventories, traffic data and crash data. In response to public complaints about five fatal crashes in the last decade, WSDOT commissioned several studies to look at the performance of cable median barriers. Based on the 1995 to 2006 data (note: the data has been updated in 2007 and 2008 but the earlier data makes the point), the crash rate with cable median barriers was 58.6 crashes/100 MVMT. These numbers were compiled from both police reported and maintenance reported crashes but they do not include crashes were repairs were not required and the police were not notified. WSDOT has detailed information on each cable median barrier location (i.e., placement, lateral offset, ditch configuration) and, in fact, most installations are placed in the same location, in the same width medians with the same slopes. While this discussion pertains only to predicting the likelihood of a crash, the severity of the collisions was also recorded and crash rates for injury and fatal crashes were likewise calculated. Based on this data, the frequency of crashes on cable median barriers installed in the same types of locations can be estimated quite accurately. In fact, any object place at the same lateral offset as the cable median barrier in the same width median with the same ditch slopes should experience a similar crash rate so this is a measure of the probability of the object at that location and with that particular approach terrain being struck. This value would likely be quite accurate for roadways with exactly the placement and slopes used in collecting the data but the crash rate tells the designer nothing about how vehicles come to be in that location or what the contributions of impact speed and angle, vehicle orientation, driver impact or many other characteristics of the encroachment might be. Of course many such analyses would have to be performed to develop enough of a range in placement options and slope configurations in order to use such an approach in RSAP but it might actually be easier to develop such crash rates for a wide variety of situations that it will be to validate the seven probability models used by RSAP to generate the encroachment conditions.

Ray and Weir performed a similar study to the Washington cable median barrier study where they calculated crash rates for longitudinal barriers in Iowa, Connecticut and North Carolina.[Ray01] In this study, data collection teams collected crashes reported to the police, crash reported to maintenance organizations and they also field surveyed site for unreported collisions. Guardrails in the three areas consisted of cable guardrails as well as strong and weak-post w-beam guardrails. The total crash rate (i.e., reported and unreported) for all types of barriers was 260 crashes/100 MVMT and 142 crashes/100 MVMT for police and maintenance reported crashes. With the exception of Iowa where the data collectors were, perhaps, a little too vigorous in detecting unreported crashes, the total crash rates in North Carolina and Connecticut were very similar regardless of the type of guardrail struck or the State.

Just based on these two simple studies, the police and maintenance reported crash rate for an object at the edge of the shoulder (i.e., Ray and Weir) is about 260 crashes/100 MVMT whereas the crash rate for an object in a median with a 6:1 foreslope located about 16 feet from the side of the highway is (i.e., the WSDOT cable median barrier study) is about 60 crashes/100 MVMT. If enough such studies were examined closely and perhaps re-analyzed to segregate out feature characteristics , fairly reliable crash rates could be obtained.

The NCHRP 17-22 and 17-11 crash data are another very promising data set for this type of activity as well as the up-coming NCHRP 17-43 project and the long-running NASS CDS data.

The relative strengths and weakness of these two approaches should be compared. If nothing else, these independent databases can be used to validate the RSAP predictions using the Monte Carlo simulation method and provide a more rational basis for calibrating and adjusting a new RSAP.

Modeling Crashes

Once the encroachment conditions are estimated, the likely path of the encroaching vehicle is calculated by simply projecting the corners of the vehicle into the roadside at the encroachment angle. If the swath intersects a roadside feature a collision is considered to have occurred. There is also an adjustment to account for pre-impact slopes since vehicles on a down slope will gain energy from going down the slopes and those going up a slope will experience an energy loss.

The severity of the crash is then estimated, as will be described in the next section, and the collision cost is calculated. The entire process is repeated 20,000 times (note: this can be modified but 20,000 is the default value) and the average collision cost for this block of crashes is calculated. Once calculated another block of 20,000 encroachments is calculated and the process continues until the average crash-cost converges on until the collision cost converges.

As described in the last section, the vehicle department conditions (i.e., speed, angle, orientation, etc.) are estimated in the encroachment model using a Monte Carlo simulation technique. There are many other characteristics of the off-road part of the vehicle travel that

RSAP does not attempt to account for like the affect of driver steering and braking input or the condition of the soil. This is thought to be a serious deficiency of the current approach although it is not know how sensitive the final results of RSAP are to the complexity of the off-road trajectory model.

Researches in NCHRP Project 17-11(2) are attempting to circumvent this weakness in the off-road portion of the RSAP prediction by linking the RSAP approach for Monte Carlo simulation of the roadway departure conditions to the vehicle dynamics program HVOSM. This would provide a more realistic estimate of the vehicle path given the encroachment conditions than the straight-line assumption of RSAP but it does nothing to eliminate or address the underlying uncertainty about the probability distributions used to estimate the encroachment conditions.

Extent of Encroachment

The lateral extent of encroachment distributions are used in two ways in RSAP:

(1) To calculate the probability for an encroaching vehicle to exceed a certain lateral distance from the edge of the lane and
(2) To adjust for the under-estimate due to the presence of paved shoulders as discussed earlier in regard to the Cooper data.

In section 6.4 on page 45 of the RSAP Engineer's Manual, the probability distributions for the two types of highways are shown in a figure. It also describes how those two under-reporting adjustment ratios, 1.878 and 2.466, are obtained. The formulas for the two distributions are as follows:

- Two-lane undivided highways - $P(D > x)=100e^{-0.262x}$
- Multilane divided highways - $P(D > x)=100e^{-0.161x}$

Where P(D>x) is the probability that an encroachment has a lateral extent, D, exceeding x meters. The underlying assumption is that the exceedence probability decays exponentially as the lateral extent (i.e., distance from the edge of the lane) increases.

Modeling Crash Severity

Introduction

The computed severity of a crash directly impacts the projected cost associated with a crash since the severity is mapped to the societal cost of the crash. A reduction in severity is the benefit in the cost-effectiveness analysis procedure. If a crash is modeled as a fatal crash when it more likely would have been a lower severity injury crash, the resulting crash cost would be significantly higher. The converse if also true, therefore, correctly modeling the crash severity is paramount to correctly implementing the cost- effectiveness analysis procedure. One accepted way to model crash severity and the way RSAP currently models severity, is through a Severity Index (SI). A SI is an indicator of the average severity for a particular set of crash circumstances, with an object, that a crash will result in a fatality, injury or property damage only (PDO). The current version of RSAP uses severity indices expressed as a function of impact speed, not roadway design speed as listed in the RDG. "For each roadside object or feature, a linear regression line was fitted through the SI values as a function of speed...." (Figure 9). This method "…relates SI values to specific impact speeds for each roadside object or feature indeed of average SI values." [AASHTO06]

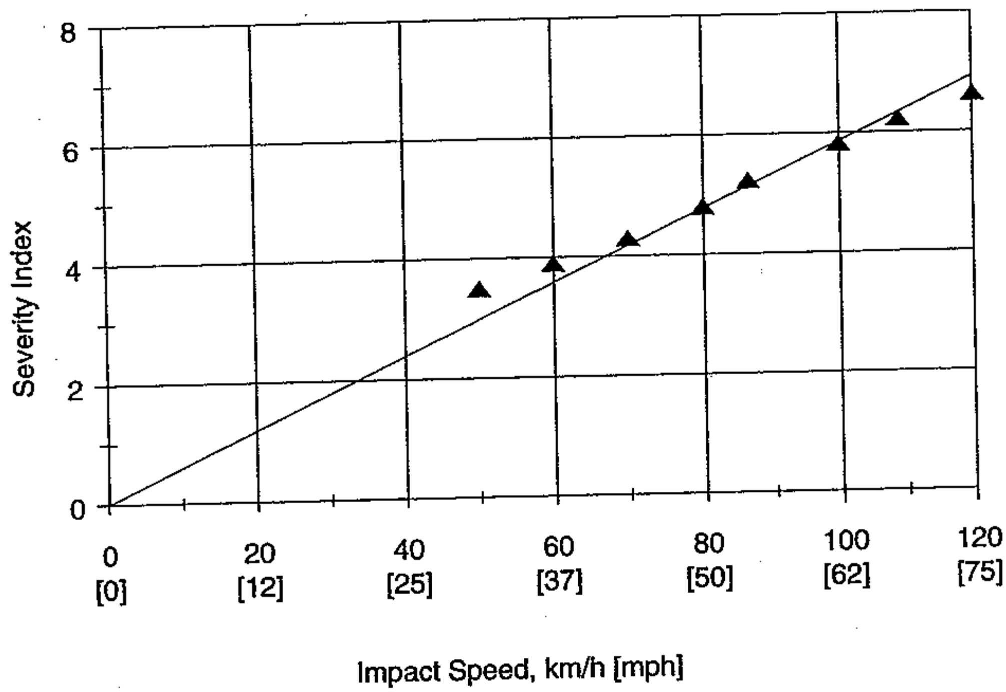


Figure 9. Example of Relationship Between SI and Impact Speed. [AASHTO2006]

One of the biggest challenges in evaluating the cost-effectiveness of alternative roadside safety improvements is the difficulty of predicting the severity of crashes after vehicles encroach on the roadside and collide with roadside features (or hazards) such as side-slopes, ditches, culverts, utility poles, trees, and guardrails. Turner and Hall (1994) conducted a rather comprehensive review of earlier efforts to establish SI values from the late 1960s to early 1990s.[Turner94] They suggested the need to have a major effort to significantly improve both the understanding of the crash impact-severity relationship and the quality and accuracy of existing predicting procedures and data. The review was, however, uncertain about the types of studies that should be undertaken to best meet the need.

The RSAP Engineer's Manual reiterates the need of such an effort.[Mak03]. It emphasizes that "severity estimation is one of the most critical components of the cost-effectiveness analysis procedure because it directly affects the crash cost calculations," and that "the severity estimates incorporated into the analysis must be as accurate as possible and must be validated." The RSAP Engineer's Manual lists the crash severity estimation as one of the limitations of the current RSAP software that requires both procedural changes and better real-world crash data to support the new procedure. The procedural change advocated in the RSAP Engineer's Manual is the so-called probability of injury (POI) approach, as opposed to the prevailing severity index (SI) approach that is adopted by the current RSAP program. Both approaches will be discussed in a later section.

Figure 3, shown earlier, is a schematic flow chart of the RSAP simulation-based benefit-cost (B/C) evaluation procedure. It gives an overview of the entire system, including the encroachment module, crash prediction module, severity prediction module, and B/C analysis module. As depicted, for a particular roadside feature, the impact conditions, which are expressed in the form of a joint set of probability distributions, depends on the placement relative to the travelled-way (e.g., right side, median, or left side) of the hardware, its lateral offset from the edge of the travel lane, other roadside conditions in the vehicle's path (e.g., slope) and roadway conditions prior to the encroachment. For example, the operating speed, median type, horizontal curvature, and vertical grade of the roadway affect vehicle encroachment conditions, including encroachment speed, encroachment angle, and vehicle orientation; and the roadside geometry, especially slopes and slope changes, and surface materials on the vehicle path affect vehicle dynamics. Both sets of factors, in conjunction with inputs from a driver input component, affect impact conditions in the end. The driver input component in the current RSAP program is, however, inactive and no driver input (e.g., steering and braking) is currently assumed. Note that the vehicle path is also called the impact envelope or hazard image in the literature (e.g., page 21 in [Mak03]).

In Figure 3, the severity prediction module refers to the components included in the box. As depicted, the key function of the module is to take a given set of impact conditions, (i.e., impact speed, angle, and vehicle orientation) and estimate the crash severity in the form of a probability distribution function. More specifically, for an impact with certain conditions, the module calculates the chance for the impact to be a fatal crash, an incapacitating injury crash, a non-incapacitating injury crash, a possible injury crash, and a non-injury or property damage only crash, which are symbolized as K, A, B, C, and O crash, respectively. Other information flowing into this module include the type and nature of the roadside feature the vehicle strikes, and for certain features, such as longitudinal barriers, whether the vehicle, given its physical attributes and impact conditions, would penetrate the features or roll over after impact. In essence, the severity prediction module takes the impact conditions as well as certain physical attributes of roadside feature and vehicle, as inputs and generates a probability distribution of police-reported levels of property damages and injuries, for which estimates of crash costs are available.

Making the decision to install certain safety devices is often a balancing act between crash severity and crash frequency. This is also the case for comparing some alternative roadside features. The importance of having accurate severity estimates in making such decisions and comparisons is illustrated with the following two examples:

1. Installation of Guardrails [Sicking09]: Bridge piers, utility poles and steep embankments are hazards that, if encountered, may result in serious injury. In order to protect motorists, barriers must be placed in front of such roadside obstacles and must be sufficiently longer than the hazard in order to limit the risk of a serious crash when vehicles leave the road in advance of the barrier. Unfortunately, barriers also pose a risk to motorists. Installing guardrails may actually increase the number of crashes and vehicles penetrating and rolling over the top or in front of the guardrail are also possible. As a result, for lower risk hazards, such as small objects and moderate slopes, the number of serious crashes associated with a guardrail can be greater than the number of similar impacts that would occur without the guardrail. In this situation, guardrail construction would increase the number of injured motorists compared to leaving the hazard unshielded. Finding this break-point between the benefit of the guardrail treatment and the hazard associated with the guardrail treatment is the essence of the B/C method.
2. Installation of Median Barriers [Miaou05]: Within its performance limits, a median barrier is designed to contain and deflect an errant vehicle in a controlled manner with acceptable deceleration and low exit angle, and is thus expected to result in less severe injury to the occupants or damage to the vehicle than the involved-vehicle would otherwise experience in a cross-median crash. In determining whether it is cost-effective to install a barrier, this benefit of reducing the expected severity of an otherwise cross-median crash has to be

compared with the generation of barrier-crashes that would otherwise not have occurred and the cost of installing and maintaining the barrier.

The Challenge

Several factors have contributed to the difficulties of estimating crash severity. Three of these factors stand out from the literature:

- Size, complexity, and changing nature of the determining variables,
- Underreporting of less severe crashes and
- Number, design variation, and combination of roadside features involved.

These factors are the source of some of the confusion and skepticism experienced by users of RSAP. A concerted research effort needs to be made to address them in a holistic and systematic manner. What follows is a discussion of each factor.

Size, Complexity, and Changing Nature of the Determining Variables

For a given impact condition, a large number of variables exert direct influences on the severity outcome of a run-off-road crash, and that the complexity of the crash impact-severity process is further compounded by their interactions. These variables include those associated with the roadside features themselves, the vehicles, the occupants, and even the availability and quality of emergency services. What follows are some examples:

- Roadside Features: geometry, including length, width, height, and shape, material (e.g., rigid, semi-rigid, and flexible barriers), maximum allowable deflection, rollover potential, speed impact resistance, and penetration or containment limit.
- Impact Location: traffic face, corner, or approach side of certain positive features, frontal or side impact of vehicles.
- Vehicles: weight, body dimensions, center of gravity, crashworthiness, airbag, door beams or side impact bars.
- Occupants: seat belt use, height, weight, health, age, seating position, number of occupants, alcohol and drug use.
- Emergency Services: response time, quality and technology of medical cares.

Thus, there are a large number of variables and relationships to select, consider, and evaluate. Since the objective is to improve roadside design decision process, it is natural to focus on those design and vehicle parameters that are expected to be most relevant to crash severity outcomes, and marginalize (or "omit") those variables that are "ancillary" (or not in focus). The variable selection decision is usually achieved through a combination of engineering judgment, theory, and findings from previous studies. To use the current RSAP program as an example, fore-slope and back-slope are the design variables selected for evaluating the crash severity of a parallel v-ditch; while for a longitudinal barrier, the variables include maximum allowable deflection, containment limit, and mounting height (as a rollover determinant). Key vehicle variables considered in RSAP program include body dimension, weight, and center of gravity of a vehicle, while airbags and door beams are marginalized. Variables related to occupants and emergency services are also completely marginalized in RSAP.

For those variables that are not in focus and marginalized, the underlying assumption is that the distribution of these variables in the available data are representative of the condition experienced by the crash population of interest. To the extent that these marginalized variables are not representative, spatially or temporally, the developed impact condition-severity relationship may be biased. To illustrate the issue, the following discussion uses seat belt usage rates and vehicle airbags as examples, both of which are marginalized in RSAP and have potentially large effect on occupant risks in many types of crashes [Crandall01].

The changes in seat belt usage rates and the number of on-road vehicles equipped with airbags and side impact protection beams have significant implications on injury risk in roadside crashes, especially those that roll over on slopes and those that strike fixed objects. In the last 25 years, there has been a marked increase in seat belt usage rates in the US: from 14 percent in 1983 to 84 percent in 2009 as shown in Figure 10. Furthermore, there is a wide variation in belt usage rates among states (e.g., 66.8 percent in Massachusetts and 97.2 percent in Michigan in 2008). For states that have the seat belt law as a primary enforcement law, their usage rates have been consistently higher than those states that do not have such an enforcement authority—on average, about 13 percent higher in 2008.

All else being equal, because of the drastic changes in seat belt usage rate, an impact condition-severity relationship developed in the 1980-1990 period is expected to be biased toward more severe crashes for today's vehicle fleet. In addition, assuming the seat belt is as effective as one expects in reducing the crash severity and the wide variation of seat belt usage rates among states is indeed accurate, then a significant variation in crash severity distribution among states should be observable with, of course, a good statistical design and reasonable controls. Therefore, the disparity in the usage rate among states actually provides an opportunity for researchers to test the effect of seat belts on impact severity for crashes involving roadside features.

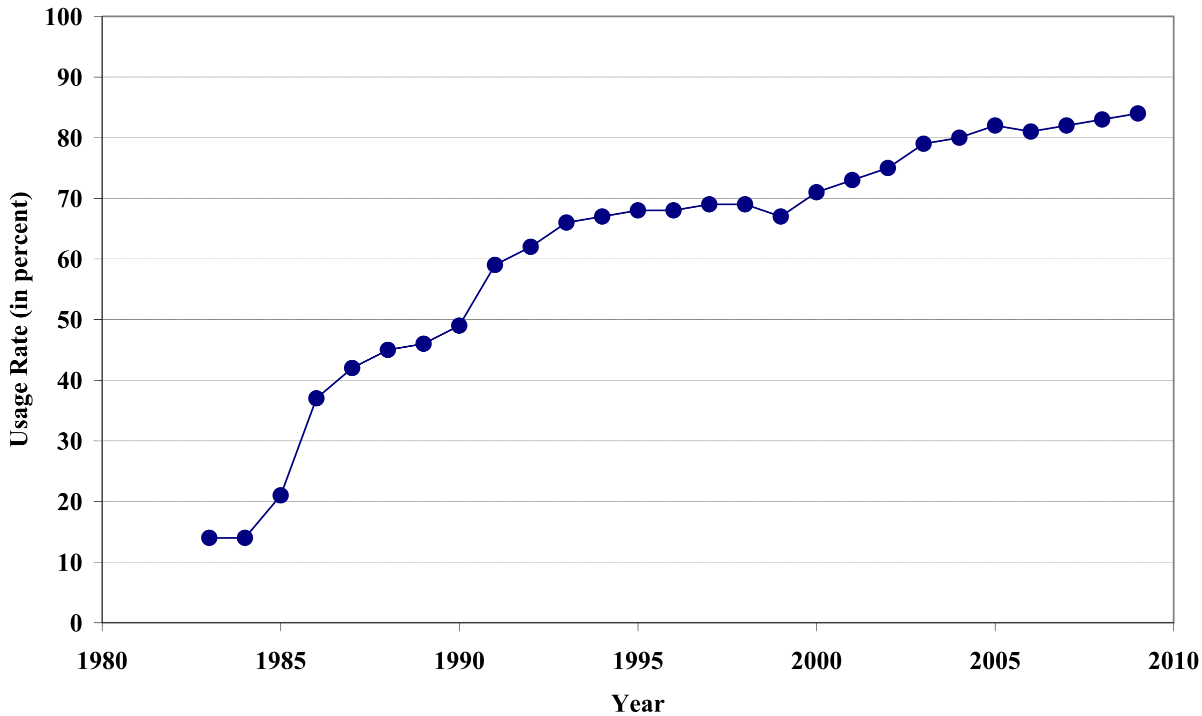


Figure 10. Seat belt usage rates in the US from 1983 to 2009. [NHTSA09]

Using Zegeer and Parker's utility pole study (1983) as an example, Turner and Hall (1994) commented on the state to state variation issue in their review as follows: "The relatively large database employed by Zegeer and Parker adds credibility to their severity estimate; this does not mean, however, that the results were identical in each of the four states studied. The amount of variability is reflected by the percentage of injury accidents, which ranged from 38.0 percent in one state to 52.5 percent in another. These results illustrate the inherent problem of using data from a small sample of states to generate average national values. There are, indeed, substantial differences from state to state."[Turner94; Zegeer83] Several factors may have contributed to the severity differences among the States, the wide variation in seat belt usage rates is certainly one of the potential factors. Another possible factor is the underreporting rates to be discussed shortly. Other factors such as differences in crash reporting threshold, weather condition, and installation and maintenance practices may all play some role.

Since 1991, Federal airbag requirements were phased in for new vehicles over several years. About 90 percent of 1997 model year cars were required to be equipped with airbags, with full compliance beginning with the 1998 model year. Airbags were also required in all 1999 model light trucks and vans. Thus, even though vehicles with airbags were rare in the 1980s and early 1990s, a large percentage of on-road vehicles are expected to be equipped with airbags today. Despite the potentially large effect these shifts have on occupant risks, most of the impact conditions-severity relationships available in the literature today were developed between early 1970s and early 1990s.

As part of a study to update severity indices, Council and Stewart (1996) were the first to develop crash severity indices for airbag-equipped vehicles.[Council96] Using a limited number of VIN decodable vehicles in North Carolina crash database from 1986 to 1992, they found that for the guardrail, tree, and utility pole classes of roadside features, for which sufficient samples existed, it appeared clearly that airbags and the related higher usage rate of belt use, significantly reduced the value of the severity index. As will be discussed later, different definitions and ranges of values of severity indices have been used in previous studies. In this particular study, two severity indices were considered: one was defined as the proportion of crashes resulting in fatal and incapacitating driver injuries and the other was defined as the average societal cost for driver injury in impacts. In developing both indices the authors focused on driver's injury, as opposed to the maximum severity of all occupants involved in a crash.

Council and Stewart's (1996) study was subsequently updated and expanded to include more data from three states in Highway Safety Information System (HSIS): Illinois data from 1990 to 1993, North Carolina data from 1990 to 1994, and Utah data from 1990 to 1994. [Council97]. To increase the comparability of airbag equipped and non-equipped vehicles, control of vehicle model years and vehicle weights was exercised in the statistical analysis. The final data set for each state was restricted to those fixed object classes for which there were at least 50 airbag-equipped vehicle crashes. The fixed objects that remained in the three data bases included trees, utility poles, highway signs, light poles, catch basins, guardrails (faces and ends), concrete barriers, bridge rail faces, and ditches/embankments. While the data across the states and across object types were not totally consistent, the authors concluded that airbags would indeed reduce the severity indices for fixed objects. The authors' best estimate of the reduction was in the range of 10 to 30 percent for point objects (e.g., trees, utility poles and signs), 40 to 50 percent for guardrails, and 10 to 20 percent for other longitudinal barriers. No conclusions concerning impacts into ditches/embankments could be drawn. Given that a much higher percentage of on-road vehicles are equipped with airbags today, an update of this type of studies seems warranted.

More recently, Gabauer and Gabler (2007) used data from the Crashworthiness Data System (CDS) of the National Automotive Sampling System (NASS), administered by NHTSA, to provide some understanding of airbag deployment and seatbelt usage rates in roadside hardware crashes.[Gabauer07] The study focused on crash cases comprising only a single impact with guardrail and concrete barrier. Inclusion of only single event crashes ensured that the object struck caused (or did not cause) the deployment of the airbag. A total of 315 NASS CDS cases from 2000 to 2004 were selected. After application of NASS national weights, these cases represent over 150,000 longitudinal barrier collisions nationwide (Note that NASS CDS data include only those crashes that involved at least one towed passenger car or light truck or van in transport on a traffic way). Based on these crash cases, belt usage rates for drivers were estimated to be about 80 percent and airbag-equipped vehicles accounted for about 83 percent of the vehicles involved. That is, about 17 percent of tow-away longitudinal barrier crashes involved vehicles that were not equipped with airbags. In those vehicles that were equipped with airbags, the driver-side bag deployed approximately two-thirds of the time after impact. Unfortunately, the study did not attempt to study the effect of airbags on crash severity. Given that a larger percentage of on-road vehicles are equipped with airbags today and more recent data are now available, it seems a worthwhile effort to update the study with severity in mind, and to understand the extent to which crash severity issues related to roadside features can potentially be addressed with the NASS CDS database.

The discussion above on seal belt usage rate and airbag equipped vehicles serves to demonstrate the importance of keeping those marginalized variables in check in developing the impact-severity relationships for roadside features. In general, there is a need to monitor marginalized variables to make sure they are reasonably represented in the available data or factored into the analysis. In addition, to reduce the bias caused by the temporal changes in these variables, the relationships need to be either modeled explicitly or updated as often as necessary with newer data to reflect the changes.

Underreporting of Less Severe Crashes

Most crash severity measures devised to date are based on police-reported crash data. An inherent bias of such measures comes from unreported crashes. As indicated in the RSAP Engineer's Manual, "crash reporting rates for roadside safety devices and hazards are very difficult to determine and mostly unknown."[Mak03] In addition, "the reporting rates are likely to vary significantly among safety hardware systems. It appears that, the more effective the safety device (i.e., the lower the resulting injury severity to the occupants and damage to the impacting vehicles), the lower is the reporting rate. The uncertainty associated with the magnitude of unreported crashes for each safety feature casts doubt on all crash-data-based severity estimates." [Mak03] Not only the underreporting inflates the values of severity measures, the difference in underreporting rates among safety features can also lead to erroneous comparisons and thus misleading benefit-cost evaluations.

Based on a literature review, Council and Stewart (1996) ventured to estimate underreporting rates for some roadside features as follows: approximately 30 to 40 percent of impacts with guardrails and median barriers might be unreported in some databases and that 10 to 15 percent of utility pole impacts, 4 to 8 percent of impacts with nonbreakaway traffic signals and luminaire supports, 50 percent of crash cushion impacts, and 30 percent of impacts with other breakaway devices might be unreported. [Council96] They also estimated that a much higher level of underreporting (i.e., up to 70 to 75 percent) could be present for objects such as small signs, delineators, and other objects that very seldom lead to driver or occupant injury. They cautioned that their estimates of underreporting were based on studies that were quite old (early 1970s and 1980s), and those estimates based on maintenance data could not clearly separate below-threshold impacts from those that should, in actuality, be in the police files.

The underreporting rate estimate for the guardrails and median barriers of 30 to 40 percent above were mainly for rigid and semi-rigid types of barriers. Citing an ongoing Missouri study, Sicking et al. (2008) has used an underreporting rate of 26 percent for cable median barriers in their B/C analyses of installing cable barriers to reduce cross median crashes.[Sicking08] The number of unreported cable barrier crashes was estimated by comparing the number of cable barrier repairs to the number of cable barrier crash reports. During 2006 and 2007, the State of Missouri recorded a total of 4,386 cable barrier crashes and 5,939 repairs to the cable barrier. Although some repairs were undoubtedly caused by highway maintenance activities such as mowing and snowplowing, it was assumed that all barrier repairs were related to vehicular impacts. It was based on this assumption that the 26 percent underreporting rate was estimated, and thus the actual underreporting rate was expected to be lower than 26 percent for flexible barriers. This recent study certainly raises some doubt as to whether the earlier 30-40 percent estimates for rigid and semi-rigid barriers were perhaps too high.

There is clearly a need not only for more definitive data on underreporting of impacts with fixed objects, but also for more current data. With respect to the means to quantify unreported crashes, there is a continuing critical need to develop better information source, especially, for determining how underreporting differs by object. Council and Stewart (1996) indicated that "since insurance and other non-crash data would be characterized by the same monetary disincentives for reporting as accident reports, it appears that perhaps the best data source for unreported accidents would continue to be maintenance data from a state that regularly monitors damage and repair to its roadside objects in a computerized system.[Council96] These maintenance-based analyses should also be conducted in states whose police data have good reporting and a relatively low reporting threshold, a large variety of fixed objects (including the ability to separate barrier ends from faces), and the ability to link injury directly to a given object." [Council96]

Another possible venue for estimating underreporting rates of impacts is through the in-service performance evaluation (ISPE), in which site visits are performed routinely as was suggested by Ray in NCHRP Report 490 discussed earlier.[Ray03] It is the process of examining how well a roadside feature functions in actual service conditions and determining if its performance is consistent with its design. In-service evaluation, however, is not just a tool for designing better roadside features. Monitoring the field performance of roadside features can also provide better information for formulating policies about the installation, maintenance, and repair of roadside features. The evaluation has been recommended and endorsed by many NCHRP reports for many years, as an integral part of the design-test-deployment-evaluation life cycle development and management of roadside safety hardware systems. But relatively few attempts have been made with varying scope and quality. The report by Ray, Weir, and Hopp (2003) is a recent NCHRP effort aimed at formalizing the process and streamlining the procedures.[Ray03] A procedural manual for planning and performing in-service evaluations of roadside hardware was developed based on the methods used and lessons learned in an evaluation study. Recent ISPE efforts include Ray and Hopp (2000), Ray and Weir (2001), Igharo, Munger, and Glad (2004), and van Schalkwyk et al. (2004).[Ray00; Ray01; Igharo04; vanSchalk04] To date, ISPE studies provide some additional data about roadside crashes, but the number of cases is very small.

The estimates of unreported crash discussed above by Council and Stewart as well as by Sicking all used maintenance reports for the estimate of unreported crashes. The idea was that some crashes are not reported to the police but are reported to the highway agency because the struck barrier requires repair.[Council96; Sicking08] Ray did the same thing in his study of longitudinal barrier terminal crashes in Iowa.[Ray00] As discussed earlier, Ray found that 40 percent of the BCT collisions were reported to the maintenance agency but not to the police. This compares reasonably well with Council and Stewart's estimate of 30 to 40 percent although it is 50 percent higher than Sicking it should be remembered that Sicking was observing cable median barriers. Interestingly, though, Ray also physically observed the terminals for damage not requiring repair and found that there was evidence that 90 percent of the events were reported to neither the maintenance agency or the police. This is an important fact to keep in mind with Council and Stewart's data as well as Sicking's since both of those studies ignored damaged barriers that did not require repairs. So, on the one hand, studies like Sicking and Council that rely on maintenance data can tend to miss the very minor unreported crashes that result in no needed barrier repairs while the visual observation studies like those done by Ray probably include erroneous information like minor rubs and scraps from maintenance and snow removal equipment. No matter which estimate one uses, however, the proportion of unreported crashes is quite high.

Uncertainties, including the magnitude of unreported crashes, are often encountered when constructing B/C analysis for evaluating highway safety improvements. These uncertainties are normally addressed with the philosophy that the final analysis should be constructed to err on the side of safety (i.e., to be biased toward more severe crashes). This philosophy is, however, difficult to maintain when comparing alternative safety features with uneven and highly uncertain underreporting rates.

Number, Design Variation, and Combination of Roadside Features Involved

Another factor that adds to this challenge of estimating impact condition-severity relationships is the fact that there are a large number of roadside features and possible design variations and combinations of features to consider. For example, there are eight general types of built-in roadside features considered by the current RSAP program, which contains a total of 278 different features. These eight types of features and the number of different features contained in each type are as follows:

- Type 1: Fore-slopes (54 features)
- Type 2: Back-slopes (25 features)
- Type 3: Parallel Ditches (12 features)
- Type 4: Intersecting Slopes (90 features)
- Type 5: Fixed Objects (34 features)
- Type 6: Culvert End (35 features)
- Type 7: Longitudinal Barriers (17 features)
- Type 8: Terminals and Crash Cushions (11 features)

RSAP also allows users to specify their own features. To get a sense of the types of features covered in the current RSAP program and the design variations within each type, Tables 9 and 10 list 12 built-in v-ditch configurations (i.e., features 80 to 91) from Type 3 features and 34 fixed objects (i.e., features 182 to 215) from Type 5 features, respectively. More details of these features will be discussed is a later section and Appendix A. Note that trapezoidal ditches are not covered by the Type 3 features and a provision to estimate crash severity for these ditches is provided in the appendix (Figure A.3).

Table 9. Twelve built-in v-ditch configurations in the current RSAP program.

```
#
# Feature Parallel Ditches
#
Type 3  80  1. 2:1 Foreslope, 2:1 Backslope
Type 3  81  2. 2:1 Foreslope, 3:1 Backslope
Type 3  82  3. 3:1 Foreslope, 2:1 Backslope
Type 3  83  4. 3:1 Foreslope, 3:1 Backslope
Type 3  84  5. 3:1 Foreslope, 4:1 Backslope
Type 3  85  6. 4:1 Foreslope, 2:1 Backslope
Type 3  86  7. 4:1 Foreslope, 3:1 Backslope
Type 3  87  8. 4:1 Foreslope, 4:1 Backslope
Type 3  88  9. 6:1 Foreslope, 2:1 Backslope
Type 3  89 10. 6:1 Foreslope, 3:1 Backslope
Type 3  90 11. 6:1 Foreslope, 4:1 Backslope
Type 3  91 12. 6:1 Foreslope, 6:1 Backslope
```

Table 10. Thirty-four built-in fixed objects in the current RSAP program.

```
#
# Feature Fixed Objects
#
Type 5 182  1. Round, 0.5 m (1.5 ft) Dia.
Type 5 183  2. Round, 1.0 m (3 ft) Dia.
Type 5 184  3. Round, >= 2.0 m (7 ft) Dia.
Type 5 185  4. Rectangle, W = 0.5 m (1.5 ft), H = 0.15 m (6 in.)
Type 5 186  5. Rectangle, W = 0.5 m (1.5 ft), H = 0.3 m (1 ft)
Type 5 187  6. Rectangle, W = 0.5 m (1.5 ft), H = 0.5 m (1.5 ft)
Type 5 188  7. Rectangle, W = 0.5 m (1.5 ft), H = 0.6 m (2 ft)
Type 5 189  8. Rectangle, W = 0.5 m (1.5 ft), H > 1.0 m (3 ft)
Type 5 190  9. Rectangle, W = 1.25 m (4 ft), H = 0.15 m (6 in.)
Type 5 191 10. Rectangle, W = 1.25 m (4 ft), H = 0.3 m (1 ft)
Type 5 192 11. Rectangle, W = 1.25 m (4 ft), H = 0.5 m (1.5 ft)
Type 5 193 12. Rectangle, W = 1.25 m (4 ft), H = 0.6 m (2 ft)
Type 5 194 13. Rectangle, W = 1.25 m (4 ft), H > 1.0 m (3 ft)
Type 5 195 14. Rectangle, W >= 2.0 m (7 ft), H = 0.15 m (6 in.)
Type 5 196 15. Rectangle, W >= 2.0 m (7 ft), H = 0.3 m (1 ft)
Type 5 197 16. Rectangle, W >= 2.0 m (7 ft), H = 0.5 m (1.5 ft)
Type 5 198 17. Rectangle, W >= 2.0 m (7 ft), H = 0.6 m (2 ft)
Type 5 199 18. Rectangle, W >= 2.0 m (7 ft), H > 1.0 m (3 ft)
Type 5 200 19. Tree, 50 mm (2 in.) Dia.
Type 5 201 20. Tree, 100 mm (4 in.) Dia.
Type 5 202 21. Tree, 150 mm (6 in.) Dia.
Type 5 203 22. Tree, 200 mm (8 in.) Dia.
Type 5 204 23. Tree, 250 mm (10 in.) Dia.
Type 5 205 24. Tree, 300 mm (12 in.) Dia.
Type 5 206 25. Tree, >300 mm (12 in.) Dia.
Type 5 207 26. Wooden Utility Pole, 200 mm (8 in.) Dia.
Type 5 208 27. Wooden Utility Pole, 250 mm (10 in.) Dia.
Type 5 209 28. Wooden Utility Pole, 300 mm (12 in.) Dia.
Type 5 210 29. Wooden Utility Pole, >350 mm (14 in.) Dia.
Type 5 211 30. Breakaway Support, Delta V = 1.5 m/s (5 ft/s)
Type 5 212 31. Breakaway Support, Delta V = 3.0 m/s (10 ft/s)
Type 5 213 32. Breakaway Support, Delta V = 4.5 m/s (15 ft/s)
Type 5 214 33. Breakaway Support, Delta V = 6.1 m/s (20 ft/s)
Type 5 215 34. Breakaway Support, Delta V = 7.6 m/s (25 ft/s)
```

The nature and severity of crashes vary significantly from one type of feature to another. As an example, fatal crashes that involved ditches (i.e., RSAP Type 3) and guardrail faces (i.e., RSAP Type 7) will be examined below to illustrate the nature of crashes. Table 11 gives the top five most harmful events (MHE) when vehicles entering ditches or striking guardrail faces were the first harmful event (FHE) based on the Fatal Analysis Reporting System (FARS) of the National Highway Traffic Safety Administration (NHTSA). By definition, MHE is the cause of the greatest trauma in a crash so in fatal crashes it is the cause of death. Out of the 1,198 fatal crashes involving vehicles entering ditches as the FHE in 2008, vehicle rollover was the MHE for over 50 percent of the crashes, followed by impacts with the ditch itself for about 18 percent, and then striking standing trees and utility poles for another 16 and 5 percent, respectively. Out of the 761 fatal crashes involving vehicles striking guardrail face as the FHE, the guardrail face itself was the MHE for 38 percent of the crashes, followed by rollovers for about 28 percent and then colliding with other vehicles on the same roadway and striking standing trees for another 9 percent and 7 percent, respectively. Thus, the most deadly events involving these two features are very different. For example, vehicle rollover is by far the most deadly event after an errant vehicle enters a ditch; while the guardrail face itself is the most deadly after hitting it.

Table 11. Top five most harmful events when entering ditches and striking guardrail face were the first harmful event. [FARS08]

Ditch as the First Harmful Event			**Guardrail Face as the First Harmful Event**		
Most Harmful Event	**Number of Crashes**	**Percent**	**Most Harmful Event**	**Number of Crashes**	**Percent**
1. Rollover	607	50.7	1. Guardrail Face	358	37.8
2. Ditch	215	18.0	2. Rollover	267	28.2
3. Tree (standing tree only)	193	16.1	3. Motor Vehicle in Transport on Same Roadway	87	9.2
4. Utility Pole	56	4.7	4. Tree (standing tree only)	66	6.9
5. Culvert	21	1.7	5. Fell from Vehicle	18	1.9
All Others Combined	106	8.8	All Others Combined	152	16.0
Total	1,198	100.0	Total	761	100.0

As indicated in the RSAP Engineer's Manual, "reconstructed in-depth crash data is perhaps the best means available for estimating crash severity. Unfortunately, collecting in-depth crash data and reconstructing the crashes is a very expensive undertaking and little data beyond the study on utility pole crashes was available." [Mak03] In the context of this report, the working definition of in-depth crash data are those that are acquired from studies where trained investigators examine vehicles, injuries, and the crash site in some detail to reconstruct the event to estimate impact speed and the resulting velocity change, either while the vehicles were still present or after their removal. An example of the in-depth crash data is the NCHRP 17-22 database that has recently been released.[Mak09].

The number and complexity of the impact condition-severity relationships that need to be developed for RSAP has serious implications in terms of the size and details of the data, and thus the resources needed to accomplish the task. It is extremely difficult and expensive, if not impossible, to develop all the impact condition-severity relationships of interest using in-depth crash data alone. Many of the relationships have to be inferred from relationships that have already been well established from crash data as well as from innovative use of kinematics analyses, simulation models of vehicle dynamics, full scale crash tests, and trauma biomechanics studies. Basically, all possible sources of data need to be used to extrapolate and validate severity models.

Looking forward, recent installation of Event Data Recorders (EDRs) in late model vehicles can potentially provide a completely different perspective on the assessment of occupant risks. [Gabauer05]. EDRs are a feature that is quickly becoming standard on all cars and light trucks. The recorder, a small metal box, is currently installed in most recent GM, Ford, Chrysler and Toyota vehicles. Most EDRs in cars and light trucks are part of the restraint system control module which senses impact accelerations and determines what restraints (e.g., airbags and/or seatbelt tensioners) to deploy. EDRs are capable of electronically recording data such as seat belt use, vehicle speed, brake status and throttle position just prior to and during a crash. Of particular interest is the EDRs' ability to document the deceleration of a vehicle during a collision event. As of August 2006, NHTSA published a final rule, standardizing requirements for EDRs to be voluntarily installed on all vehicles manufactured after September 1, 2010, but stopped short of requiring their installation

Given the difficulties of estimating crash severity described above, the software framework of the crash prediction module in RSAP should be as inclusive and as user friendly as possible. In order for the RSAP program to be able to make the best use of all possible data sources available now and in the future, a flexible research approach needs to be adopted to develop the needed impact-severity relationships. The data sources to be considered will be a mix of empirical and analytical data, including police-level and in-depth crash data, and data from full-scale crash tests, computer simulation models of various fidelities, and analytical models on vehicle dynamics and biomechanics. Given the limitations of the data and complex configurations of the features, some levels of engineering judgment will always be unavoidable for some of the roadside features. Providing better functionalities to facilitate users to calibrate the impact-severity relationships with their own data and allowing more user input options, such as adding the seat belt usage rate and allowing users to change the default rate, are some possible enhancements to consider in updating RSAP.

Severity Measures

Over the past 45 years researchers have proposed and developed alternative methods to quantify impact condition-severity distribution (IC-SD) relationships. While some progress has been made it has come slowly. Because of the difficulty and lack of in-depth data to develop such relationships directly, many have taken a multi-step approach. The most popular approach was a two-step approach that introduces an intermediate variable, called the severity index (SI), which connects impact condition and severity distribution. The idea was for the SI value to first represent some sort of "average" crash severity for a particular impact condition, such as impact speed. That is, the first step is to establish an IC-SI relationship. A conversion table is then developed to assign each SI value to the relative likelihood that a collision will result in a fatal, some level of injury, or property damage crash. For simplicity, this severity index to severity distribution conversion table will be called "SI to SD table."

Several definitions of SI have been used and the lack of direct comparability among these indices has led to some confusion by users in the past. For example, some earlier research had defined SI as the portion of all crashes resulting in a fatality or an injury. For such measures, the SI value is between 0 and 1 and is essential the percentage of fatal and injury crashes. This SI was found to be simple but potentially misleading because researchers have since established that results vary from state to state, on different road systems, at different highway speeds, for different classifications of the roadside features and from year to year. Severity indices calculated in this manner were also sensitive to the underreporting of minor crashes in the crash database, which has the effect of artificially inflating the SI values.

To avoid the problems associated with the crash data, a popular alternative SI measure was later defined on a scale of 0 to 10, representing "no significant property damage" at the zero end to "certain to be fatal" at the maximum value of 10. As Turner and Hall (1994) indicated, using this SI measure in the 1980s and early 1990s, "serious efforts have been made to develop justifiable severity indices using innovative techniques, including analyses of large accident databases, in-depth studies of particular objects, evaluation of vehicle damage, application of accident cost models, and the results of crash testing. In most cases, these studies have increased the level of understanding of severity indices, although the variations in values recommended by different studies have not been eliminated." [Turner94] This SI definition was used in the original 1977 Barrier Guide cost effectiveness technique and was carried over into the Roadside program and was likewise adopted in RSAP. More details about the SI adopted in the current RSAP program will be presented in the next section.

A good example used by Turner and Hall (1994) to emphasize the incomparability of these two scales of indices is as follows: "Glennon's severity indices, on a scale of 0 to 1, cannot be directly compared to Weaver's severity indices, which are on a scale of 0 to 10. Glennon's values cannot be multiplied by 10 to convert them to Weaver's scale. One reason for this is that the object definitions were not always identical. A second reason is that the designated severity values were not distributed similarly across the two scales, i.e., Glennon's largest value was 0.60 even though his scale reached to 1.00. Weaver's largest value was 9.3 on a scale of 10.0." [Turner94]

As the RSAP Engineer's Manual pointed out, "No analytical technique has yet been identified as the definitive method for determining severity index values. Multiple investigative efforts have produced divergent answers. In at least two instances, researchers found greatly different results by employing different methods to develop severity indices from a single data set." [Mak03] A stratification of severity indices to reflect varying distances from the road, varying roadway alignment, varying impact speeds, and various roadside features were understood to be required to produce more realistic values. This compilation of data would obviously demand a very large database, careful preparation and screening of the data, and a thorough statistical analysis to identify the true relationship between these factors and the severity indices for any roadside feature.

An interesting SI measure on the scale of 0 to 10 was developed using a computer simulation program by Ross. [Ross93] It was used to evaluate the benefits of rounding the hinge at the intersection of the shoulder and side-slope. In the study, the HVOSM computer simulation program was used to determine occupant risk parameters for encroachments on unrounded and rounded side-slopes which, in turn, were used to estimate a severity index for input into another benefit-cost analysis program. Vehicle acceleration and stability measures from the simulation models were used to formulate the SI as follows. Occupant risk was measured in terms of vehicle accelerations and stability as determined by roll angle. The following formula was used to generate a combined severity index:

$$SI = \begin{cases} \dfrac{a}{4} + 7\left(\dfrac{\phi}{90}\right)^2 \leq 10, & if \;\; 0 < \phi < 90 \text{ deg} \\ 7, & if \;\; \phi \geq 90 \text{ deg} \end{cases}$$

Where

- SI = Severity index
- a = Average resultant vehicle acceleration during any 50 ms (millisecond) period measured in g's, and
- ϕ = Vehicle roll angle (deg)

A rollover case with $\phi \geq 90$ degrees was judged to have an SI of 7. For the case where $\phi < 90$ degrees, the maximum SI value is determined by analyzing the following two situations and choosing the larger value:

- The value of *a* is the maximum average acceleration during any 50 millisecond period and ϕ is the vehicle roll angle at the midpoint of the period.
- The roll angle ϕ is the maximum vehicle roll angle during the entire encroachment period, occurring at time *t*, and the value of *a* is the 50 millisecond average resultant vehicle acceleration during the time period *t*-0.025 to *t*+0.025 seconds.

Another popular index, which has a rich history in full scale crash testing and simulation models, is the Acceleration Severity Index (ASI). (see [Sturt09]). ASI has evolved as a practical means of comparing the rigidity of barriers and was not originally intended as a direct measure of injury or the potential for injury (Note that ASI should not be confused with abbreviated injury scale (AIS) which is derived from medical assessment of a victim's injuries and is widely used in studies of the injury outcomes of real-world crashes).

A different thread of research efforts has been to associate ASI values to theoretical head impact velocity (THIV) and then to some biomechanics injury measures, such as Head, Neck or Chest Injury Criterion (HIC, NIC, and CIC). The objective is to use the ASI severity measure to determine if the crash testing and simulation outcomes of roadside barriers are acceptable from some injury risk point of view. But, there has been a long debate as to whether a correlation between ASI and injury risk really exists. Earlier studies were generally negative on the existence of this correlation. More recent studies do show some interesting correlation (see studies cited in [Sturt09]).

ASI provides an indication of the deceleration of a vehicle over a 50ms rolling period relative to some tolerance limits of occupants as follows:

$$ASI(\Delta t) = \sqrt{\left(\frac{a_x}{c_x}\right)^2 + \left(\frac{a_y}{c_y}\right)^2 + \left(\frac{a_z}{c_z}\right)^2}$$

where ASI(Δt) indicates that the ASI value is a function of time increment Δt; a_x, a_y and a_z are the vehicle accelerations in the *x* (forward), *y* (lateral) and *z* (vertical) directions measured in units of gravity (*g*) and averaged over a rolling Δt = 50 ms period; and c_x=12g, c_y=9g and c_z=10 g are the tolerance limits of occupants in each direction. The ASI value used in determining occupant's injury severity is the maximum value of ASI occurring during a crash.

RSAP Severity Indices

As discussed, a severity index (SI) is intended to represent some sort of "average" crash severity for a particular set of impact conditions. Although there are several methods for estimating crash severity, the most commonly used method in roadside safety studies involves developing a link between vehicular impact conditions, especially impact speed, and SI. This is the method used in the current RSAP program and some of its predecessors.

The severity estimates in the current RSAP program are largely based on the SI values tabulated in the 1996 AASHTO Roadside Design Guide (RDG). The SI values range from zero to ten where zero represents "no significant property damage" and 10 represents a crash that is "certain to be fatal." A conversion table is then used to assign each SI value to the relative likelihood that a collision will result in a fatal, some level of injury, or property damage crash. The severity index to severity distribution (SI to SD) conversion table incorporated into the

RSAP program is shown in Table 12. Each row in the table links an SI value to a distribution of police-reported crash severity levels. For any SI value falling between two of the nearest values in the table, a linear interpolation is used to calculate the distribution.

Table 12. Severity Index to Severity Distribution Conversion Table used in RSAP program.

Severity Index	**Severity Distribution (%)**						
(SI)	None	PDO1	PDO2	C	B	A	K
0	100.0						
0.5		100.0					
1		66.7	23.7	7.3	2.3		
2			71.0	22.0	7.0		
3			43.0	34.0	21.0	1.0	1.0
4			30.0	30.0	32.0	5.0	3.0
5			15.0	22.0	45.0	10.0	8.0
6			7.0	16.0	39.0	20.0	18.0
7			2.0	10.0	28.0	30.0	30.0
8				4.0	19.0	27.0	50.0
9					7.0	18.0	75.0
10							100.0

Note: The usual convention for police reported crash severity is used where:
K= Fatal,
A=Incapacitating Injury,
B=Non-incapacitating Injury,
C=Possible Injury and
PDO= Property Damage Only (No Injury).

Although the SI values are generally assumed to have a linear relationship with impact speeds in RSAP, which will be discussed next, this SI to SD conversion table provides a much skewed relationship between the distribution of occupants risk and severity index. Thus, the ultimate relationship between impact speed and probability of injury is a skewed relationship. Generally speaking, as impact speed increases, the SI value increases and the associated severity distribution changes gradually from skewed right distributions to skewed left distributions where a skewed right (left) distribution is a distribution with a longer tail on its right (left) side.

This SI to SD conversion table has been singled out by the RSAP Engineer's Manual as one of the most serious limitations of this SI or two-step approach. Specifically, a given SI value is associated with specific percentages of fatal, injury, and PDO crashes and the range of the distribution is limited to five consecutive severity levels. This is deemed not flexible or sensitive enough to account for different hazard types with unusual severity distributions. For example, bridge rails over deep bodies of water would be expected to have a low proportion of severe injury and fatal crashes when vehicles are successfully redirected but a nearly 100 percent fatality rate when vehicles go through or over the bridge railing. For this particular example, a mixture of two severity distributions might be more appropriate.

As indicated in Engineer's Manual, the indices in the 1996 RDG were based on engineering judgment developed in the 1970s, tempered with general crash study methodologies and results over the years. In addition, although severity indices were intended to be representative of an average crash, it is believed that the SI values were more representative of high speed impacts and, therefore, overstated the average impact severity. With the exception of a newly released study by Sicking, there has been no concerted research effort to understand the accuracy and representativeness of these SI values when compared to the crash experience that actually occurred on the roadsides.[Sicking09] As suggested in Engineer's Manual, the SI values currently incorporated in RSAP need to be reviewed critically and revised as appropriate.

The severity of a crash must be linked to the type of features struck, as well as the impact condition and vehicle size involved in the crash. As shown earlier in Figure 3, RSAP assigns an SI value for each simulated impact with a roadside feature based on simulated impact speed, impact angle, and weight and dimension of the simulated vehicle. The roles of these variables in estimating crash severity in RSAP are discussed next. But, first, a quick and general summary is given below:

- Vehicle Impact Speeds and Angles: For all features in RSAP, impact speed is the most important determinant in estimating severity. For longitudinal barriers, impact angle is further factored into the impact speed to calculate lateral speed, which was previous found to be more predictive of crash severity for this type of barriers. A linear impact speed-SI relationship (with an upper limit of 10) is always assumed in RSAP for all features.
- Vehicle Orientation at Impact: In the current RSAP program, vehicle orientation at impact is used to better define the vehicle swath during encroachment. It is, however, not considered in estimating severity. The RSAP Engineer's Manual does suggest the need to incorporate this capability in the future (Section 6.5.2 in Engineer's Manual).
- Vehicle Weight and Dimension: In addition to defining vehicle swath and thus impact probability, vehicle weight, dimension, and center of gravity (c.g.) height are used to determine the propensity for vehicles to penetrate certain safety features and for heavy trucks to roll over after hitting longitudinal barriers.

The original SI tables in the 1996 RDG were tabulated by highway design speed. The developers of the current RSAP made an effort to replace design speed with impact speed. According to the RSAP Engineer's Manual, a method was developed to basically reproduce the SI values shown in the 1996 RDG. For each roadside feature, a linear regression line was fit through the RDG SI values as a function of speed. These regression lines would almost always originate at the zero point since an impact speed of zero (km/hr) should not produce any damage to the vehicle or injury to the occupants. Sicking further elaborated that "the slope of the regression line was then calibrated by using RSAP to predict average IS [impact severity] values for each of the functional classes of highway used in the program. Predicted severity levels for urban collector, rural collector and urban arterial, rural arterial, and freeways were then compared to values tabulated for design speeds of 31, 43.5, 56, and 71.5 mph (50, 70, 90, and 115 km/h), respectively." [Sicking09] This calibration method was indicated to have resolved some of the inconsistencies in the SI values presented in the 1996 RDG. [Mak03; Sicking09].

RSAP's developers recognized that large vertical drops would not necessarily have an SI of zero for an impact speed of zero because gravity would also play a large role in the probability of injury. Therefore, the regression lines for vertical drops were not fit through the zero point.

Despite the description in RSAP Engineer's Manual and Sicking et al. (2009), the mathematical detail behind the calibration method described above is not particularly clear. [Mak03;Sicking09] In addition, for some of the features, different SI values were assigned to different impact positions in the 1996 RDG (e.g., different SI values were provided for impacts at the approach side, corner, and traffic face of some culvert ends and fixed objects). This distinction of impact position on features is no longer considered (explicitly) in the current

RSAP, and it is also not clear how these different SI values, due to different impact positions of features, were weighted in the calibration.

Based on the regression calibration method described above, the expected SI value is expressed as a linear function of impact speed, *V*, for different roadside features in the RSAP program as follows:

$$\mathrm{SI} = \min(a + u \times b \times V,\ 10)$$

or, equivalently,

$$\mathrm{SI} = \begin{cases} a + u \times b \times V, & \textit{if } a + u \times b \times V < 10 \\ 10, & \textit{if } a + u \times b \times V \geq 10 \end{cases}$$

where *a* is the intercept term of the regression line, *b* is the slope of the regression line, the parameter *u* is called the "crash severity adjustment factor," which is a user adjustment factor for the slope, and *V* is impact speed. The formula limits the SI value to be between *a* and 10. The intercept term *a* is fixed to zero for most features, the slope parameter *b* is a positive real value representing the increase of SI value with respect to a unit increase in impact speed *V*, and the crash severity adjustment factor *u* is also positive with a default value of 1.0. To be explained shortly, the term "impact speed" is used here in a general sense. Depending on features, it actually refers to vehicle entry speed, speed at impact, or lateral component of speed at impact.

The impact speed-SI relationships incorporated into the current RSAP are presented in the following figures in Appendix A.

- Figures A.1-1 to A.1-4: Type 1 Features, Fore-slopes (4 Charts)
- Figure A.2: Type 2 Feature, Back-slopes (1 Chart)
- Figure A.3: Type 3 Feature, Parallel Ditches (1 Chart)
- Figures A.4-1 to A.4-3: Type 4 Features, Intersecting Slopes (3 Charts)
- Figures A.5-1 to A.5-2: Type 5 Features, Fixed Objects (2 Charts)
- Figure A.6: Type 6 Features, Culvert End (1 Chart)
- Figure A.7-1 to A.7-2: Type 7 Features, Longitudinal Barriers (2 Chart)
- Figure A.8: Type 8 Features, Terminals and Crash Cushions (1 Chart)

Figure A.7-2 is a separate set of SI values for longitudinal barriers covered in Figure A.7-1 when encroached vehicles penetrate, roll over the top of, or roll in front of the barrier. In these figures, when applicable, containment (or performance) limits and repair cost per impact for the feature are indicated.

Users are also allowed to specify the impact speed-SI relationships for their own features by providing the following three parameters: (1) SI at zero impact speed, (2) SI at 100 km/hr (62.2 mph) impact speed, and (3) average repair cost per impact. These parameter values are entered through the RSAP user interface. The user interface reads all the data associated with a user defined roadside feature, calculates the slope of the linear impact speed-SI relationship (i.e., the increase in SI value per unit increase in the impact speed) and then sets the SI value at zero impact speed (i.e., the intercept term of the regression line). The calculated slope and intercept term are then passed on to the RSAP main program.

Depending on features, the "impact speed" in the formula above may refer to vehicle entry speed, vehicle speed at impact, or the lateral component of vehicle speed at impact. For the first four types of features (i.e., fore-slopes, back-slopes, parallel ditches, and intersecting slopes) it means vehicle entry speed, *V*. For fixed objects, culvert ends, and terminals and crash cushions, it is indeed the speed at impact *V*. For longitudinal barriers, it is the lateral component of the speed at impact (i.e., $V\sin(\theta$) where θ is impact angle. Thus, the speed-SI relationships of longitudinal barriers account for the important effects of impact angle on impact severity.

RSAP currently includes two sets of procedures to deal with vehicle penetration of features and rollover after hitting features. For example, RSAP first identifies whether an impacting vehicle would be likely to penetrate the first-struck hazard. For breakaway objects, such as trees, wooden utility poles, and breakaway supports (i.e., Type 5 Fixed Objects Features in RSAP), the penetration is predicted if the impacting vehicle is above a threshold value of kinetic energy calculated as:

$$KE = \frac{1}{2} m V^2$$

where

KE = Kinetic energy of impacting vehicle (joules=kg*(m/s)^2)
m = Mass of impacting vehicles (kg)
V = Impact speed (m/s)

Similarly, longitudinal barriers (RSAP Type 7 Features) are predicted to be penetrated when the impact severity (IS) of an impact is higher than the containment limit for the barrier test level. The IS value is calculated as:

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

where

IS = Impact severity
m = Mass of impacting vehicles (kg)
V = Impact speed (m/s)
θ = Impact angle (deg)

If feature penetration is predicted, RSAP calculates the energy gained or lost in impacts with roadside features that are penetrated. For roadside features other than side-slopes, the energy associated with the capacity or containment limit of the feature is subtracted from the vehicle's initial kinetic energy (or its lateral component in the case of a guardrail). A new speed for the vehicle is then calculated on the basis of the remaining energy and this new speed is used for the next impact. A roadside slope, provided it is not very steep, would not be expected to affect the vehicle's kinetic energy appreciably; however, the resultant rise or drop in the vehicle's center of gravity during slope traversal would affect the vehicle's potential energy. Thus, the potential energy associated with traversing a roadside slope is added (or subtracted) from the initial kinetic energy of the vehicle to determine a new speed for the next impact. Further, RSAP estimates the crash severity of the first feature struck as well as any subsequent features in the vehicle's path. The highest severity of any feature in the vehicle's path is then utilized in the calculation of crash cost.

Some types of roadside features, such as longitudinal barriers, could cause impacting vehicles to roll over, which has a higher severity than a re-directive impact. Since the actual mechanisms involved in rollovers are not well understood, RSAP incorporates two crude rollover algorithms to identify impact conditions under which a vehicle is likely to roll over in front of (i.e., on the traffic side of) a barrier and roll over the top of a barrier. The rollover routines incorporate simplified impulse and momentum calculations and are primarily intended to be accurate for analyzing heavy truck impacts. The key truck and impact parameters used in the "roll in front of the barrier" algorithm are the truck's center of gravity height and width, barrier mounting height and impact angle. For the "roll over the top of the barrier" algorithm, additional parameters are used including distance from vehicle center of gravity location to the extreme bottom corner of truck frame, height of truck axle center, and the radius of gyration of truck and load about the bottom corner of truck frame. As shown in Figure A.7-2, higher severities are assigned to rollover impacts than non-rollover impacts (Figure A.7-1).

Rollover of heavy trucks when hitting longitudinal barriers is the only rollover event currently considered by RSAP. These rollovers involving longitudinal barriers are part of the rollovers initiated by hitting fixed- and non-fixed objects, which represent a relatively small fraction (less than 14 percent) of total rollover cases on high speed roadways (i.e., roadways with posted speed limits $\geq$ 45 mph). Other types of rollovers not considered by RSAP include those initiated by "soft soil" (68 percent) and slope of ditches and embankments (13 percent). [Miaou04] It is vaguely suggested in RSAP Engineer's Manual that this deficiency of RSAP could be mitigated by users through some adjustments of the impact speed-SI relationships to reflect the probability of injury due to rollovers.

Since rollover crashes tend to be much more severe than other types of crashes, especially for those crashes involving unbelted occupants, they should be given a high priority in updating the impact-severity relationships for RSAP.

Severity Index Calibration

As part of the study to develop guardrail implementation guidelines, Sicking recently calibrated the RSAP impact-severity relationships for guardrails using real world crash data from Kansas and the NASS GES – a state and a national database. [Sicking09] The procedure developed by Sicking, as described in NCHRP Report 638, is a practical and important first step forward. It allows the controversial impact-SI relationships in the RSAP program to be checked against the crash experience that actually occurred on the roadsides and then revised if necessary. The procedure can potentially be used for calibrating other roadside features in RSAP.

A schematic flow chart of the NCHRP 22-12(2) severity calibration procedure is presented in Figure 5. As depicted, for a particular type or sub-type of feature, such as guardrails, utility poles, trees, ditches, and culverts, the procedure consists of two parallel sub-procedures. The sub-procedure on the right starts with acquiring real-world or in-depth crash data associated with the type of features in consideration. Then, the severity distribution for the type of features is generated and adjusted for underreporting. It is typically assumed in the adjustment that all unreported crashes are property damage crashes. The final step in the process is to calculate the expected crash costs by assigning dollar values to each of the severity levels using standardized cost values recommended by FHWA.

The sub-procedure on the left starts the default impact-severity relationships in the RSAP program. The severity distribution and crash cost from the RSAP are compared with those from the sub-procedure on the right. The crash severity adjustment factor in the RSAP program is then adjusted up or down to increase or decrease the overall severity and crash cost. Recall that in the last section, the crash severity adjustment factor is a positive valued user parameter with a default value of 1.0. The adjustment is continued until the output from the left and right sub-procedures are reasonably close. The final crash severity adjustment factor is then used in the RSAP for future evaluation involving that type of features. Before using the RSAP program as a calibration tool in the procedure, an input scenario that represents the typical real-world setup, including placement, of the type of features has to be determined.

Sicking decided to adjust guardrail crash costs based on the assumption that 26 percent of guardrail impacts go unreported. [Sicking09] This crash cost adjustment was accomplished by assuming that all unreported crashes involved property damage only. RSAP guardrail crash severities were then adjusted to match the revised Kansas guardrail crash cost, which was generally in agreement with the cost from NASS GES data. The final adjustment was accomplished by reducing the crash severity adjustment factor from 1.0 to 0.7.

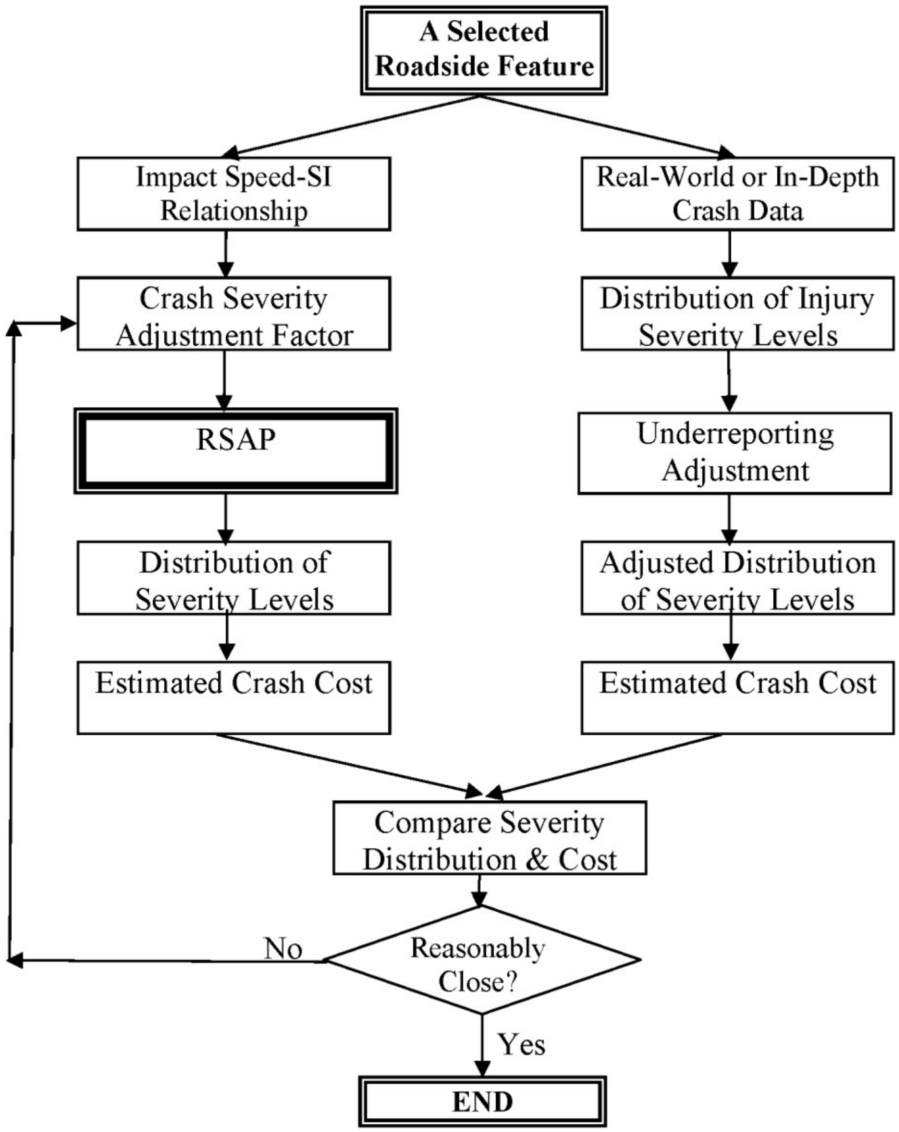


Figure 11. NCHRP 22-12(2) severity index calibration procedure.

Limitations

Although RSAP is a significant technical improvement over its predecessor, ROADSIDE, it still has serious technical drawbacks and limitations, some of which are the result of lack of data or lack of resources to obtain the necessary data. Some examples of its technical limitations include:

- By ignoring driver control input (e.g., braking and steering), RSAP assumes a straight line path and a constant speed for an encroaching vehicle. With this assumption, the impact speed is the same as the encroachment speed and the impact angle is the same as the encroachment angle.

- RSAP considers rollovers initiated by hitting fixed-objects, which represent a relatively small fraction of total rollover cases on high speed roadways (i.e., less than 14 percent). Other types of rollovers ignored by RSAP include those initiated by soft soil conditions on the roadside (68 percent), the slope of the embankment (13 percent) and non-fixed objects.[Miaou04]
- RSAP does not consider cross median crashes explicitly. The User's Manual does describe a way to "trick" the program into emulating these types of crashes, which have enormous cost implications because of their severity. The RSAP Engineer's Manual, however, does not recommend the use of this procedure in median barrier warrant studies.
- RSAP does not separate out intersections or access points along a road segment for special considerations. As it stands, the software does not make any provisions for intersections or on/off ramps to be considered as separate roadway elements. In fact, it does not even allow the access density along a highway section/segment to be specified.

Bugs, Errors and Discrepancies

There are a variety of bugs, errors and discrepancies that have been discovered in RSAP over the past decade. Discrepancies are differences between the algorithms described in the RSAP Engineer's Manual and those actually coded in the program. For the reader's convenience, the part of the code that determines encroachment frequency for a given AADT, which is mainly contained in a subroutine called INITIAL4, is listed in Table 14 at the end of this section. Errors are simply when a mistake was made in either formulating an algorithm or coding the program. Bugs are a result of faulty programming logic. All three types of problems have been discovered in RSAP and the following sections describe some of the bugs, errors and discrepancies that are known at this time.

Discrepancies

<u>*Base Encroachment Rates*</u>

The RSAP Engineer's Manual states that "it was estimated that encroachments were under-reported by a ratio of 2.466 for two-lane undivided highways and 1.878 for multilane divided highways. Thus, the encroachment frequency was adjusted upward by these ratios to account for under-reporting of encroachments because of paved shoulders.[Mak03]" The following statement is used in the code for this adjustment:

```
ENCFRQ = ENCFRQ*0.621371*LATMOD/100
```

The base encroachment rate ENCFRQ is first multiplied by a constant 0.621371 to convert the rate from a "per mile per year" basis to a "per km per year" basis (i.e., USCU to SI conversion). It is further multiplied by the ratio "LATMOD/100" to adjust for the under-reporting. From the data table (input from SUBROUTINE "INPUT4"), it is apparent that the values for LATMOD are 150.34 and 159.1224, respectively, for two-lane undivided and multilane divided highways. This means that the actual ratios used in the code are 1.5034 and 1.591224, respectively, for the two types of highways and not 2.466 and 1.878 as stated in the Engineer's Manual. The discrepancies are quite large and have a significant impact on the encroachment rates. The base encroachment rate curves would have been much higher than what has been shown in Figure 12 if 2.466 and 1.878 were used—about 64 percent higher for two-lane undivided highways and 18 percent higher for multilane divided highways as shown below in

Figure 13.

Lane Encroachment Rates for Multi-Lane Highways

RSAP assigns the same lane encroachment rate to each lane as the four-lane highway regardless of the number of lanes involved. The following three statements in Section 4.2.1.4 of Engineer's Manual regarding lane encroachments deserve some attention:

- "The encroachment rate is assumed to be the same for all lanes [Mak03]."
- "Assignment of traffic to each lane is done by simple proportion. It is assumed that the rightmost travel lane in each direction carries twice as many vehicles as any other lane until it reaches capacity. Then, any traffic above this capacity is apportioned to the other lanes until all lanes reach capacity [Mak03]."
- "The probability for an encroachment to originate from a particular lane is the assigned traffic volume to that lane divided by the total traffic volume for all lanes [Mak03]."

Since the traffic volume for the rightmost lane is assumed to be twice as many vehicles as any other lane (before reaching the capacity), the probability that a lane encroachment originates from the rightmost lane is twice that of any other lane based on the second and third statements. This, however, contradicts the first statement because if the lane encroachment rate is assumed to be the same for all lanes, as indicated in the first statement, then the probability for a lane encroachment to originate in each lane should be the same. This also presumes that the traffic volume is equally divided among the lanes when, in fact, it is well known that the right most lane generally carries higher traffic volume at least at free-flow conditions.

Examination of the code reveals that, in fact, all three statements were indeed implemented in RSAP. The first statement about the same lane encroachment rate for each lane was implemented in Subroutine INITIAL4 and the total number of lane encroachments, represented by a variable EXCNUM, is later used in Subroutine CONVER to compute annual crash cost. The second statement is implemented in Subroutine INITIAL1B, while the third statement was in Subroutine INITIAL1. At this time, the research team has not been able to decide how these contradictory assumptions are reconciled in the code and how the evaluation results might be affected.

There are other problems with the way RSAP calculates lane encroaches on multi-lane highways. In the Engineer's Manual, the base roadside encroachment rate curve for divided highways is shown below as a function of AADT in Figure 12 (i.e., Figure 13 in the Engineer's Manual). This figure is misleading in that it implies the same curve for divided highways with more than four lanes when, in fact, this roadside encroachment rate curve is only for four-lane divided highways.

To appreciate the analytical implications of the constant lane encroachment rate assumption for multilane divided highways, the roadside encroachment rates for six-lane and eight-lane highways with 12-ft wide lanes were calculated following the procedure used in the RSAP code. The rates calculated are shown in Figure 13.

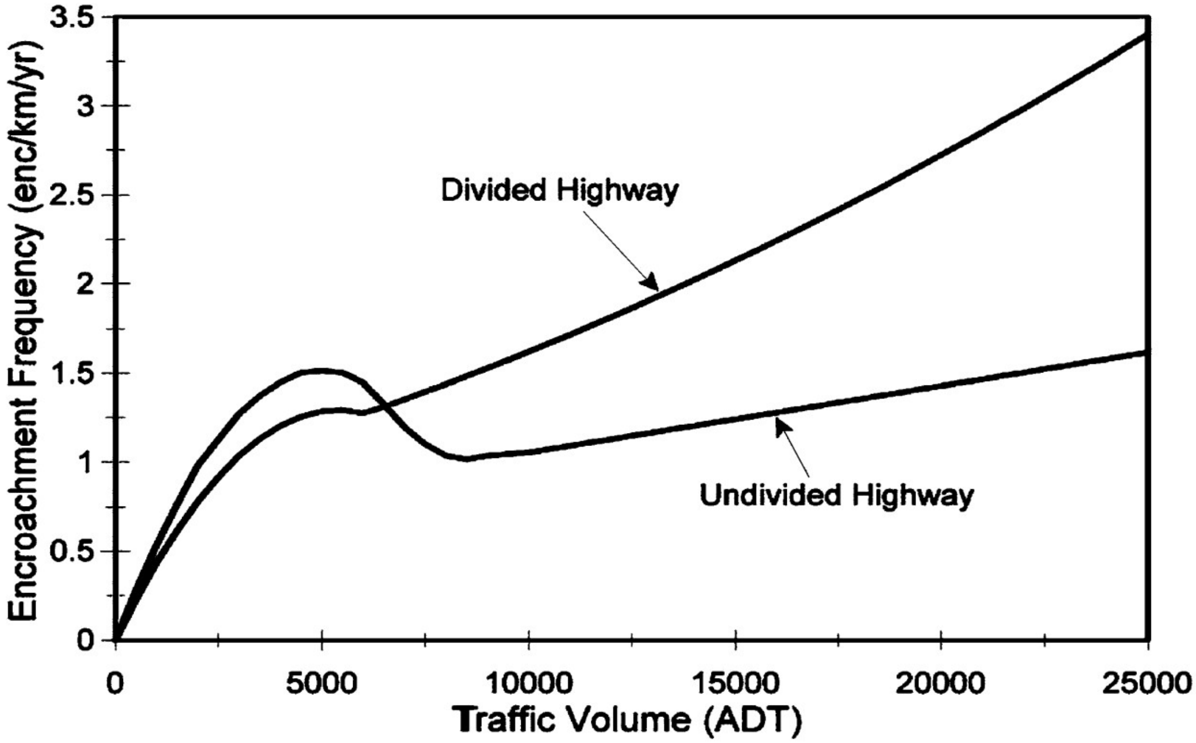


Figure 12. Base Roadside Encroachment Rate Curve for Divided Highways. [Mak03]

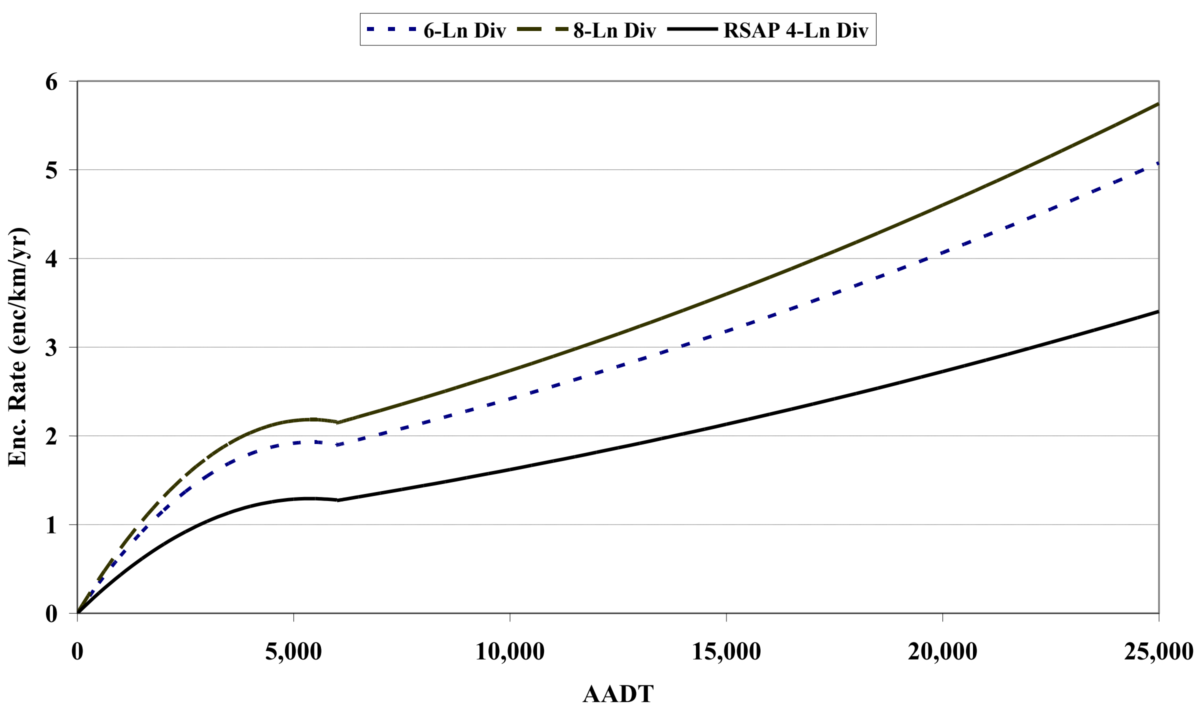


Figure 13. Roadside Encroachment Rates for 6 and 8-Lane Divided Highways:12-ft Wide Lanes. [Mak03]

Lateral Extent of Encroachment

As described earlier, the RSAP Engineer's Manual gives the probability distributions for the extent of lateral encroachment for the two types of highways as:

- Two-lane undivided highways - $P(D > x)=100e^{-0.262x}$
- Multilane divided highways - $P(D > x)=100e^{-0.161x}$

where P(D>x) is the probability that an encroachment has a lateral extent, D, exceeding x meters. The underlying assumption is that the exceedence probability decays exponentially as the lateral extent (i.e., distance from the edge of the lane) increases. The RSAP code, however, uses third order polynomial functions rather than the exponential equations as shown below:

- Two-lane undivided highways:
  $P(D > x) = 100-17.3684958x + 1.06635164x^2 – 0.022778549x^3$
- Multilane divided highways:
  $P(D > x) = 100-12.9879734x + 0.76952812x^2 – 0.0179107x^3$

These polynomial functions can produce negative probabilities for some values of lateral extent (i.e., generally above 20 m), x so the code forces the probability to zero when the calculation from the function turns out to be negative. These functions are plotted below in Figure 14 for comparison. The solid lines are the exponential functions described in Engineer's Manual and the dotted lines are the cubic polynomial curves used by the code. The differences between the two sets of distributions are obvious. The code is giving higher proportions of lateral extent of encroachment for lateral distances less than about 20 meters and does not allow lateral distance to exceed about 22 meters.

A member of the research team was able to obtain and examine some memoranda between Dr. Lindsay Griffin and Mr. King Mak regarding a study entitled "Re-Analysis of Cooper Encroachment Data." Computer outputs, discussion of analyses, and various graphs on lateral extent of encroachment distributions are contained in these memoranda dated between September 1996 and March 1997. The data and graphs presented in Engineer's Manual appear to have been taken from this particular study. For some reason, however, the results of the study were not made available to Dr. Zimmerman when he revised the RSAP code and thus the discrepancy described found here. The cubic polynomial equations used in the code were probably developed by Dr. Zimmerman for his thesis research in 1995-96 period.

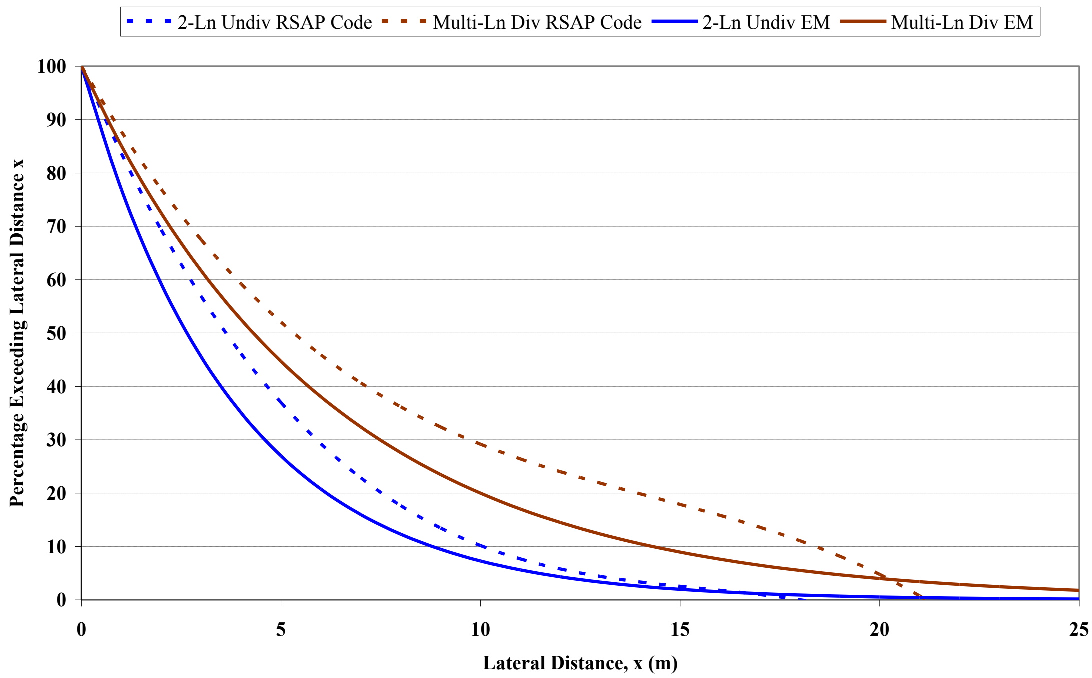


Figure 14. Exceedance Probability: Code vs. Engineer's Manual.

Traffic Growth Adjustment Factor

The traffic growth adjustment factor, as described earlier, is given by the following equation:

$$\text{Traffic growth adjustment factor} = \sum_{n=1}^{N} (1+i)^n / N$$

where:

i = The annual percent traffic growth and
N = The project life in years.

This is, however, not what is actually coded in the program. Checking the code shows that a much more complicated scheme is employed to calculate this factor. In the code, AADT is grown each year by an annual percent traffic growth factor, TGR, and the encroachment rate, ENCFRQ, is then calculated for each year based on the calculated AADT. This is done for every year during the project life. The encroachment rates are first summed over the project life to get PWSUM. This sum is then calculated as follows to arrive at the adjusted encroachment rate:

```
ENCFRQ = PWSUM*((TGR/100)/(1-(1+TGR/100)**(-PLA)))
```

The basis of the formula above is not really clear, however, the year-by-year calculation may actually be more accurate. The actual difference between the two versions of the calculation is not clear under different traffic growth percentages, project lives, and encroachment rate curves. However, if the formula and the code are correct, the difference can be expected to be significant only if the growth rate is high and the encroachment rate curve is nonlinear within the range of the AADTs in the project life. To be on the safe side, the validity of the code formulation should be checked and, if the formula is correct, the Engineer's Manual should be revised to describe the calculations the way they are actually performed in the code.

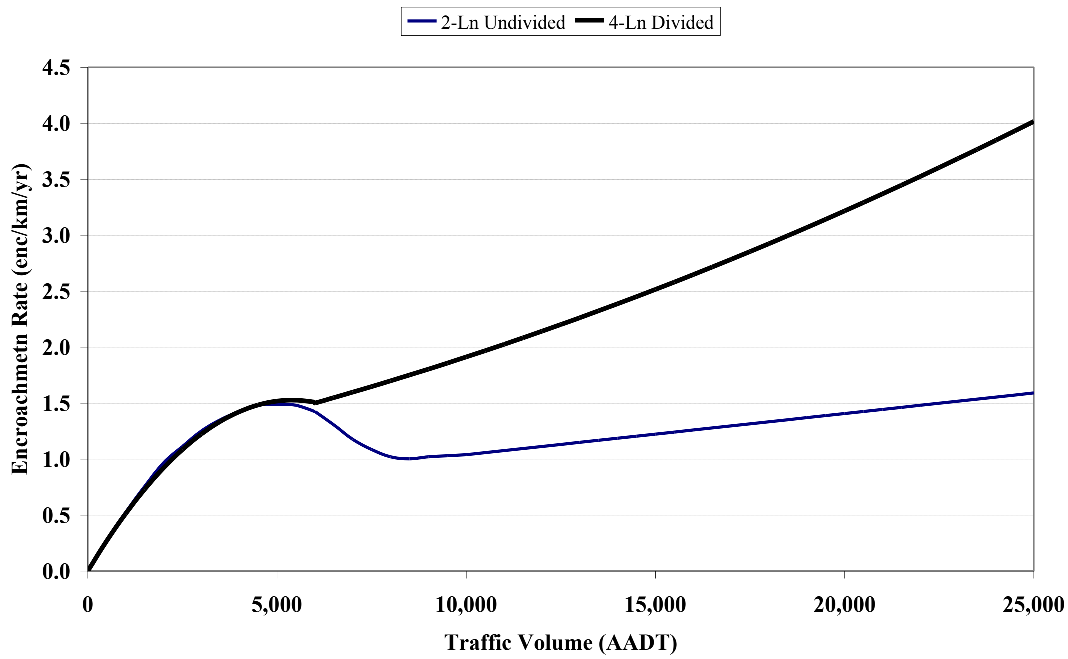


Figure 15. Base Encroachment Rates Using Under-Reporting Ratios in EM.

<u>*User-Defined Adjustment Factor*</u>

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.

Program Bugs

According to Wikipedia, "a software bug is an error, flaw, mistake, failure, or fault in a computer program that prevents it from behaving as intended (e.g., producing an incorrect or unexpected result). Most bugs arise from mistakes and errors made by people in either a program's source code or its design, and a few are caused by compilers producing incorrect code. A program that contains a large number of bugs, and/or bugs that seriously interfere with its functionality, is said to be buggy. Reports detailing bugs in a program are commonly known as bug reports …" [Wiki09] This section is a partial bug report focusing only on the results of a visual inspection of the RSAP source code; nothing is said about the design and compilers.

Program bugs in RSAP have been noted by other researchers. For example, McGinnis, in an NCHRP report prepared for a study on guardrail run-out lengths said "bugs are known to exist in the current version of RSAP, and the program's developer is hoping to be able to correct them in the next update. " [McGinnis, 2004] For his study, McGinnis noted further that "unfortunately the encroachment rates shown in the RSAP output are known to be incorrect so it is not possible to determine if the problem lies in the encroachment rate module or in the crash cost module. … These crash cost errors make it impossible to use the current version of RSAP to compute optimum runout length. " [McGinnis04]

Sometimes, program bugs were noted in previous studies through comparisons of program outputs and those reported by the Engineer's Manual. Without checking the code, it could be difficult to distinguish a bug from a discrepancy between the Engineer's Manual and the code as reported in the last section. This section discusses program bugs discovered from a visual inspection of the code. Even though this review was intended to focus on just the Encroachment Module, it was often found necessary to examine other modules to understand the code segments of interest because of the interrelationships among modules. In any case, there are probably other program bugs in RSAP that have yet to be discovered.

Base Encroachment Rates

The base encroachment rate for a given AADT is represented in the code as ENCFRQ. To deal with the inability to distinguish between intentional (or controlled) encroachments from unintentional (or uncontrolled) encroachments, RSAP makes an assumption that 60 percent of the encroachments are unintentional encroachments. Thus, the encroachment rate is multiplied by an adjustment factor of 0.6 which is reflected in the statement ENCFRQ = ENCFRQ*0.6" in the code. As the code shows, this adjustment is not performed when DIV(I) equals 1 or 4 (i.e., for two-lane undivided and one-way highways). There is some confusions in the code as to how the array DIV(I) (i.e., highway type) is actually defined, which will be discussed shortly.

```
IF (DIV(I).EQ.1.OR.DIV(I).EQ.4) THEN
  IF (ADT1.GE.10500) THEN
    ENCFRQ = (ADT1-10500)*0.00004+1.15
  ELSE
    ADT2 = ADT1/500
    ENCFRQ = ADTINT(ADT2)
  ENDIF
ELSE
  ENCFRQ = 0.000806*ADT1-0.0000000745*ADT1**2
  IF (ADT1.GT.6000) ENCFRQ = 1.43+0.000102*ADT1+0.00000000281*ADT1**2
ENCFRQ = ENCFRQ*0.6
ENDIF
ENCFRQ = ENCFRQ*0.621371*LATMOD/100
PWSUM = PWSUM+ENCFRQ
```

Why the 60 percent reduction should not be applied to one-way and two-lane undivided highways is not clear.

Traffic Growth Adjustment Factor

Annual percent traffic growth is represented by the variable TGR in the code. This variable is read as input in Subroutine INPUT0 as a percentage. For example, if the traffic growth is five percent, the value input is 5. In the code this variable is immediately divided by 100 to yield the decimal fractions as follows:

```
READ(9,*) TGR
READ(9,*) UDEF
TGR = TGR/100.
```

This variable is then used in Subroutine INITIAL4 to grow the AADT for the planning period as follows:

```
ADT1 =ADT1*(1+TGR)
```

which is correct. It is then used to adjust encroachment rates as follows:

```
ENCFRQ = PWSUM*((TGR/100)/(1-(1+TGR/100)**(-PLA)))
```

Here, TGR is divided by 100 again. At this point, because TGR/100 is becoming so small that this adjustment is practically the same as dividing PWSUM by the project life, PLA. That is, no adjustment, and thus no growth, is taken place in RSAP regardless of the input. The same bug is found in another part of the program in Subroutine INITIAL1B.

Highway Types

For the I-th highway segment, its highway type is represented by the variable DIV(I) in the code. The DIV(I) variable is referenced inconsistently and very confusingly throughout the code including subroutines INITIAL0, INITIAL1 and INITIAL4. According to the following code from Subroutine OUTPUT, the variable DIV(I) is assigned a value of 1 for divided highways, 2 for undivided highways and 3 for one-way highways:

```
   WRITE(40,40) DIV(I),I
40 FORMAT(F4.1,20X,'ROADWAY DIVIDED (1), UNDIVIDED (2), OR ONE WAY (3
  *), ALTERNATIVE  ',I2)
```

This assignment of values is obviously incorrect if we check the formula and algorithms applied to different highway types in the code. For example, if the code listed earlier when the base roadside encroachment rate was discussed is examined, the encroachment rate formula for divided and undivided highways is reversed. Moreover, for DIV(I)=3, which is supposed to be one-way highways, the code is assigning multilane encroachment rate for it and DIV(I)=4 is not even defined. Since this array was found to be referenced differently in different subroutines, the possibility that highway types might have been mixed up in the code is a very real possibility. According to communications with Zimmerman who wrote the original code, the original idea was to use the following convention for the highway type:

- DIV(I) = 1: Undivided
- DIV(I) = 2: Divided
- DIV(I) = 3: Half of a divided highway on an independent alignment (One Travel Direction)
- DIV(I) = 4: One-way roadway

For some reason, when the RSAP code was revised throughout the years, this convention was not consistently followed leading to the confusion in the code today.

Even if the convention described by Zimmerman had been used consistently in the code, there is still an issue about the handling of "half of a divided highway" (i.e., when DIV(I)=3). Should the AADT be specified as the bi-directional or uni-directional AADT? Most likely, the code is expecting the user to specify a bi-directional AADT since that is how the input is handled in every other case. If this is the case, then should not the base encroachment rate calculated in the code be halved since only one travel direction is considered? In any event, there is a need to make sure the code uses a consistent convention for the highway type. In addition, the computational formula for encroachment rates and the user input on AADT for one-way highways and one-directional divided highways needs to be thought through and more carefully implemented.

Curvature Adjustment of Swath Equations

In the code, the degree of curvature, CURDEG, is computed from CURRAD in Subroutine INPUT1 as follows:

```
IF (CURRAD(I,J).EQ.0) THEN
  CURDEG(I,J) = 0.0
ELSE
  CURDEG(I,J) = 1746.3805/CURRAD(I,J)
ENDIF
```

When the curve radius is input, the program immediately calculates the degree of curvature, CURDEG, in unit of degrees/100-ft station. CURDEG is then used in four subroutines (i.e., CASEA, CASEB, CASEC and CASED) to calculate the vehicle impact point. In these subroutines, it is used as if the variable is in unit of degrees per 100 meter stations. For example, the following code segment shows the calculation of a variable TA using CURDEG and X2 and X0. At this point in the code, CURDEG is in deg/100-ft station while X2 and X0 are in meters.

```
    Y0 = 0
    Y2 = YE
    X2 = TRAJ(Y2,Y0,M,X0)
C   CURVATURE ADJUSTMENT TO POINT 2
    IF (CURLORR(NUMIMP,SEGREF).GT.0.0) THEN
      Z = 1
      IF (X2.LE.LENGTH(NUMIMP,SEGREF)) THEN
        TA = (CURDEG(NUMIMP,SEGREF)/2)*(X2-X0)/100.*PI/180
        YA = X2*TAN(TA)
```

The correct calculation for the variable TA (in unit of radian) should have been

TA = (CURDEG(NUMIMP,SEGREF)/2)*(X2-X0)/30.48*PI/180.

That is, (X2-X0) should have been divided by 30.48, not by 100. Note that (X2-X0)/30.48 gives the number of 100-ft arcs which is what the code is intended to produce. This bug is repeated many times and spread out over the four subroutines mentioned above. Correcting this bug should make a big difference in determining the impact point on a curved segment. The correct calculation would have generated an angle, TA, that is 3.3 times higher than what the RSAP is currently calculating.

There are potentially other USCU to SI unit conversion problems in the code. Zimmerman has indicated that the original RSAP was coded in USCU units and later it was changed to SI units. Dr. Zimmerman recalled that, in the recoding, it happened that sometimes the input (in SI units) had to go through an SI to USCU conversion and then go back and forth several times. In retrospect, that recoding decision saved a lot of work in the short term but might be a potential source for some difficult to find errors in the longer term as the previous examples illustrates. Since RSAP is a large program, one cannot rule out the possibility that other necessary conversions might be missed. Dr. Zimmerman has suggested that these conversions back and forth should be avoided and are something to fix in the update.

Lane Encroachment Rates

Since not all lane encroachments become roadside encroachments, an analytical procedure was devised in RSAP to assign the appropriate lane encroachment rates to each lane so that the sum of roadside encroachments originating from all lanes would equal the base encroachments rate estimated from the Cooper data for each and every possible AADT. The procedure is not discussed in the Engineer's Manual. For a given AADT, the following lines of codes in RSAP calculate the lane encroachment rate by highway type:

```
IF (DIV(I).EQ.1.OR.DIV(I).EQ.4) THEN
  EXCONE = ENCFRQ/2.9226
ELSE
  EXCONE = ENCFRQ/3.1816
ENDIF
```

Here, ENCFRQ is the base roadside encroachment rate for the given AADT and EXCONE is the corresponding lane encroachment rate. That is, the lane encroachment rate is obtained as the base encroachment rate divided by 2.9226 for undivided and one-way roads and obtained as the base encroachment rate divided by 3.1816 for multilane highways (both one-way and two-way). According to Dr. Zimmerman, the two constants 2.9226 and 3.1816 were calculated using the lateral extent of encroachment distributions described earlier. Key assumptions in the calculation include:

(1) Four-meter wide travel lanes,
(2) Each lane is equally likely to produce the lane encroachment and
(3) Left- and right-hand lane encroachments are equally likely to occur.

Based on these assumptions, the following interpretation of how these two constants were meant to be derived can be deduced. As will be shown, the constant derived for the two-lane undivided highway is incorrect while the constant for the four-lane divided highway is correct. For two-lane undivided highways there are four different ways for a lane encroachment to occur:

- Primary travel direction to the right,
- Primary travel direction to the left,
- Opposing travel direction to the right and
- Opposing travel direction to the left.

For a given lane encroachment, assume that these four possible ways of encroaching are equally likely to occur (i.e., each has a probability of 0.25). The right-hand encroachments exit the roadway immediately and would become roadside encroachments with a probability of 1.0. For the left-hand encroachments, some of them would recover before they run off the roadway. Assuming a lane width of 4.0 m and plugging in this distance into the lateral extent of encroachment distribution equation for two-lane undivided highways presented earlier, a probability of 0.4612982 for a lane encroachment to reach the roadside when exiting the lane to the left. Thus, for a randomly generated lane encroachment, the chance for it to become a roadside encroachment is:

$$(0.25 \times 1) + (0.25 \times 0.4612982) + (0.25 \times 1) + (0.25 \times 0.4612982) = 0.7306491.$$

That is, for a randomly generated lane encroachment, it has about 73 percent chance of becoming a roadside encroachment. Thus, the total number of lane encroachments that need to be simulated to produce ENCFRQ roadside encroachments will be ENCFRQ/0.7306491. Assuming the same lane encroachment rate for each lane, we need to generate ENCFRQ/(0.7306491*2) lane encroachments "per lane" to produce ENCFRQ roadside encroachments. This amounts to generate ENCFRQ/1.4613 lane encroachments per lane. This number is twice what RSAP is currently generating. To sum up, the constant used in RSAP to calculate lane encroachment rate for two-lane undivided highways is incorrect and, as a result, RSAP is currently generating just half of the lane encroachments that it should simulate for two-lane undivided highways.

The same procedure applies to a four-lane divided highway. Recall that the base roadside encroachment rate curve for divided highways in RSAP includes those encroachments onto the median area even though the Cooper data did not measure median encroachments. This significantly increases the number of possible lane encroachment results. To simplify, it is assumed that the medians are wide enough so that the probability of a vehicle crossing the median is ignorable. This assumption eliminates those encroachments that cross the median and stopped at the opposing lanes and those that cross both the median and two opposing traffic lanes and then leave the roadway to the far left. With this assumption, there are eight possible lane encroachment types: 2 travel direction $\times$ 2 lanes per travel direction $\times$ 2 sides (i.e., left and right) per lane.

Again, using the assumption that an encroachment is equally likely from any lane, each lane encroachment type has a probability of 1/8 of occurring. Using the same four-m wide travel lane assumption and the lateral extent of encroachment distribution for four-lane divided highways in RSAP code, we have the following probabilities for a lane encroachment under each type to become a roadside encroachment (1 for outer lane and 2 for inner lane)

- Primary Direction, Outer Lane, Right: 1.0
- Primary Direction, Outer Lane, Left: 0.5921427
- Primary Direction, Inner Lane, Right: 0.5921427
- Primary Direction, Inner Lane, Left: 1.0

- Opposing Direction, Outer Lane, Right: 1.0
- Opposing Direction, Outer Lane, Left: 0.5921427
- Opposing Direction, Inner Lane, Right: 0.5921427
- Opposing Direction, Inner Lane, Left: 1.0

Again, for a given lane encroachment, assume that these eight possible ways of encroaching are equally likely to occur. Following the same procedure as in the two-lane case, multiply each roadside encroachment probability above by 1/8 and then sum up all eight lane encroachment types to yield 0.7954. The probability of a randomly generated lane encroachment becoming a roadside encroachment is, therefore, 79.54 percent. Thus, the number of lane encroachments needed to generate ENCFRQ roadside encroachments is ENCFRQ/0.7954. Again, assuming equal number of lane encroachments for each lane then ENCFRQ/(0.7954*4) lane encroachments per lane must be generated. This amounts to ENCFRQ/3.1816 lane encroachment per lane which is what is coded in RSAP.

Maximum Number of Lanes Allowed for a Highway Segment

The RSAP Engineer's Manual and User's Manual both claim that the program can handle evaluations of projects with a maximum of 20 different safety improvement alternatives, 20 consecutive roadway segments for roadways of up to 16 lanes and 1,000 roadside features. Examination of the dimension declared for some of the variables in the code, however, shows that only up to eight lanes can be accommodated; and, if any of the road segments has more than eight lanes, the code should crash. This dimensional problem can best be explained using Subroutines INITIAL1 and INITIAL1B. In these two subroutines, the following variables are declared: ENCO(22,16), ENCP(22,16), LADJO(8), LADJP(8), OPP(22,16), PRIM(22,16). Using the following code fragment as an example (e.g., taken from subroutine INITIAL1):

```
      DO 111 L=1,JMAX/2
        B = 2*L-1
        C = 2*L
        PRIM(I,B) = LADJP(L)*PRIM(I,B)
        PRIM(I,C) = LADJP(L)*PRIM(I,C)
        OPP(I,B) = LADJO(L)*OPP(I,B)
        OPP(I,C) = LADJO(L)*OPP(I,C)
 111    CONTINUE
```

In the code above, JAMX is the number of "lane encroachment directions," which is twice the number of lanes for each road segment (i.e., left- and right-encroachments for each lane). If the number of lanes is 16, then JMAX=32 (=16x2). This will require variables LADJO and LADJP both to have a dimension of 16 (instead of the 8 specified in the code). Two other dimensional arrays, PRIM and OPP, need to have a dimension of (22,32) instead of (22,16). The same problem happens in other parts of the code for arrays ENCO and ENCP.

Lane Encroachment Rates for Highways with Odd Number of Lanes

RSAP assigns the same lane encroachment rate to each lane as the four-lane highway for all divided highways. That is, the lane encroachment rate is assumed to be the same for all lanes and the lane encroachment rate is based on the value for a four-lane divided highway regardless of the number of lanes actually involved. It may be rare that users would run RSAP with a scenario where highways have odd numbers of lanes, such as 5 or 7 lanes but when they do and if the highway is not "one-way," the number of lane encroachments will be assigned to each of the specified lanes plus one additional lane. That is, a five-lane highway will be treated as if it were a six-lane highway when assigning lane encroachments.

LANNUM(I) is the number of lanes for segment I and it is, of course, an integer. Variables D and E are declared to be real numbers earlier in the code and EXCNUM(I) is the total number of lane encroachments assigned to segment I. The value of D in the statement D = LANNUM(I)/2," when LANNUM(I) is an odd integer will be rounded up since LANNUM(I) must be an integer. For example, when LANNUM(I) is 5, then D=3.0, indicating three lanes in each direction. Thus, a phantom lane is created. Subsequent lines of code, as shown below, will then give the same lane encroachment rate to each of the lanes including the phantom lane.

```
C     DETERMINE NUMBER OF LANE EXCURSIONS
      SUMEF = 0.0
          IF (ONEWAY.EQ.1) THEN
            D = LANNUM(I)
          ELSE
             D = LANNUM(I)/2
          ENDIF
      E = 17-D
      EF1 = 0.0
      EF2 = 0.0
      DO 5 J=2,NUMSEG-1
        DO 4 K=1,D
          EF1 = EXCONE*CURADJ(J,1)*GRADJ(J,1)*LENGTH(I,J)/1000
          EF2 = EXCONE*CURADJ(J,2)*GRADJ(J,1)*LENGTH(I,J)/1000
          SUMEF = SUMEF+EF1+EF2
    4   CONTINUE
    5 CONTINUE
      EF1 = 0.0
      EF2 = 0.0
      IF (ONEWAY.EQ.1) THEN
                  SUMEF = SUMEF*2
                  GOTO 11
          ENDIF
C         END OF NEW CODE
      DO 7 J=2,NUMSEG-1
        DO 6 K=16,E,-1
          EF1 = EXCONE*CURADJ(J,3)*GRADJ(J,2)*LENGTH(I,J)/1000
          EF2 = EXCONE*CURADJ(J,4)*GRADJ(J,2)*LENGTH(I,J)/1000
          SUMEF = SUMEF+EF1+EF2
    6   CONTINUE
    7 CONTINUE
   11 EXCNUM(I) = SUMEF
```

If highways with an odd number of lanes are not to be allowed in RSAP, then the User's Manual should make this clear and the program should keep the users from specifying such types of highways. If they are to be allowed, then the code has to be revised to properly deal with this type of highways.

The lane encroachment rate problem described here for highways with an odd number of lanes is not the only variable that relates to number of lanes. How highways with an odd numbers of lanes are handled for other related variables in the code should be examined.

Severity Calculation Coding Errors

Several RSAP coding errors were recently brought to the researchers' attention by Dr. Mariano Pernetti, University of Naples, Naples, Italy. These errors were uncovered when running certain evaluation scenarios using RSAP version 2.0.3

An evaluation scenario was set up to compare two alternative features using RSAP. The baseline was the built-in fore-slope feature "54 VERTICAL DROP, H >= 22.0 m (72 ft)," which has a SI value of 10 for all impact speeds. In addition, the feature was placed fairly close to the travel lane to ensure that almost all encroachments resulted in interactions with the feature. Variables associated with roadways, such as section length, traffic volume, encroachment adjustment factor and other inputs were arranged to produce an outcome of about one encroachment per year. From the RSAP output, it was found that the expected cost per crash was higher than the cost of a fatal crash, which is the maximum possible cost per crash. After examining the RSAP code, it was determined that it was a result of a coding error where a "real variable" was assigned to an "integer variable." As a result, the value of the real variable was truncated to an integer value. This truncated integer value, which represents a scaling factor in the Monte Carlo simulation, was then used to scale crash costs and caused crash costs of all severity levels, including the fatal crashes, to be artificially inflated (i.e., rounded up).

As mentioned earlier, in RSAP, users are also allowed to specify the impact speed-SI relationships for their own features by providing the following three parameters: (1) SI at zero impact speed, (2) SI at 100 km/hr (62.2 mph) impact speed, and (3) average repair cost per impact. Using basically the same scenario as described above, an attempt was made to create a user defined vertical drop that mimicked the built-in vertical drop. This was achieved by (1) giving a SI value of 10 at zero impact speed, (2) setting the SI value to be 10 at 100km/hr impact speed, and (3) providing a zero repair cost. From the RSAP output, it was found that both the number of crashes and crash costs are zero for this user defined feature. After some experiments using different SI values for zero and 100 km/hr impact speeds, it was concluded that there is a coding error in the current RSAP user interface. The researchers' understanding was that the user interface read all the data associated with a user defined roadside feature, calculated the slope of the linear impact speed-SI relationship (i.e., the increase in SI value per unit increase in the impact speed) and then set the SI value at zero impact speed (i.e., the intercept term of the regression line). The calculated slope and intercept term were then sent to the RSAP main program for further evaluations. It was found that the slope of the regression line was sent to the main program correctly but the intercept term was always sent as zero regardless of how users define the feature. This means that the RSAP results will be incorrect for any user defined feature with a non-zero SI value at zero impact speed.

The containment limits of longitudinal barriers in RSAP are shown in Figure A.7-1. While the test conditions for the six test levels (from TL-1 to TL-6) as required by the NCHRP Report 350, as well as the maximum test impact severity (IS), are presented in Table 13. By comparing the containment limit and the maximum test IS for each test level, one can see that, except for the TL-4 barriers, the containment limit of a longitudinal barrier is always set at its maximum test IS. There is no explanation in the RSAP Engineer's Manual why the containment limit for a TL-4 barrier, which is set at 352,802.8 joules, is 2.56 times that of its maximum test IS of 137,813.0 joules. Coding error seems to be the most plausible explanation for the inconsistency.

Table 13. Maximum test impact severity under six test levels as specified in NCHRP Report 350.

Test Level	Impact Condition #1	Impact Condition #2	Impact Condition #3	Maximum Test Impact Severity ($IS = 0.5m(V\sin(\theta))^2$ (joules))
TL-1	820kg, 50km/hr, 20°	2,000kg, 50km/hr, 25°		34,453.5
TL-2	820kg, 70km/hr, 20°	2,000kg, 70km/hr, 25°		67,528.6
TL-3	820kg, 100km/hr, 20°	2,000kg, 100km/hr, 25°		137,813.0
TL-4	820kg, 100km/hr, 20°	2,000kg, 100km/hr, 25°	8,000kg, 80km/hr, 15°	137,813.0
TL-5	820kg, 100km/hr, 20°	2,000kg, 100km/hr, 25°	36,000kg tractor van, 80km/hr, 15°	595,442.5
TL-6	820kg, 100km/hr, 20°	2,000kg, 100km/hr, 25°	36,000kg tractor tank, 80km/hr, 15°	595,442.5

Note: Impact condition in the table is listed in the order of vehicle weight, impact speed, and impact angle.

Other Potential Bugs

In reviewing the code, some of the integer variables are not clearly declared and, as a result, the code might not pass some of the FORTRAN compilers. Even though these are relatively minor issues and may very well be perfectly alright with some compilers, for the sake of developing a cleaner and more consistent code, they are briefly discussed as follows.

The code just presented above includes:

```
B = 2*L-1
C = 2*L
```

In FORTRAN 77, the scalars on the left hand side, B and C, if not declared as integers, are automatically treated as real values; while the values on the right hand side are integers because L is an integer. Also, given that B and C are real, using expressions such as PRIM(I,B) and OPP(I,C) could likely cause problems where array indexes should be integer. Furthermore, there are statements like the following:

```
PRIM = 0
OPP = 0
ENCO = 0
ENCP = 0
ENCC = 0
```

LADJP = 1.0
LADJO = 1.0

These variables are one or two-dimensional arrays; some older FORTRAN compilers would not accept this kind of expressions.

Table 14. RSAP Subroutine INITIAL4.

```
      SUBROUTINE
INITIAL4(EXCNUM,ADT,NUMIMP,PL,TGR,UDEF,ONEWAY,AENCFRQ,
     *EXCONE)
      REAL
ADT(20),AENCFRQ(20),CURADJ,CURRAD,CURLORR,D,E,EF1,EF2,ENCFRQ,

*EXCNUM(20),EXCONE,FC,GRADE,GRADJ,IMPNUM,LANNUM,LANWID,LATA,LATB,
     *LATC,LATD,LATE,LATF,LATMOD,LENGTH,MWID,NUMIMP,NUMSEG,PL(20),PLA,
     *PWSUM,SUMEF,TGR,UDEF
      INTEGER ONEWAY
      COMMON /ADJ/ CURADJ(22,4),GRADJ(22,2)
      COMMON /BASIC/
NUMSEG,IMPNUM,NUMHAZ,CRANGE,SRANGE,VRANGE,ORANGE,
     *LRANGE
      COMMON /LATX/ LATA,LATB,LATC,LATD,LATE,LATF,LATMOD
      COMMON /ROADWAY/ DIV(20),FC(20),LANNUM(20),LANWID(20),
     *LENGTH(20,22),MWID(20,22),SPLIM(20)
      COMMON /ROADWAY2/ CURRAD(20,22),CURLEN(20,22),GRADE(20,22),
     *CURLORR(20,22),CURDEG(20,22)
C     CALCULATES ENCROACHMENT FREQUENCY FOR A GIVEN ADT.
      I = NUMIMP
      PLA = 0.0
      PWSUM = 0.0
      DO 50 L=1,IMPNUM
        IF (PL(L).GT.PLA) PLA = PL(L)
   50 CONTINUE
      ADT1 = ADT(I)
C     TRAFFIC GROWTH ADJUSTMENT AND ENCROACHMENT FREQUENCY
      DO 90 J=1,PLA
      ADT1 =ADT1*(1+TGR)
C     MODIFIED 5/22/2001
      IF (DIV(I).EQ.1.OR.DIV(I).EQ.4) THEN
        IF (ADT1.GE.10500) THEN
          ENCFRQ = (ADT1-10500)*0.00004+1.15
        ELSE
          ADT2 = ADT1/500
          ENCFRQ = ADTINT(ADT2)
        ENDIF
      ELSE
        ENCFRQ = 0.000806*ADT1-0.0000000745*ADT1**2
        IF (ADT1.GT.6000) ENCFRQ = 1.43+0.000102*ADT1+0.00000000281*
     *         ADT1**2
        ENCFRQ = ENCFRQ*0.6
      ENDIF
      ENCFRQ = ENCFRQ*0.621371*LATMOD/100
      PWSUM = PWSUM+ENCFRQ
   90 CONTINUE
      IF (TGR.EQ.0.0) THEN
        ENCFRQ = PWSUM/PLA
      ELSE
        ENCFRQ = PWSUM*((TGR/100)/(1-(1+TGR/100)**(-PLA)))
      ENDIF
```

```
            AENCFRQ(I) = ENCFRQ
      IF (DIV(I).EQ.1.OR.DIV(I).EQ.4) THEN
        EXCONE = ENCFRQ/2.9226
      ELSE
        EXCONE = ENCFRQ/3.1816
      ENDIF
      EXCONE = EXCONE*UDEF
C     DETERMINE NUMBER OF LANE EXCURSIONS
      SUMEF = 0.0
C           NEW CODE, ADDED 5/14/2001: ADJUSTS FOR
PROBLEM WITH
C           ENCROACHMENTS ON ONE-WAY ROADWAYS
            IF (ONEWAY.EQ.1) THEN
              D = LANNUM(I)
            ELSE
              D = LANNUM(I)/2
            ENDIF
C           END OF NEW CODE
      E = 17-D
      EF1 = 0.0
      EF2 = 0.0
      DO 5 J=2,NUMSEG-1
        DO 4 K=1,D
          EF1 =
EXCONE*CURADJ(J,1)*GRADJ(J,1)*LENGTH(I,J)/1000
          EF2 =
EXCONE*CURADJ(J,2)*GRADJ(J,1)*LENGTH(I,J)/1000
          SUMEF = SUMEF+EF1+EF2
    4   CONTINUE
    5 CONTINUE
      EF1 = 0.0
      EF2 = 0.0
C   NEW CODE, 5/14/2001; CORRECTS ONE-WAY LANE
ENCROACHMENTS TO
C           EQUIVELANT TWO-WAY LANE ENCROACHMENTS
      IF (ONEWAY.EQ.1) THEN
                    SUMEF = SUMEF*2
                    GOTO 11
            ENDIF
C           END OF NEW CODE
      DO 7 J=2,NUMSEG-1
        DO 6 K=16,E,-1
          EF1 =
EXCONE*CURADJ(J,3)*GRADJ(J,2)*LENGTH(I,J)/1000
          EF2 =
EXCONE*CURADJ(J,4)*GRADJ(J,2)*LENGTH(I,J)/1000
          SUMEF = SUMEF+EF1+EF2
    6   CONTINUE
    7 CONTINUE
   11 EXCNUM(I) = SUMEF
      RETURN
      END
```

HIGHWAY AND ROADSIDE DESIGN SOFTWARE

Highway Design Software Suites

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 a higher level. The concept of Building Information Modeling (BIM) is overtaking the Architectural/Engineering/Construction (AEC) industry. BIM has introduced the site/building construction side of Civil Engineering to the concept of integrated practice, supported by a parametric, object-oriented model of the building, which hosts the specific details of the design. This model of the building allows an integrated team to collaborate around the model, sharing common design plans and eliminating the need to keep multiple drawings of the same component, thereby reducing error. The AEC industry is struggling with the development of BIM standards to replace CAD standards but these data-rich models have been recognized as valuable throughout the life-cycle of a project.

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 the creation of error on documents which reference the same item. [Eastman07; Jaselskis04] 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.

While these tools offer exciting opportunities to those who use them, interoperability between the various software programs 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). [CADALYST08]

AutoCAD Civil3D by Autodesk

Civil3D is a suite of software tools which includes AutoCAD, Autodesk Map3D (Map3D), highway design tools, and survey tools. Civil3D 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 that is in turn composed of other objects like tangent sections and curved sections. 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 all 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 accesses 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 alignment information.

Map3D, 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. Map3D reads Spatial Data Files, many raster formats, and many database formats. [Autodesk08] The Civil3D software suite, capitalizing on its Map3D platform can import and export available data from many state Geographic Information Systems (GIS) and Google Earth.

Highway Design Suites by Bentley

Bently offers GEOPAK built on the Microstation platform and InRoads which is cross-platform compatible with Microstation or 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. Both tools export to the LandXML exchange language.

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. [InRoads08]

Roadside Design Programs

FHWA Interactive Highway Safety Design Model (IHSDM)

The IHSDM offers a suite of five software tools for the safety evaluation of highway geometrics. This software, developed by the Federal Highway Administration (FHWA), is a decision-support tool for checking existing or proposed highway designs. It provides an estimate of the expected safety performance of two-lane rural roads.

> "IHSDM can check designs against relevant design policy values, estimate the crash frequency expected for a specified geometric design, and estimate other safety and operational performance measures (e.g., 85th percentile speed and percent time spent following) that help diagnose factors that contribute to expected safety performance." [IHSDM08]

The five software tools available for two-lane rural roads and the tasks preformed by each tool are:

1. "The *Policy Review Module* checks highway-segment design elements for compliance with relevant geometric design policies (i.e., the AASHTO Green Book).
2. The *Crash Prediction Module* estimates the frequency and severity of crashes that could be expected on a highway based upon its geometric design and traffic characteristics.
3. The *Design Consistency Module* helps diagnose safety concerns at horizontal curves by providing estimates of the magnitude of potential speed inconsistencies.
4. The *Intersection Review Module* has diagnostic review capabilities. The diagnostic review is an expert system that systematically evaluates an existing or proposed intersection geometric design to identify potential safety concerns and suggest possible treatments to address those concerns.
5. The *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." [IHSDM08]

The *Crash Prediction Module* considers roadway variables including: lane width, shoulder width and type, horizontal curve length and radius, presence of spiral transition, super-elevation, grade, driveway density, passing lanes and short four-lane sections, two-way left-turn lanes, and roadside hazard rating. Intersection variables considered include skew angle, traffic control, presence of left- and right-turn lanes, and sight distance.

Crash frequency is estimated through a combination of statistical base models and accident modification factors. The base model uses crash data from four States. The accident modification factors adjust the base model estimates for individual geometric design element dimensions and for traffic control features. "The algorithm can be calibrated by State or local agencies to reflect roadway, topographic, environmental, and crash-reporting conditions. The algorithm also provides an Empirical Bayes procedure for a weighted averaging of the algorithm estimate with project-specific crash history data." [Krammes03]

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. 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 exiting and entering curves, and an algorithm for estimating speeds on vertical grades." [Krammes03]

The model was calibrated using speed data collected from six States. The module identifies two potential consistency issues: (1) large differences between the assumed design speed and estimated 85th percentile speed, and (2) large changes in 85th percentile speeds from an approach tangent to a horizontal curve.

The IHSDM software runs independently of highway design software, however, data can be imported from highway design software to the IHSDM through LandXML. LandXML is the land development data exchange standard language. Originally, "…FHWA entered into cooperative research and development agreements with commercial vendors of roadway design software, including Bentley Systems' … and CAiCE Software Corporation." [IHSDM08] (note: the CAiCE software has been bought by AutoDesk and is now integrated into Civil3D). LandXML was eventually adopted as the means of exchanging data. Autodesk and Bently have signed an agreement to develop the LandXML standard and both vendors provide the export option within their various land development software platforms. LandXML is discussed in more detail below.

FHWA SafetyAnalyst

The SafetyAnalyst provides six software tools for use in the evaluation and programming of safety improvements. SafetyAnalyst is an analytical tool "for guiding the decision-making process to identify safety improvement needs and develop a system wide program of site-specific improvement projects." [SafetyAnalyst08] The SafetyAnalyst is able to identify crash patterns and determine the frequency of a particular type of crash on a system wide scale or at a specific location. The six tools used include:

1. "The *Network Screening Tool* identifies sites with potential for safety improvements.
2. The *Diagnosis Tool* is used to diagnose the nature of safety problems at specific sites.
3. The *Countermeasure Selection Tool* assists users in the selection of countermeasures to reduce accident frequency and severity at specific sites.
4. The *Economic Appraisal Tool* performs an economic appraisal of a specific countermeasure or several alternative countermeasures for a specific site.
5. The *Priority Ranking Tool* provides a priority ranking of sites and proposed improvement projects based on the benefit and cost estimates determined by the economic appraisal tool.
6. The *Countermeasure Evaluation Tool* provides the capability to conduct before/after evaluations of implemented safety improvements." [SafetyAnalyst08]

The SafetyAnalyst is a stand-alone package with these minimum data requirements:

Roadway Segment Characteristics Data

- Segment number,
- 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
- Average Annual Daily Traffic (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 AADT and
- Minor-road 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 AADT.

Crash Data

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

The SafetyAnalyst provides six software tools for evaluating and programming safety improvements. This stand-alone software is used to identify crash patterns and determine the frequency of a particular type of crash on a system wide scale or at a specific location.

Other Programs

SafeNET is a safety management tool developed by the UK Department for Transport. It includes crash prediction models for intersections and roadways.[Washington06] 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.

The PlanSafe program is a stand-alone planning level safety prediction software developed under NCHRP 8-44. [Washington06] 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 15. 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.

The SafetyAdvisor is a stand-alone software tool developed for performing a safety assessment of highway and roadside designs. [Ray93] This program calculates a safety scale based on the characteristics of the highway, supplied by the user and is based on the same probabilistic risk-based model as used by NCHRP Report 148, the 1977 Barrier Guide, the Roadside Program and RSAP. 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 an injury is estimated by adding injury and fatal crashes (A+K) for each impact scenario i

Table 15. PLANSAFE Regression Models.

MODEL FORMS
Total Accident Frequency Model
$Log(Accident\_Frequency+1)$ $= 5.020 + 0.474 \times 10^{-1}(POP\_PAC) + 0.196 \times 10^{-3}(POP16\_64) + 0.151 \times 10^{-2}(TOT\_MILE)$
Property Damage Only Accident Frequency Model
$Log(PDO\_accident\_frequency+1)$ $= 4.762 + 0.515(PH\_URB) + 0.566 \times 10^{-1}(POP\_PAC) + 0.392 \times 10^{-5}(VMT)$
Fatal Accident Frequency Model
$Log(Fatal\_accident\_frequency+1)$ $= 0.652 - 0.924 \times 10^{-1}(INT\_PMI) + 1.762(PNF\_0111) + 1.389(PNF\_0512) + 0.263 \times 10^{-3}(POP00\_15) + 0.319(PPOPMIN)$
Incapacitating and Fatal Accident Frequency Model
$Log(Incpacitating\_and\_Fatal\_accident\_frequency+1)$ $= 2.257 - 0.659 \times 10^{-1}(INT\_PMI) + 3.328(PNF\_0111) + 3.674(PNF\_0512) + 0.512 \times 10^{-3}(POP00\_15)$
Nighttime Accident Frequency Model
$Log(Nighttime\_accident\_frequency+1)$ $= 4.092 - 19.167(MI\_PACRE) + 3.524(PNF\_0111) + 1.414(PNF\_0214) + 3.588(PNF\_0512) + 0.861(PPOPMIN) + 0.238 \times 10^{-3}(WORKERS)$
Pedestrians Accident Frequency Model
$Log(frequency\_of\_accidents\_involving\_pedestrians+1)$ $= 1.443 - 0.706 \times 10^{-5}(HH\_INC) + 0.129(POP\_PAC) + 0.884 \times 10^{-4}(POPTOT) - 0.902(PWTPRV)$
Injury Accident Frequency Model
$Log(frequency\_of\_injury\_accidents+1)$ $= 3.108 + 0.153(HU\_PACRE) + 0.768(PPOPURB) + 0.443 \times 10^{-5}(VMT)$
Accidents Involving Bicycles Frequency Model
$Log(frequency\_of\_Accidents\_involving\_bicyclists+1)$ $= 0.655 \times 10^{-1} + 0.252 \times 10^{-3}(HU) + 0.162 \times 10^{-2}(TOT\_MILE) + 0.292 \times 10^{-5}(VMT) + 1.539(WORK\_PAC)$

These models can all be easily updated based on new research. In fact, perhaps the most notable innovation in the SafetyAdvisor code is that none of the probabilistic models are actually hard coded into the software. All the models are represented in a very flexible algebraic form such that a user can easily modify and change the models to account for local conditions or new research findings. This basic idea should be carefully reconsidered for the updated RSAP since updating the program for new encroachment or severity models should be made to be a simple process not requiring changes to the computer code itself.

While the Safety Advisor was highly graphical for its time, it was labor intensive to input roadway characteristics because at the time there were no industry standard exchange formats available like Land XML. Ray acknowledges that an interface with CAD programs like InRoads and Civil3D would reduce the required input time and increase the amount of data available to the safety analysis. [Ray93]

Another notable feature of the SafetyAdvisor software was that it was one of the prototypes for the FHWA's IHSDM software suite.[Ray92] Ray was one of three authors of "scoping reports" that recommended how the software should be structured and what its functionality should be. The IHSDM proposed by Ray was highly graphical and presented a drive-through view of the roadway that calculated safety scores based on Equation 2 presented earlier.

Data Exchange

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. [LandXML08] 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 an xml extension as shown in Figure 16. These files can be used to transfer the 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.

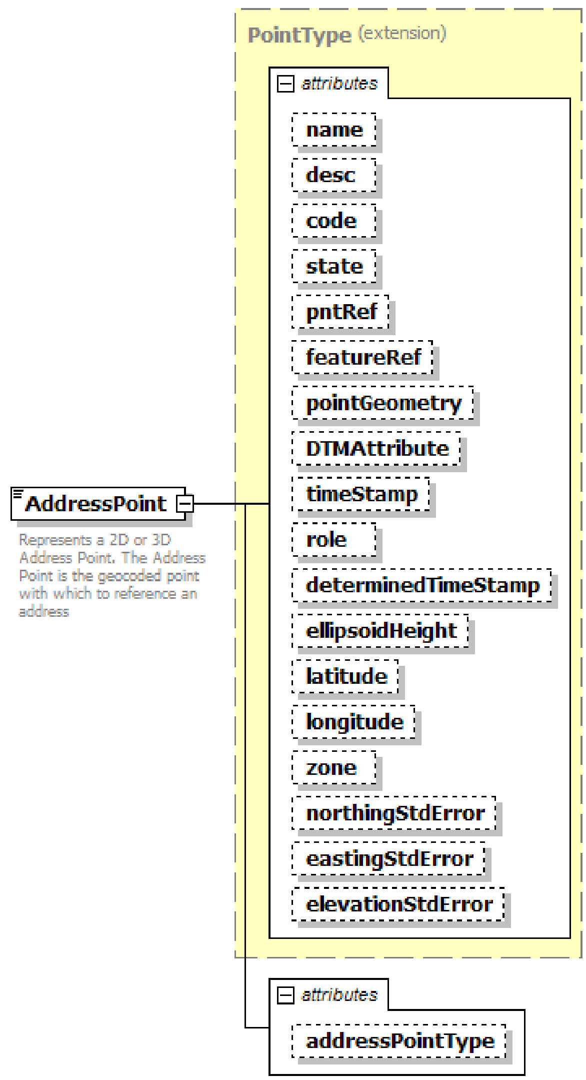


Figure 16. LandXML Data Diagram. [LandXML08]

```
<Line dir="57.238726414837" length="717.45104993012">
                    <Start>-1208.1536004425 -1901.50091776313</Start>
                    <End>-604.825656719668 -1513.259496262266</End>
                </Line>
                <Curve rot="cw" chord="216.997907580412" crvType="arc"
delta="65.707261209934" dirEnd="351.531465204903" dirStart="57.238726414837" external="38.07846494127"
length="229.36161011626" midOrd="31.988164028749" radius="199.999999999999"
tangent="129.156321830531">
                    <Start>-604.825656719668 -1513.259496262266</Start>
                    <Center>-713.053645664329 -1345.072985480355</Center>
                    <End>-515.234268279419 -1315.619735557024</End>
                    <PI>-496.213901149155 -1443.367851406227</PI>
                </Curve>
                <Line dir="351.531465204903" length="925.283497264735">
                    <Start>-515.234268279419 -1315.619735557024</Start>
                    <End>-651.497298753779 -400.42470888981</End>
                </Line>
                <Curve rot="ccw" chord="223.753769398867" crvType="arc"
delta="68.026474419828" dirEnd="59.55793962473" dirStart="351.531465204903" external="41.281195870791"
length="237.457191429938" midOrd="34.218328305118" radius="200." tangent="134.96894265289">
                    <Start>-651.497298753779 -400.42470888981</Start>
                    <Center>-453.677921368868 -370.971458966479</Center>
                    <End>-555.011279794616 -198.54306666939</End>
                    <PI>-671.373668752995 -266.927347880338</PI>
                </Curve>
                <Line dir="59.55793962473" length="757.21761282006">
                    <Start>-555.011279794616 -198.54306666939</Start>
                    <End>97.817798193397 185.113952161532</End>
                </Line>
                <Curve rot="cw" chord="210.350643532125" crvType="arc"
delta="63.454549787512" dirEnd="356.103389837218" dirStart="59.55793962473" external="35.138962104282"
length="221.498163832551" midOrd="29.887826151668" radius="200.000000000001"
tangent="123.654079995279">
                    <Start>97.817798193397 185.113952161532</Start>
                    <Center>-3.515560232351 357.542344458622</Center>
                    <End>196.022099994436 371.133597205139</End>
                    <PI>204.425169266205 247.765368206371</PI>
```


Figure 17. Example LandXML Data Export.

Software Platform and Programming Issues

A computer program is a series of instructions the 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 and is well suited for web applications. [Gaddis09] 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 programming tasks involving 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 be unsuitable for developing the type of graphical user interface that most users expect in modern engineering software. This is not surprising since Fortran pre-dates the whole idea of graphical user interfaces by several decades. 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 but with object-oriented features that make it ideal for developing graphical user interfaces. [Gaddis09] VB is known for its strong ability to integrate different programs and languages. For example, RSAP2010 could be coded with the computational engine in C and the graphical user interface in VB.

Options for RSAP to interface with CAD-based highway design software include a separate, direct interface specifically coded for each program (i.e., Civil3D, 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 which is not particularly ideal. 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. [CADALYST08]

Land XML is an industry standard language for interoperability, as discussed above.[LandXML08] The FHWA's IHSDM, 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.).

RSAP2010 could be developed with the ability to receive geometric data from a CAD-based highway design software suites (e.g., Civil3D or InRoads) to conduct benefit-cost 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 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. Most data like base encroachment rates, lateral extents of encroachment, horizontal and vertical curvature adjustment factors can easily be saved as default text data files that are simply read by the software. This way, when new data or new research results in a new model of, say, base encroachment, only the default text data file needs to be up-dated. Likewise, this strategy is useful for customizing RSAP for local users since a local agency could develop its own data tables for lateral extent of encroachment or the adjustment factors. These data tables could be selectable from a menu within the program with the default data tables specified for routine use.

Summary

As shown in the previous sections, RSAP provides an exceptionally detailed framework for analyzing the roadside. Encroachment rates, vehicle departure conditions, roadside and highway geometry, roadside feature placement, impact severity, vehicle mix and many other characteristics of the roadside can be explicitly modeled using the RSAP framework. The primary difficulty with the RSAP approach is developing the underlying statistical models that represent each of these characteristics. The validity and appropriate of many of these distributions needs to be carefully assessed especially in light of the age and uncertainty about many of the underlying studies. Nonetheless, RSAP has been a valuable roadside analysis tool and, with some critical review of the underlying statistical models, can be greatly improved such that it better represents modern crash characteristics.

RSAP was a state-of-the-art program in its day but the pace of software and hardware development has been extremely rapid in the past 10 years. While RSAP was developed in a very modular fashion for its day, even more modularity is possible today and much more sophisticated user environments are available. It is now possible to inter-link other software products such that user input is much easier allowing the software to be used more effectively at the project level.

Numerous bugs and errors have been discovered in the present version of RSAP and these much be repaired. The example presented earlier showed that while the original version of RSAP (i.e., version 1) used to generate the RDG examples agrees fairly well with the HSM, the current version of RSAP (version 2.0.3) is in error by a factor of 10.

As described earlier, the purpose of this project is to update the RSAP software, repair the known bugs and errors, update some of the default data relationships and improve the manuals and user documentation. The review of the literature presented in this chapter have provided a useful background for how RSAP has evolved and pointed out several critical areas where it needs to be improved.

CHAPTER 3
RESULTS OF SURVEY OF PRACTICE

A survey was conducted to ask RSAP users and potential users 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 B.

The survey was assembled using the on-line tool 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 resulting in a completion rate of 84 percent. The remaining 1900 or so that did not respond in any way are presumed to know nothing about RSAP or are not active in the roadside safety aspects of highway design. 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 discuss each question and describe the research team's assessment of the responses.

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

Respondents 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 18. 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 18.

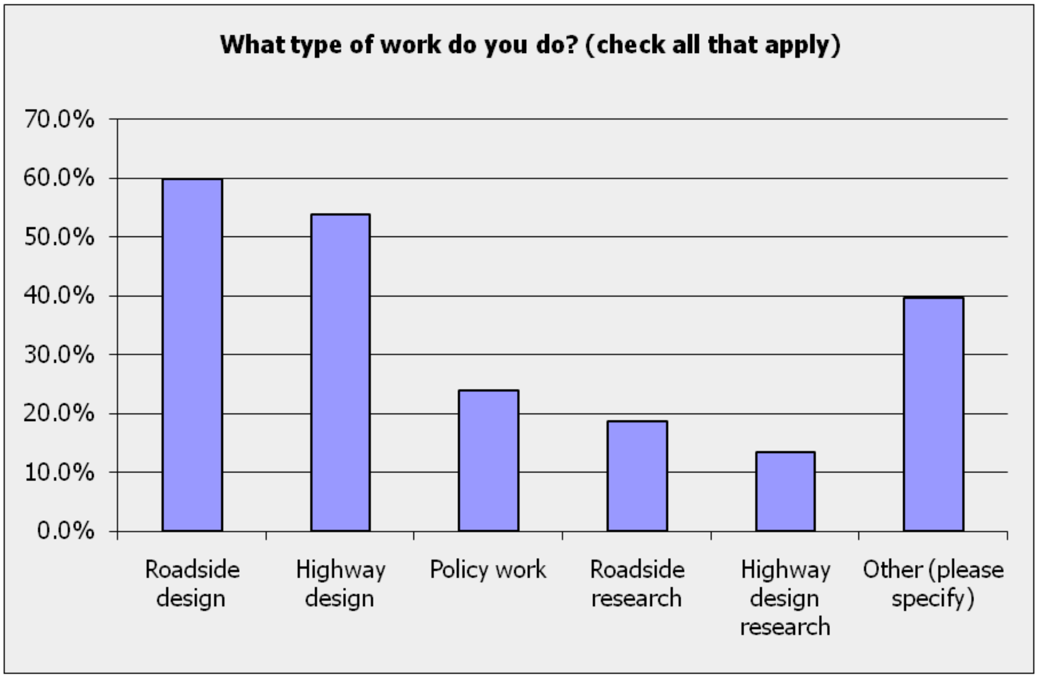


Figure 18. Distribution of Respondents' Work Categories.

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

Eighty six percent of the respondents use some form of CAD-based software tools for documentation and plan production as shown in Figure 19. 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.

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 there is great potential for an easy-to-use and effective benefit-cost program.

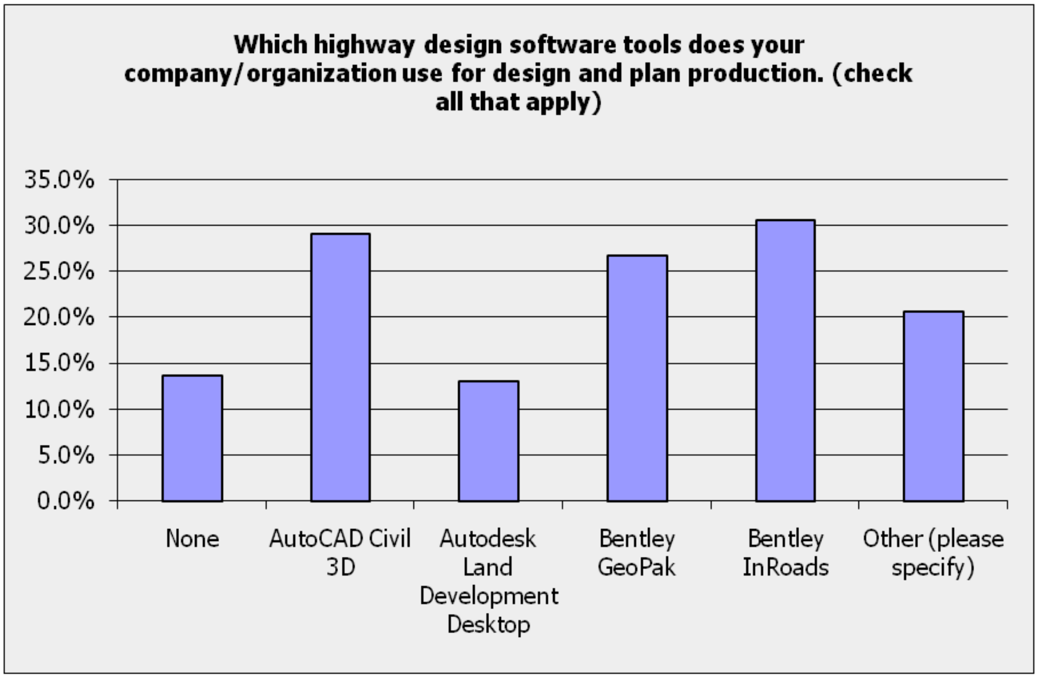


Figure 19. Distribution of CAD Software Use.

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 could provide valuable insight to help a project designer, but RSAP appears to be underused as shown in Figure 20. Understanding why RSAP is underused will help improve use statistics and project designs. This probably indicates that RSAP is largely used as a policy tool rather than for specific project decisions.

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.

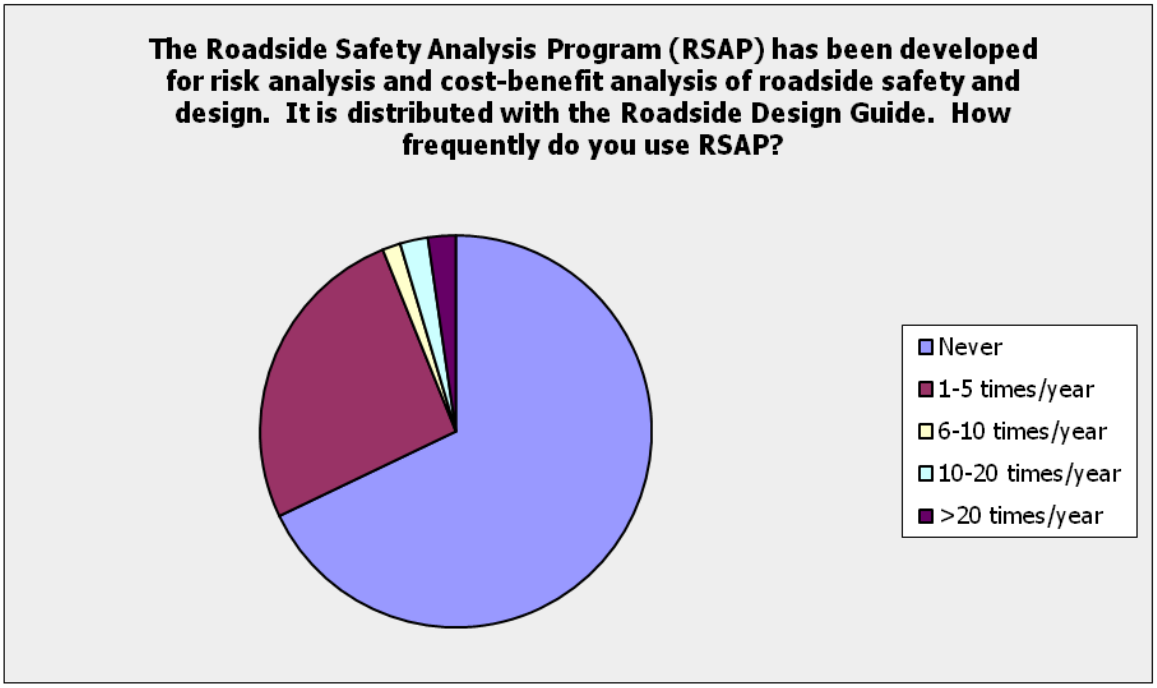


Figure 20. Distribution of RSAP Use Frequency.

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 where 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 fore-slopes.”
- “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 fores-lope/back-slope 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 fore-slope and back-slopes 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 make 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 Civil3D or Bentley InRoads?

Eight-five percent of the respondents agree that integrating RSAP with design tools like AutoCAD Civil3D 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 Civil3D 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.

Perhaps most significant, however, is that the RSAP user community appears to be quite small. While this might be looked at as discouraging news it can also be viewed as a place of great potential. If an updated RSAP can be developed that provides a significantly increased value to roadside designers, it appears that there is plenty of demand for such a tool and there is certainly nothing else in the marketplace that is competing with RSAP.

CHAPTER 4
RESEARCH PLAN

A work plan for the second phase of the project is presented in this chapter. The second phase of the project consists of the following three tasks as originally presented in the RFP and the proposal:

Task 6: Execute the Plan
Task 7: Alpha and Beta Testing
Task 8: Final Report

Based on the literature review and survey of practitioners described in the previous chapters, recommendations are presented in this chapter regarding software platform alternatives, user interface improvements, updates to the severity index procedure, recommendations for incorporating new research into default data tables as it becomes available, and suggestions for software validations and comparison with the pending Highway Safety Manual (HSM). These tasks will be accomplished in Task 6 based on the research plan shown in this chapter. Expanded work plans for Tasks 7 and 8 are also included. For each topic, the research team's recommendation is presented along with gaps in the knowledge that will have to be filled by performing additional work. The portion of the RFP quoted below mentions nine specific issues that, at a minimum, should be addressed in the work plan. While the order has been changed and some of the items have been grouped together or split apart, all nine items are addressed in the following chapter.

Revised Work Plan

Original Statement of Work:
Develop a revised work plan for updating RSAP, based on the findings of Tasks 1 and 2 and the research agency's experience that will:

a. *Identify software platform alternatives and make recommendations, including the rationale, on platform selection.*
b. *Develop a prioritized list of potential user functionality improvements, including, but not limited to, the user interface (input screens, output format, default values); benefit/cost and incremental benefit/cost assessment; default values of installation, maintenance, and repair costs; and checks for inconsistencies with flags. Input and output should include visual representations of features, data, and scenarios whenever possible.*
c. *Recommend a procedure for updating severity indices with NCHRP Project 22-12(2) inputs and other sources.*
d. *Evaluate whether the updated severity indices could distinguish between rigid, semirigid, and flexible barriers.*
e. *Recommend a procedure for incorporating updates into the Encroachment Rate Model, based on the results of NCHRP Project 17-22 and other sources.*
f. *Identify needed revisions to the embedded default relationships and data tables, including crash costs and lists of basic user selectable elements.*
g. *Add functionality for implementing alternate tables of user-defined default values and preferences to allow a user to customize RSAP for consistent local use.*
h. *Outline a software validation approach including Alpha and Beta testing of the software to confirm user friendliness and effectiveness of updates. Panel members will participate in Alpha and Beta testing. Users identified in the survey and others shall be invited to*

participate in Beta testing.
Compare the updated RSAP's crash predictions with those of the Highway Safety Manual to evaluate consistency between the two approaches.

Original Budget: $99,708

There are three general types of tasks that must be accomplished in Phase II: (A) tasks dealing with programming, software and algorithmic issues, (B) tasks dealing with updating and improving the underlying data and creating external data tables and (C) tasks involving verification, validation and testing of the software. These tasks are summarized in the following sections. The italicized text at the beginning of the section represents the research team's recommendation.

There is a great deal of work that needs to be done to create a completely functional, validated and useful RSAP. The tasks required cannot be completely accomplished with the time and funding available in this project as will be discussed in the "contractual" section at the end of this chapter. The research team believes that the first and highest priority is to develop a piece of software that is bug-free and verified that can be used to explore the validity and accuracy of the existing and improved data models. Once the code itself has been developed and has been shown to be free of errors and bugs, new or improved models can be integrated into solution procedures. One of the key methods needed to accomplish the long-term goal of having a reliable, validated code is to rigorously separate the probabilistic computations from the underlying data. The existing RSAP program includes a great deal of data and assumptions in the computational algorithm so it is only possible to change the underlying assumptions and data in many cases by re-coding the software. This must be avoided at all cost in the update so that all data, assumptions and engineering judgment are contained in external, easily changed data tables. Proceeding in this way creates a long-term strategy where RSAP can be incrementally improved over time based on a stable computational platform. This leads to three important programming objectives:

---

1. *Move **ALL** data, assumptions, engineering judgment to **data tables** located in text files **outside** the main program.*
2. *Focus on the **probabilistic** calculations in the computational engine.*
3. *Focus on the **user interface** and making data input and output report generation as easy as possible. To this end, include connections to highway design suites.*
4. *Specifically design the program to allow for easy **incremental improvement** of the data and models.*

If the program can be re-written by carefully separating the probabilistic calculations from the data, the program can be incrementally improved by modifying and replacing data tables. The research team believes this is the only way to accomplish the goals of the research without getting mired in endless discussions and research on the data itself. A flow chart for the research is shown in Figure 21.

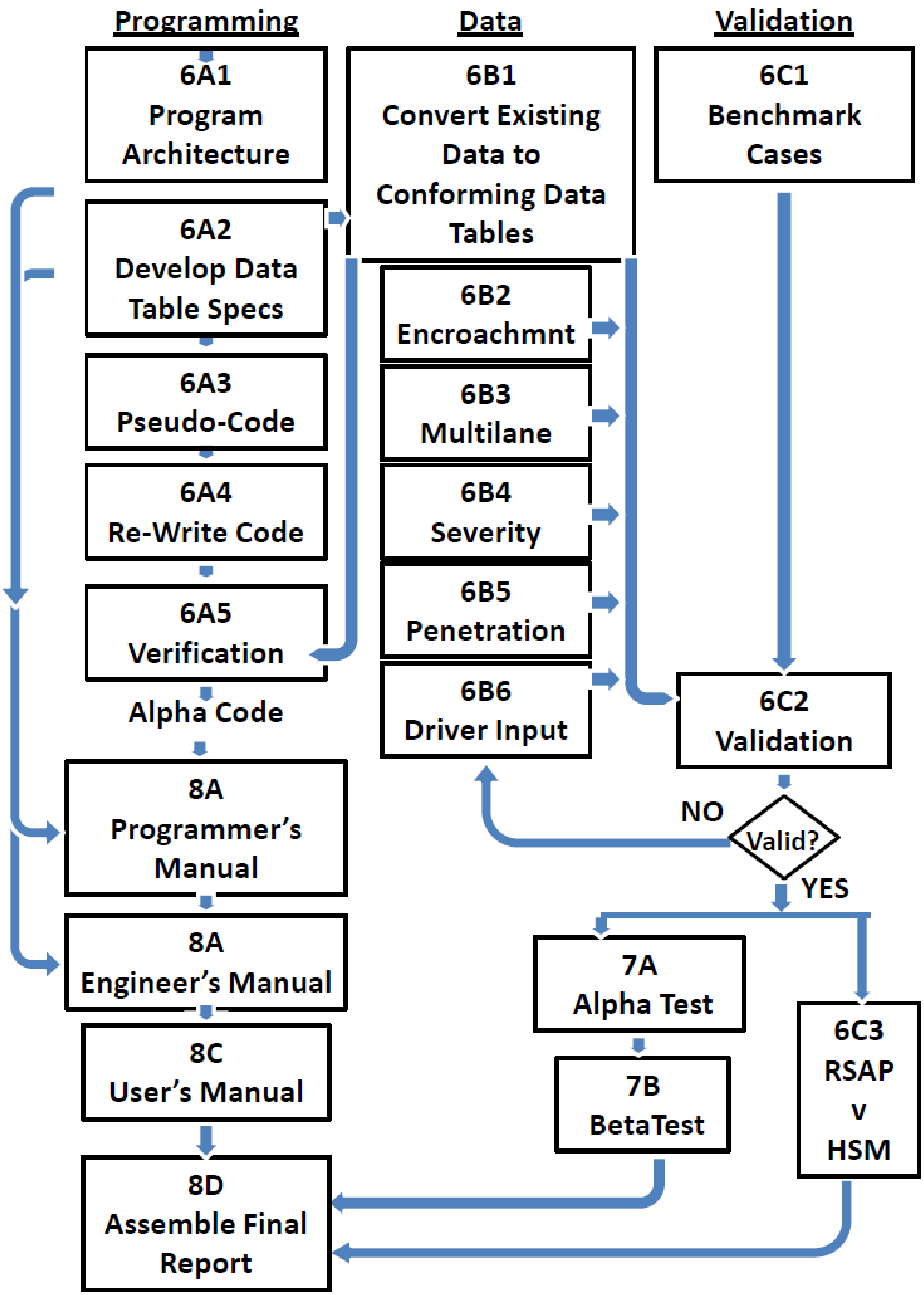


Figure 21 Flow Chart of NCHRP 22-27 Phase II Tasks

TASK6 A: Programming, Software and Algorithms

A review of existing and pending highway safety analysis software was conducted and was presented earlier in the literature review. Likewise, a survey was conducted of highway and roadside designers as well and the results were also presented earlier in this report. With the literature review and survey as background, the research team proposes the following for the updated version of RSAP. As stated in the programming objectives, a key objective is to separate data, assumptions and engineering judgment to external data tables.

<u>Task 6A1: Program Architecture</u>

Recommendation: *Develop a detailed program architecture including flow charts and key software module descriptions.*

Budgeted Cost: *$5,000*

Developing a clear and concise program architecture is the first step in designing the program and in documenting how the program functions. The architecture concentrates on tracking the information flow through the program. Key modules and subroutines are identified and the objective of each program module is clearly identified. The relationship of the modules is clearly demonstrated by the flow charts and architecture. The result of this task will be documented in the Programmer's Manual which will be included in the final report.

There are some serious algorithmic design issues that will need to be addressed. For example, most of RSAP currently uses the Monte Carlo method. This has advantages and disadvantage. For example, the Monte Carlo method allows for addressing a broad range of conditions but has the disadvantage of being very data intensive and computationally demanding (i.e., long run times). A more deterministic method (i.e., like the program Roadside) is computationally faster but tends to lump data together more broadly. The research team believes that the new program will be a mixed method to some degree – deterministic portions as well as Monte Carlo portions. Dealing with convergence and weighting are important and serious algorithmic design issues and they will begin to be addressed by organizing and blocking out the code in this task.

Task 6A2: Develop Data Table Specifications

Recommendation: *Identify all the data tables that must be created based on the program architecture developed in Task 6A1. Specify what variables will be used by the program to search the data tables and what values the program will read back from the data tables. Expand the number of adjustment factors to represent a wider range of highway geometries (i.e., lane width, number of lanes, shoulder width and type, rumble strips, horizontal curvature, grade, etc.). Represent all data in the form of external text files that can be easily updated without changes to the computational engine. Allow users to substitute user-defined data tables for any of the data tables and adjustment factors used in RSAP.*

Budgeted Cost: *$10,000*

This is a key task in the work plan since it is the definition of what data tables will be available and how the data tables will be structured that will enable the data to be moved outside the computational engine. RSAP depends on a number of data tables, some of which are accessible to the user and some of which are not. The encroachment and severity models, for example, are largely hidden from the user's view in the existing RSAP. It makes sense to make these embedded relationships more accessible to facilitate more frequent updates of the program that would not require actual re-coding. Partly, this is a software design and data structuring issue but it is also a data representational issue. While data supporting for these embedded data tables is difficult to get, it should be possible to provide a mechanism where States, researchers and other users could specialize their data based on local conditions. For example, the current RSAP encroachment model is based on the Copper data, collected in Canada. It seems reasonable that the encroachment model based on this old Canadian data may not be a good representation of encroachments in, say, present-day Arizona. Likewise, even if the encroachment model is updated using the Projects 17-22 and 17-11(2) data, these data were collected using a nationwide statistical sampling scheme that would obscure or eliminate regional differences. If the Monte Carlo simulation technique instead relied on an external data table, a user could chose to use either the national average data (i.e., the encroachment model based on the 17-22/17-11(2) data) or a special locally derived data table. A similar argument could be made for the severity model. There may be local conditions that affect the severity model so if the user, or more likely the user's agency, can develop a more locally realistic severity model for a particular roadside feature, it should be able to do so.

As an example, the base encroachment rate should be moved into an external data table. Currently, the Cooper encroachment data is built into the program so changing details of the encroachment model requires modifying the program. If the table were external to the program, only the table would have to be changed. Base encroachment is expected to be a function of (1) highway type (i.e., divided or undivided), (2) functional classification and (3) AADT. If the data is located in a data table, the program simply reads the data table looking for the entry conforming to the highway type, functional class and AADT of the study segment and returns the encroachment value. The data table can represent the Cooper data, the Hutchison-Kennedy data, or some new analysis of encroachment data since all models are dependent on AADT, highway type and functional class. In fact, the user could have the option to select among several encroachment models since they would simply be represented by different data table files.

Continuing this example, some researchers think that access density might also be an important predictive variable for modeling encroachments so it may be wise to add access density to the list of variables represented in the data table or as an adjustment factor. Even though we may not have information related to access density at this time, the table can be structured so that it can be added at a later time. While providing the flexibility to add new data search variables in the future is very attractive, it presents some difficult problems in designing the algorithms since each new variable must be accounted for in the weighting scheme and in the convergence calculations. The research team will need to balance the flexibility of adding new data elements to the practical constraints of computational time and difficulty of estimating sample weights.

Some algorithms in the current RSAP could be more generally represented as data tables. For example, the collision model uses the encroachment conditions to plot a swath across the roadside and determine if a hazard intersects the swath. The current RSAP uses a simple straight-line swath (i.e., the vehicle proceeds in a straight line). Driver input would certainly create many instances where the vehicle path is not straight but, rather, curvilinear. The key concept in the method used by RSAP is to do a mathematical intersection of two geometric shapes to determine if they intersect. If the vehicle path were represented in a data table as a series of XY points on a curvilinear line (actually, three lines representing the three exposed corners of the vehicle) then the program can still mathematically compare the roadside feature geometry to the non-linear swath to check for interferences; it just does so in a more general way. If the data table were structured in this way, driver input and curvilinear paths could be incorporated into RSAP at some later time without having to re-program the code.

The purpose of this task will be to identify all the required data tables as well as all the required input values that will be used to search the data tables. Decisions about what search variables are needed now and which might be needed in the future.

Task 6A3: Pseudo-code documentation

Recommendation:	*Prior to writing the actual code, write a complete pseudo-code for the computation portion of the program. This will create documentation for the program that will be included in the Programmer's Manual that will make de-bugging and maintaining the code in the future much easier. This will also allow the panel to examine the algorithms being used without panel members having to be proficient in the programming language.*
Budgeted Cost:	*$10,000*

Unfortunately there is no programmer's manual for the existing RSAP program. While the Engineer's Manual provides some information on the algorithms used in the program, the treatment is cursory such that knowing exactly how the code operates requires that someone actually look at the source code. With pseudo-code, the algorithms are written out in text and equation form so that it is clear exactly how the calculations are performed and what variables are being passed into and out of particular subroutines. The pseudo-code will contain flow charts of the program identifying subroutines and code modules and there will be pseudo-code for each subroutine and module in the computational engine. This will enable the research team and the panel to examine the procedures and discuss them without knowledge of the actual programming language used. The pseudo-code will be documented in the Programmer's Manual and made available with the rest of the program documentation.

Task 6A4: Re-write the Software

Recommendation:	*Re-code RSAP using vb.net and target the application to a Windows user interface. Use vb.net wpf for the user interface and C or C# for the computational engine. Allow for the importation of highway characteristics using the Land XML data exchange language.*
Budgeted Cost:	*$60,288*

The purpose of this subtask will be to re-code both the computational engine and user interface and allow for easier up-dating and user control over the data tables (item 3a in the RFP). The coding will follow the pseudo-code described in Task 6B1 exactly and if changes to the algorithms are necessary the pseudo-code will be updated such that the actual code and the pseudo-code agree.

The research team recommends that the basic structure of the computational algorithm be maintained: the computational algorithm is procedurally and computationally a good framework for representing crashes and should be retained. By now, there is a long history of this basic procedure running back through earlier versions of RSAP, BCAP, Roadside, ABC and other programs so the basic framework has proven to be a useful conceptual model for roadside safety analysis.

The code itself, however, should be completely rewritten. The current code is known to contain many bugs and errors as described earlier and the code is written in old programming languages that are not as easy to interface with other modern languages and operating systems. If the current code were relatively bug free it might make sense to continue with Fortran/C++ and simply modify the code but since the existing code is very buggy, it makes more sense to simply re-code the entire program. The team believes that it will be easier and less expensive to re-code the program than de-bug and improve the existing code. Re-coding it will make the code much more compatible with current versions of Windows.

The target hardware/software platform will continue to be Windows-based operating systems running on PCs. The research team believes that there is little demand for either an Apple or Unix-based application.

The programming language vb.net is a modern object oriented visually-based programming language specifically designed for developing Windows-based applications. There are a variety of sub-languages for different purposes available within vb.net. vb.net wpf, for example, is a language that is developed specifically for developing the typical Windows style graphical user interfaces that most people are familiar with from MicroSoft Office products like Word and Excel. Vb.net also supports linkages to a variety of other languages including C, C++, C# (i.e., pronounced C sharp) and many more. Vb.net is a “managed” programming interface so that memory allocations, allocation of multiple threaded processes, garbage collection and variable passing is all prearranged within vb.net making the coding much simpler and the resulting programs more robust and efficient. The vb.net products are all available within VisualStudio which is the tool for building vb.net applications. Also, all of the highway design suites use vb.net so making connections to AutoDesk Civil3D and/or Bentley’s InRoads would be much easier if the program is already in vb.net.

The research team recommends that the computational engine for RSAP be re-written using C or C#. C# is simply the object oriented visual version of the C/C++ programming languages. As discussed in the literature review, RSAP is currently coded in Fortran, with much of the default data hard coded. Accomplishing updates to RSAP as new research becomes available currently requires re-coding of the software. This updated version should include provisions to allow for periodic updates of default data which does not require re-coding the software. Also, Fortran was developed long before graphical user interfaces so it is not straightforward to integrate the interface and the computational engine. Starting again in C# would make integrating the code across platforms and modules easier. C# has all the necessary mathematical functions (e.g., random number generators, trigonometric functions, etc.) needed for the RSAP computational engine and it has been used already in many structural calculation projects. Further, variable typing, value passing and integration with other codes is much easier with C# in the VisualStudio framework than Fortran would be.

The research team recommends re-coding the graphical user interface (GUI) for RSAP using vb.net wpf (i.e., Windows Presentation Foundation). Many survey respondents expressed interest in changes to the GUI. These suggested improvements include a more graphical environment with improved data entry capabilities, standardizing data entry on a project baseline, and the additional choices for reports. Re-coding the GUI will allow for accommodating these user requests. Vb.net wpf is a language that is specifically designed to create the types of modern graphical user interfaces most people are familiar with in MS Windows environments. This is a tremendous advantage over C++. When RSAP was originally coded, C++ was an excellent choice since, at the time, it was the language best suited for developing user interfaces. Much has happened in the software industry in the past decade, however, and now tools like VisualStudio’s vb.net wpf make developing the user interface much easier. The research team has already experimented with using vb.net wpf and found it very easy to create Windows-style graphical user interfaces.

The research team also recommends that RSAP include an option to import and export LandXML data while maintaining manual data entry options in RSAP. LandXML has emerged as an industry standard for exchange of geometric data between CAD based software packages. The FHWA’s IHSDM supports this standard and accepts data imported from LandXML as do the most common commercial highway design suites like AutoDesk’s Civil3D and Bentley’s InRoads and Geopak. Many survey respondents noted that the data entry is tedious and requested improved data entry capabilities. Providing linkage to common highway design software will make RSAP much more useful to designers and also allow for much more realistic project evaluations. This way, if a designer has a project already created in, say, Civil3D, the highway geometry can simply be exported to RSAP for analysis avoiding a lot of tedious manual entry of geometry.

As discussed earlier, all data should be external to the code in text lookup files. This will allow RSAP to be updated as advances in research are available without code re-writes. This is extremely important because it is unlikely that there will be time or resources available in this project to perform all the data enhancements that are needed or desired. By rigorously keeping all data external to the program, RSAP can be continuously improved simply by adding, editing or changing the external data tables.

Results should be presented to the user in a form similar to that used by the IHSDM. The researchers believe highway safety software should make an effort to move toward standardization where possible. In addition to the tabular data provided, graphs should be provided showing encroachments by segment, crashes by segment, crash/maintenance/repair costs by segment, benefit/cost by segment, etc. Providing results in the same graphical form helps to move toward this goal. This is described further in Task 6B3.

One of the purposes of this task will be to develop the user interface features that will define what the user interface looks like, what reports are generated as output, how data will be input into the program and how default data tables and values will be implemented (item 3b in the RFP). The survey indicated that some users thought integration with highway design software packages was desirable but there were other respondents that wanted to be able to use RSAP as a stand-alone program. The research team recommends that both be done: there should be an option to import highway design data from commercial highway design software products like Civil3D and InRoads but it should also be possible to enter data manual directly into RSAP.

In principal, it is possible to develop a totally graphical user input interface in RSAP that would function much like the highway design suites. This, however, would be quite expensive and would largely be a duplication of the considerable effort put into user interfaces by the commercial developers. An alternative is to allow importing data to and from the commercial package through LandXML to allow for graphical input of data but still allow for text-based input in the stand-alone RSAP.

The user interface for RSAP will be a standard MS Windows based graphical user interface similar to the existing interface. The user interface will has a settings tab that allows users to chose data tables and include custom data tables for the computational engine.

Task 6A5: Verification

Recommendation: *Develop and execute a debugging plan that ensures that the calculations performed by RSAP are correct. The plan should be developed and executed in parallel with the development of the code such that each subroutine and module can be independently validated. The check should include the full range of data input expected as well as erroneous and false input to make sure the program detects incorrect or inconsistent input as well as correctly processes data across the full range of valid input.*

Also, remove the RSAP 2.0.3 download from the TRB website and notify AASHTO that the predictions of RSAP 2.0.3 currently being distributed with the RDG are believed to be in error. Users should use caution in using and interpreting the results of RSAP 2.0.3. The panel might want to consider switching back to RSAP 1.0 in the interim.

Budgeted Cost: *$10,000*

Verification refers to the process of ensuring that a numerical technique or program produces the results intended by the programmer. Verification is different than validation in that verification only ensures that the underlying mathematical models generate the intended results. Validation has to do with checking the predictions of the program with the actual results in the field. Validation is addressed in Task 6C2.

The current version of RSAP (i.e., RSAP 2.0.3) is clearly afflicted by numerous code bugs. As shown earlier in the literature review, there is an order of magnitude difference between the predictions of RSAP 1.0 and RSAP 2.0.3. It is not completely clear how much of this is a result of programming errors and how much is due to modeling issues. In NCHRP Report 638, Sicking shows the severity model is certainly responsible for some of the differences but it is unclear where the problems are and what the magnitude of the problems are. This puts the research team and panel in a difficult position because it is not clear which of these versions of the software is more correct. Interestingly, the predictions of RSAP 1.0 and the HSM CPM are quite similar which is very encouraging but RSAP 2.0.3 is different by a factor of 10.

TRB currently allows users to download RSAP 2.0.3 from their website. Given the extent and seriousness of program bugs and issues identified in this report, it is research team's opinion that TRB should warn the users about these problems and possible take the program off the NCHRP website until they are resolved. The research team recommends that in the interim period before a revised RSAP is available, that users of RSAP 2.0.3 need to be warned that the results may not be correct. The panel may want to (1) warn users of the inconsistencies or (2) recommend that RSAP 2.0.3 not be distributed with the RDG until a revised version that is free of bugs and that has been validated is available.

In any case, a software verification or debugging plan will be developed during the re-coding of the RSAP program to ensure that the program is free of bugs and calculation errors. . A subroutine-by-subroutine procedure will be developed and documented such that the calculations can be carefully checked both during this development and in any future program revisions. The verification data can be included in the Programmer's Manual along with the pseudo-code. The end product of this task will be an RSAP main program that is relatively robust and bug-free. Unlike the previous versions of RSAP, a verification report will be incorporated into the Programmer's Manual that documents the verification exercises. This report will be included in the final report such that future researchers or programmers will have the benefit of knowing what steps were taken to verify the code.

TASK 6B: Data Representation

The following subtasks involve either developing new or improved statistical models or improving some of the algorithmic procedures in RSAP.

Task 6B1: Convert Existing Data to Conforming Data Tables

Recommendation:	*Convert the data models and default data in the existing RSAP into data tables conforming to the specifications developed in Task 6A2.*
Budgeted Cost:	*$10,000*

The current version of RSAP includes a great deal of data, some accessible to the user and some not. As discussed earlier, defining specifications for the data tables will be accomplished in Task 6A2. Some of algorithms in the current RSAP may be better suited for representation as data rather than coded into the computational engine. The purpose of this task will be to convert all data and some of the algorithms in the current RSAP into data tables that conform to the specifications of Task 6A2. This will enable the re-written program to be used in the short term using essentially the data and assumptions of the current RSAP.

Task 6B2: Encroachment Model Updates

Recommendation:	*Re-model the Cooper encroachment data using more appropriate and modern statistical techniques to develop a more correct and robust encroachment model that can be used until better data is available.* *Obtain and assess the data bases used in the development of the HSM AFMs and use these data to model encroachments and lateral extents of encroachments.* *Use the Washington State cable median barrier data to model encroachments and lateral extent of encroachments.*
Budgeted Cost:	*$50,000*

Encroachment modeling has been problematic since the very beginning of the use of cost-effectiveness procedures in roadside safety. It is presumed that a completely new data collection and modeling effort is not within the scope of this project. The newly award NCHRP 17-43 data may be helpful in coming years but it is expected that that data will not be available for some time and, in any case, the 17-43 like the 17-22 data is based on sampling crashes rather than segment characteristics. Estimating encroachment conditions requires tracking all the crashes, reported an unreported, on a particular segment whereas the 17-43 and 17-22 approaches rely on sampling crashes on a variety of segments. While the 17-43 and 17-22 could have some utility in updating RSAP they are not specifically structured to be used directly. Since there is no new data available, this task concentrates on re-analyzing existing data or looking at promising existing data sets as a medium-term solution. There are basically three options presented in this section:

- Re-model the Cooper data,
- Develop a new model with the HSM data and
- Develop a new model with the Washington State cable median barrier data.

These three options are not mutually exclusive. The research team could do all of them, none of them or some combination. In addition, the models should all be compared and contrasted with each other to find areas of agreement and disagreement. We believe that process will teach us a lot about encroachment modeling that can be used in the future.

Re-Modeling" of Cooper Encroachment Data

As discussed earlier, the Cooper data were used to obtain estimates of two key parameters used in RSAP: roadside base encroachment rates and lateral extent of encroachment distributions. Many concerns regarding the Cooper encroachment data were discussed at length earlier. At the top of the lists are: (1) The data is more than 30 years old; (2) The data is statistically flawed due to the way highway segments were delineated by Cooper; (3) Cooper was unable to distinguish intentional encroachments from unintentional encroachments in the data; and (4) vehicle encroachments within or just slightly beyond the paved shoulder area were difficult to detect and thus severely under-reported.

Any relationship developed with this data set need to be used with these limitations in mind. For example, it was explained earlier why the Cooper data is statistically flawed—bias was introduced into the segment data during "data reductions." The consequence of this flaw is that whatever relationships developed from the data regarding the encroachment frequency/rate will be overstated. If a particular factor, say, access density, has a positive influence on encroachment rates, the size of this influence would be exaggerated when estimated from the Cooper data. Unfortunately, the exact effect of this bias is not known, and being a legacy and vintage data set it is probably not worthy of a special study to correct the bias even if it were possible to do so.

Despite these concerns, the Cooper data is still the latest encroachment data available to date. Base roadside encroachment rates and lateral extent of encroachment distributions, when properly estimated from the Cooper data, could still be used in RSAP until better estimates become available.

The statistical regression models and estimation methods adopted to analyze the Cooper data were inappropriate. In the last few decades there has been a dramatic development in the statistical and biomedical sciences on specialized statistical regression methods for analyzing discrete types of response data, such as the encroachment frequency data, and "censored data," such as the lateral extent of encroachments. Most scientists and applied statisticians now realize that it is unnecessary and often inappropriate to use statistical methods for continuous data with discrete responses. In addition, using a conventional regression model that ignores the censoring nature of the encroachment data can seriously underestimate the lateral extent of encroachments.

Recall that lateral extents of encroachments fall into a general class of statistical data called "censored data." The lateral extent of an encroachment was "right censored" when the encroached vehicle hit a fixed object or ran into a ditch. It is censored in the sense that the lateral extent was not completely observed or only partially observed when a collision occurred, and the lateral extent would have been greater if the object or ditch that the vehicle struck had not been present on the roadside. Ignoring this censoring nature of the encroachment data can seriously understate the lateral extent of the encroachments. Since 37% (718 out of 1,949) of the roadside encroachments in the Cooper data involved collisions, it is critical that this censoring nature of the data be explicitly captured in the regression models.

A quick exploratory study conducted by Maiou using a specialized regression model on Cooper encroachment rate data for "two-lane" highways indicated that the estimated encroachment rates from the model are two to three times higher than those reported in the RSAP Engineer's Manual (EM). In addition, contrary to the findings of earlier studies, AADT and access density are both found to be highly significant, both statistically and practically. There are many other explanatory variables contained in the Cooper data that this quick exploratory study did not examine, and their relationships with encroachment rates deserve a more formal and systematic modeling study.

At a minimum, the revised estimates from the "re-modeling" efforts can be used in RSAP until better estimates become available and can provide better benchmarks for this and future roadside efforts to improve encroachment data. Any relationship identified from this vintage data set, such as the effect of access density on encroachment rates, can provide important clues in other data collection and analysis efforts to update encroachment data for RSAP and in any restructuring efforts of RSAP codes, especially on the Encroachment Module.

Estimate Run-Off-Road Crashes, Encroachment Rates, and Lateral Extent of Encroachment Distributions using Crash Data from the HSM

This task is a data gathering, analysis, and modeling effort aimed at achieving two important objectives for the development of RSAP2010: (1) providing estimates of roadside encroachment rates and perhaps lateral extent of encroachment distributions that current RSAP desperately needs updated, and (2) generating estimates of run-off-road (ROR) crashes for different mainline and roadside scenarios, which the predictions of RSAP2010 can be compared to and even benchmarked on.

The data to be used in this task are those that have already been collected and used for Highway Safety Manual (HSM). As discussed earlier in this report, given the investment that the safety community has made in developing the HSM (i.e., more than \$3 million dollars), the RSAP development team should make the best use of the data and other resources that have been gathered or produced for developing HSM. In addition, it is important for the research team to make sure that RSAP2010 will be compatible with those crash prediction models and AMFs to be published in HSM. Using the same data sets as those used in HSM makes the compatibility issue a lesser problem. In addition, calibration methods that have already been developed for HSM to adjust crash prediction models for a particular geographical area or highway agency can be utilized in RSAP2010 with perhaps some modifications emphasizing on roadside features.

The potential data from HSM to be gathered and modeled are those from the four NCHRP projects that have already been completed or are on-going:

- NCHRP Project 17-18(4), which, among other things, develops a prototype chapter on ***rural two-lane highways***. (completed on 10/31/03, \$200,000)
- NCHRP Project 17-26, which develops a quantitative safety prediction methodology on ***urban and suburban arterials***. (completed on 3/31/08, \$1,096,403)
- NCHRP Project 17-29, which develops a quantitative safety prediction methodology on ***rural multilane highways***. (completed on 4/30/08, \$700,218)
- NCHRP Project 17-45 Enhanced Safety Prediction Methodology and Analysis Tool for ***Freeways and Interchanges***. (on-going)

Of these projects, the data from NCHRP Project 17-29 and 17-45 either will not be available in time for this project or they are not collecting roadside data so the data to be reviewed can only come from projects 17-18(4) and 17-26.

After these HSM data are acquired, an exploratory study should be conducted to understand the strengths and limitations of these data and a modeling plan should be devised and, when approved, executed. The statistical methods to be used to develop ROR crash prediction models, which can then be used to estimate key encroachment parameters and predict ROR crashes for comparisons, were discussed earlier in the literature review.

Conducting this task could help to resolve some of the compatibility and related issues discussed in this report between RSAP and HSM. It is envisioned that the completion of this and some of the other tasks discussed earlier will also open up doors for RSAP to tap into many of the products generated, or to be generated, from HSM related studies and developmental efforts. It has the capacity of making RSAP2010 a mainstream product, as opposed to being listed as one of a long list of "other utilities and software tools," in HSM.

Use the Washington State Cable Median Barrier Data to Develop an Encroachment Model

Washington State DOT conducted a comprehensive review of its cable median barrier policy in 2007 and updated it in 2008 and 2009. A major part of the review was assembling a comprehensive database of median crashes related to cable median barriers, unprotected medians where cable median barriers were later installed and some concrete median barrier locations. The resulting database is very clean and has a great deal of potentially useful information in the context of this project. Maintenance data is also available so it should be possible to include unreported crashes in the analysis. The data includes accurate traffic data for each year and barrier location, placement data is available as well as the usual police reported types of data. The research team believes that this data set would be very useful in developing encroachment rates and lateral extents of encroachment that can be used to compare to the Cooper data.

The Washington data would also serve as a very important validation data set since the RSAP predictions could be checked against the real-world crash data. In addition, one of the limitations with the existing RSAP is the way it handles median cross-over issues. The Washington data set would be a good choice since it was developed specifically to examine before and after median cross-over crash studies. Incorporating cross-median crashes is a data modeling issue that was not addressed in the original RSAP. One way to consider cross-median crashes is that when the encroaching vehicle's lateral extent of encroachment is such that it enters into the opposite lanes of travel, a cross-median event has occurred. Whether the event becomes a crash depends on if there are other vehicles in the opposite lanes for the encroaching vehicle to interact with. This would presumably be a function of AADT. The severity must be based on the likely number of vehicles involved, the number of fatal and injured persons and the type of vehicle. The WSDOT data can be used to assess the severity of cross-median events for segments that have and do not have median barriers.

Task 6B3: Multilane Adjustment Factor

Recommendation:	*Eliminate the lane-by-lane simulation of encroachments and replace it with a multilane adjustment factor that is applied to the base encroachment rate. As a starting point, the adjustment factor can be based on the recommendations of the HSM and checked with crash data being used to re-assess the base encroachment model in Task 6A1.*
Budgeted Cost:	*$10,000*

Even though the interest of RSAP is on the roadside, it actually simulates on-road vehicle encroachments lane by lane. The general formulation for the encroachment probability model in the RSAP Engineering Manual (EM, on page 20) does not mention lane encroachments at all. This lane-based analytical and simulation procedure receives very little discussion in EM however it plays a major role in RSAP code development and in its analytical implications. A large proportion of the RSAP code and system memory are devoted to this lane-based simulation procedure which involves intensive bookkeeping operations. As discussed earlier, the lane encroachment analytical procedure in current RSAP does not make good behavioral sense and the assumptions behind the procedure are highly questionable and cannot be validated. In the same section, arguments were also provided for the abandonment of this procedure in RSAP from both data availability and program functionality perspectives. It was suggested that abandoning this procedure would allow the RSAP to focus on the roadside as it should. It would also allow a much leaner, cleaner, and efficient RSAP code to be produced.

Instead of simulating encroachments lane-by-lane as is done in the current version of RSAP, the research team recommends replacing it with a simple multilane adjustment factor. This adjustment factor would be added to the existing pool of adjustment factors for the base encroachment rate in RSAP to deal with the changes in encroachment rates for multilane highways (as the number of lanes increases). The values for this multilane adjustment factor can be evaluated as part of the re-assessment of the base encroachment rate and the adjustment factors in the HSM should also provide useful information as well.

Task 6B4: Updated Severity Indices

Recommendation:	*Develop a method for estimating crash severity based on observable crash data consistent with the probability of impact approach suggested in the RSAP EM. Use the new method to develop new severity models for at least the basic eight types of features in RSAP.*
Budgeted Cost:	*$50,000*

A more rational method for developing severity indices based on observable crash data will be developed in this sub-task (items 3c and 3d in the RFP). The existing severity index method is subjective since it is based on the opinions of experts although historically the SI values have also been calibrated to some extent based on observed data. It would seem preferable to root the severity model in observable data that can be validated and checked. Grounding the severity model on observable data will also allow the severity model to distinguish between rigid, semi-rigid and flexible barriers and even between types of barriers in a particular category depending on the availability of data. Even specific types of barriers could be modeled as long as there was crash data available to develop a severity probability distribution. This would enable, for example, comparisons of a concrete median barrier to a strong-post w-beam median barrier. Likewise, the method can be used to determine severity indices that are currently of questionable validity (i.e., slopes)). In fact, the RSAP engineer's manual recommends using a procedure, called the POI or probability of injury method, where observable crash data are used to estimate the severity of crashes but, unfortunately, they were not able to implement the procedure due to the limits on resources in the original project. The research team recommends basically following this recommendation of the earlier RSAP development team.

The number and complexity of the impact condition-severity relationships that need to be developed for RSAP has serious implications in terms of the size and details of the data, and thus the resources, needed to accomplish the task. It is extremely difficult and expensive, if not impossible, to develop all the impact condition-severity relationships of interest using in-depth crash data alone. Also, the data used to develop severity models should be limited to data collected after 1997 due to the expected changes in severity relationships due to the repeal of the national speed limit, the introduction of airbags into passenger vehicles and improvements in seat belt use-rates. Older data will tend to over-estimate severities since they do not account for these more modern conditions. Likewise it is not possible to model all the hazards needed by RSAP within the limits of the time and funding for this project. Many of the relationships have to be inferred from relationships that have already been well established from crash data, as well as from innovative uses of kinematics analyses, simulation models of vehicle dynamics, full scale crash tests, and trauma biomechanics studies. Looking forward, recent installation of Event Data Recorders (EDRs) in late model vehicles can potentially provide a completely different perspective on the assessment of occupant risks in the future. In short, a procedure for developing the severity relationships needs to be developed in this project that can be used in subsequent projects, by the States and by users to gradually improve the severity relationships in RSAP.

Given the difficulties of estimating crash severity described above, the software framework of the crash prediction module in RSAP should be as inclusive and as user friendly as possible. In order for the RSAP program to be able to make the best use of all possible data sources, available now and in the future, a flexible research approach needs to be adopted to develop the needed impact-severity relationships. The data sources to be considered will be a mix of empirical and analytical data, including police-level and in-depth crash data, and data from full-scale crash tests, computer simulation models of various fidelities, and analytical models on vehicle dynamics and biomechanics. Given the limitations of the data and complex configurations of the features, some levels of engineering judgment will always be unavoidable for some of the roadside features. Providing better functionalities to facilitate users to calibrate the impact-severity relationships with their own data and allowing more user input options, such as adding the seat belt usage rate and allowing users to change the default rate, are some possible enhancements to consider in updating RSAP.

Since crash costs are expected to remain linked to the usual KABCO police reporting scale, the severity model needs to generate the expected KABCO rating of each encroachment. Ideally, the KABCO probability distribution should involve the impact conditions (i.e., speed, angle, vehicle type, vehicle orientation and driver inputs) and the default data table should be structured to account for all these potential inputs. In the short term, it may not be possible to completely fill in the complete data table for all possible objects and scenarios but at least the framework will be available in the future.

The main difficulty with this method is that under and un-reported crashes must be carefully accounted for in order to derive an accurate KABCO distribution as demonstrated by Sicking in NCHRP Report 638. While studies that do this are the exception rather than the rule, there are some studies that have used maintenance records combined with police records to estimate the proportion of unreported crashes. Another difficulty is getting a full range of vehicle types and impact conditions. For example, for most typical data collection activities, there may be very few if any heavy vehicle crashes so engineering judgment may be required to fill in values of these low probability cells in the data table.

In any case, the severity model ideally should be represented by a data table for each type of roadside object (i.e., tree, utility pole, flexible guardrail, etc.). This table should list a KABCO distribution by impact speed, impact angle and vehicle mass. Obviously some of the cells in this data table will be difficult to populate (e.g., high-speed, high-angle impacts with heavy vehicles) and will probably have to be supplemented with engineering judgment. Nevertheless, this method would eliminate the artificial severity index relationship and allow for a more direct representation of the severity of crashes with different types of objects that can be checked and improved as further research is conducted.

Some severity models can be developed in this task based on existing data. For example:

- Low-tension cable median barrier based on the WSDOT data,
- Ray developed severity measures for deep rock cut crashes based on data from Ontario,
- NCHRP 490 developed severity distributions for strong-post w-beam guardrails, the BCT and cable guardrails.
- Sicking developed improved severity distributions for strong-post w-beam guardrails in NCHRP 638.

All the above data sets have some measure of unreported crashes and this is a necessity for datasets used for modeling crash severity. There are likely other studies and data available as well. For example, the NASS CDS data may also be useful. There are over 30 years of data available and even restricting the scope to post-1997 results in 12 years of data. The data is nationwide and is a statistical sample of crashes. Each crash record contains scene diagrams, detailed sequence of events, a variety of objects struck, vehicle types and other data so while the cases are not "reconstructed" there is a wealth of useful information.

Modeling rollover collision is another area where severity modeling needs to be re-examined. The severity of different slope combinations in the current RSAP is of questionable validity. Also, the case of rolling over barriers like bridge railings should be investigated as well since the severity of rollover and non-rollover events are likely to be quite different.

Since all the required severity models cannot be developed in this project, a short term strategy is also needed. The existing SI values can be used to generate data tables in the form discussed above. RSAP current has speed-SI relationships for each type of feature so these values can simply be expanded to speed-KABCO data tables in the interim. The result would be identical for objects already included in RSAP but this would allow for better data to be inserted when such models become available.

Task 6B5: Penetration of Features

Recommendation:	*Replace the method used for determining if a hazard has been penetrated using the impact severity with a probability of penetration based on observable crash data.*
Budgeted Cost:	*$25,000*

RSAP estimates if a feature has been penetrated in the initial impact using a variety of methods. The impact severity (IS) measure, defined as $IS=0.5m(V \sin \Theta)^2$ where V is the impact velocity, Θ is the impact angle and m is the vehicle mass, is used for longitudinal barriers whereas the kinetic energy is used for objects like signs, luminaires and trees. For longitudinal barriers, since the mass, impact velocity and impact angle are assumed based on the encroachment conditions, all three terms of the IS are known and can be calculated. The limiting IS for each type of hazard is assigned in RSAP based on crash test experience and some engineering judgment about how much reserve capacity is in the system above what was observed in the crash tests. The IS is a somewhat controversial value since it is not technically a physically correct quantity. IS has units of energy (e.g., ft-lbs) but energy does not have directionality (i.e., it is not a vector) yet IS is attempting to quantify energy in a certain direction. Momentum, which does have directionality, would probably be a better measure but momentum does not have units of energy and damage is generally represented in units of work (i.e., energy). In any case, any gross energy or momentum approach is limited because penetration is often the result of complex interactions between the barrier and the vehicle that are often not captured by a simple measure of energy or momentum. For example, cable barriers have been penetrated (note: in this context penetration can mean penetrating through the barrier because the barrier fails or underride or override) by small cars travelling at modest highway speeds due to the way the cables and bumpers interact especially on non-level terrain. On the other hand, there have been instances of cable barrier retaining busses and heavy trucks far above what would be the presumed IS based on testing. Also, a truck with a high center of gravity may roll over a barrier even at modest impact conditions. Instead of using a mechanics based measure, the research team recommends using a crash-data based probability of penetration of the hazard. This would be preferable since the likelihood of penetration can be rooted in observable data that can be checked and updated if necessary. For some objects it may be necessary to base this probability of penetration on mechanics in the short term but the objective ought to be basing the probability of penetration on observable data. This has already been done by a number of researchers, for example, on cable median barriers where the probability of penetration for all vehicle types and all speeds is about three percent.

The probably of penetration can be added to the severity data for each feature such that, at least in principal, the probability could be listed by encroachment conditions in the same way that the KABCO severity data would be listed. Thus, in the updated RSAP, when an encroachment is determined to produce an impact with a hazard the following procedure can be employed.

1) Go into the data table for the particular type of struck object,
2) Given the vehicle mass, impact speed and angle and driver inputs lookup the probability of penetrating the barrier,
3) Calculate the crash severity of the initial object impact and multiply that cost by one minus the probability of penetration,
4) Determine if there are any hazardous objects behind the barrier that would be struck if penetrated,
5) Calculate the crash severity of any objects behind the barrier and multiply that cost by the probability of penetration,
6) Sum the crash costs of all the impacts with the initial barrier and hazardous objects behind it weighted by their probabilities. This is the likely crash cost of the encroachment.

This procedure is basically what is in RSAP now. The main difference is how the determination of penetration is made. The existing RSAP uses the IS value of the encroaching vehicle with respect to the limiting IS for longitudinal barriers whereas the proposed procedure could use observable crash data, IS calculations, kinetic energy or any other measure that is based on the encroachment conditions. The research team believes this is a better approach since it allows for different methods to be used and also addresses the real issue, the probability of a penetration, rather than hiding it behind engineering judgment or an assumption about the mechanics of the crash.

Task 6B6: Driver Input and Curvilinear Paths

Recommendation:	*Modify the Monet Carlo method to include driver braking and steering input. Create the facility to pass the driver inputs, terrain geometry and encroachment conditions to a look up table. The lookup table can then return the curvilinear geometry of the trajectory and indicate whether or not a rollover has occurred.*
Budgeted Cost:	*$25,000*

Currently RSAP assumes a straight-line path and no driver inputs. This has been recognized for a long time as a limitation in the code. One way to incorporate driver inputs would be to use the encroachment conditions established by the Monte Carlo simulation and pass those variables (i.e., encroachment speed and angle, vehicle type, location, etc.) to a vehicle dynamics program like HVOSM. The program could then return the swath of the vehicle and indication of whether rollover has occurred back to RSAP and RSAP would proceed as it currently does (i.e., comparing the swath to the location of hazards to determine if an impact occurred). The difficulty with this is that RSAP models tens of thousands of encroachments which would mean HVOSM would be called tens of thousands of times. This would be computational demanding in the extreme and is, therefore, not feasible.

Another approach would be to perform HVOSM runs for a broad but select number of encroachment conditions and off-road geometries and save the results in a large data table. RSAP would enter the data table with the encroachment conditions (i.e., speed, angle, vehicle type, location, etc.) and the table would encode the curvilinear swath geometry. This would be much more computationally efficient since HVOSM is never run from RSAP but the limitation would be that there would be only a fixed number of cases available in the data table. Also, the data table would probably have to be limited to a handful of roadside geometries (e.g., every conceivable slope and ditch configuration could not be reasonably be included).

Three new random numbers would have to be generated – one indicating the percent of braking (i.e., zero for no braking and 1.0 for full lockup), another indicating the percent of steering (i.e., zero for straight ahead steering and 1.0 for full steer based on the vehicle type) and the third indicating if the steering is to the left or right. RSAP would pass the driver inputs (i.e., the three randomly generated values just discussed), the encroachment conditions and the terrain geometry to the data lookup feature and the lookup feature would return the following three pieces of information:

1. A polynomial describing the leading edge of the swath,
2. A polynomial describing the opposite trailing edge of the swath and
3. An indicator for whether the vehicle rolled over or not.

In the interim, the polynomials could simply be the straight line approximations currently used resulting in what is in RSAP now (i.e., driver input is ignored). In the future, however, the data table for more complex situations could be inserted which would allow RSAP to account for the driver inputs. The basic idea is that driver inputs change the swath and affect if the vehicle will rollover or not. The program should be constructed such that these can be incorporated in the future.

TASK 6C: Validation

Task 6C1: Benchmark Cases

Recommendation:	*Develop at least five bench mark cases that will be used to validate the program as well as serve as example problems in the Roadside Design Guide.*
Budgeted Cost:	*$12,000*

Thorough testing of the updated software will be essential to ensure that the program functions as desired and produces accurate and correct results. The first step in this process will be to develop a series of standard benchmark cases that can:

(1) Be included as example problems in the RDG,
(2) Be used to validate and check the code when future improvements or enhancements are made and
(3) To validate the RSAP predictions against some real-world data sets.

The test cases will be chosen to represent common roadside design situations and they will also be chosen such that there are available crash data which can be used to validate the data. For example, the State of Washington has performed a very in-depth review of its cable median barrier policy which included collecting detailed data on all crashes involving cable median barriers in the state. Washington has a standard geometry layout for most of the installations and a good database that allows researchers to exclude non-standard installations. A benchmark problem based on the typical geometry and traffic data from Washington should, therefore, generate data that are comparable to the historical Washington State cable median barrier crash data. Such an exercise will validate RSAP and give users confidence that it generates reasonable predictions. It should be noted, however, that since RSAP is predicting crashes there is expected to be wide variation possible in the actual crash data. RSAP needs to generate a prediction that is presumably close to the mean so in accessing "validity" of RSAP the likely error bands of the observed data will also need to be addressed. For this reason, the larger the data set of observable crash data that can be used in the validation exercise the better since the observed crash rates will be more precise.

Task 6C2: Validation

Recommendation:	*Validate the updated RSAP code using the benchmarks developed in Task 6C1. Validate the benchmark examples using actual crash data and document the results of the validation effort.*

Budgeted Cost: *$15,000*

Prior to the Alpha and Beta testing, the new RSAP software will be validated by running the benchmark cases against crash-data solutions as described in the last task. The team has already observed that the test cases in the RDG do not match the current version of the software supplied with the RDG. Ultimately, the new benchmark cases can be used in future updates of the RDG.

There are 278 built-in roadside features, grouped into eight general categories, in the current RSAP program. It will not be possible to validate every one of these features within the limitations of this project so the procedure must be general enough such that users can validate features and report back to the development team or TCRS after the project is complete. In general, the police-level real world data on the crash severity distribution for a particular "type" (or “sub-type”) of roadside features, such as parallel ditches and certain types of fixed objects like utility poles, can provide us with something to check or validate against so that the overall severity outcome from the RSAP program associated with that type of roadside features is in the right order of magnitude (assuming a good underreporting correction can be made). As mentioned earlier, the only “reality check” with the real-world crash data conducted so far was by Sicking et al., (2009) for guardrails. Note that RSAP currently uses a single impact speed-SI relationship for all longitudinal barriers (Figure A.7-1). This made Sicking et al.’s calibration study relatively simpler when compared to other types of features, where the relationships are much more complex.

The final report will contain descriptions of the real-world validation exercises performed on the benchmark cases.

Task 6C3: Compare RSAP and HSM

Recommendation:	*Use the benchmark cases developed in Task 6C1 to compare the updated RSAP to the IHSDM CPM (i.e., the computer implementation of the HSM).*
Budgeted Cost:	*$5,000*

The same benchmark cases developed for Task 6C1 will be used to compare the RSAP predictions with the CPM module of the IHSDM (i.e., the software implementation of the HSM). Of particular interest will be how closely the predictions compare, where the HSM is not able to detect changes in the roadside design and estimates of the crash costs on the segments (item 3i in the RFP). The research team will document the cases and note the areas where there is both agreement and disagreement. Since the two methods are different, we expect there will also be areas which finding equivalences is not straightforward.

TASK 7: Alpha and Beta Testing

Original Statement of Work:

Conduct Alpha and Beta testing to validate the full range of updated RSAP capabilities, and revise/validate software accordingly.

Recommendation:	*Provide the source code, executable code, data tables, user's manual, engineer's manual, programmer's manual and benchmark cases on a website. Recruit at least five alpha testers to review the software and documentation and provide comments. A workshop will be held to train the alpha testers in the use of the software and to work on cases that the alpha testers bring to the workshop. Resolve any problems or inconsistencies identified by the alpha testers. When all the issues from the alpha test are resolved, open up the distribution of the website materials to a larger second group of beta testers. Another workshop will be held to train the beta testers and work on problems they bring with them to the workshop. Resolve any problems or issues identified by the beta testers. When all issues identified by the beta testers have been resolved, prepare the materials for submission to the AASHTO TCRS.*
Budgeted Cost:	*$39,816*

The purpose of this task will be to conduct alpha and beta testing of the software (item 3h in the RFP). Names of interested alpha and beta testers have already been collected during the survey process. After the research team has validated the code in Task 7A and assured that it is bug free in Task 6B3, the executable code, data tables, draft user's manual and the benchmark problems will be distributed to the panel and a select group of alpha testers to initiate the testing.

Since the improved RSAP needs to be included with the next major update of the RDG, time is critical. In order to shorten the testing period, two workshops will be held – one with alpha testers and then a follow-up session with beta testers.

About one month prior to the scheduled workshops, an email listserv and a website will be set up where versions of the code, data tables and manuals can be downloaded by testers in order to prepare for the meeting. The listserv and the website will also be used to collect user questions, comments and problems with the software and allow the research team to respond to the group. If corrections to the code, data tables or manuals are required, new versions can be posted on the website for re-downloading by the testers. The website will be constructed so that anyone can see all the comments as well as the research team's responses.

The alpha test will be comprised of the panel and no more than five external testers. The five external testers will be chosen from experienced users of RSAP. For example, National Capitol Engineering (NCE) in Canada has made extensive use of RSAP in its highway design value engineering projects. Their familiarity with all the previous versions of RSAP and their routine use of the program make them particularly good alpha testers. Similarly, Washington State DOT has had a history of using RSAP in their design decisions so they would also make a good alpha tester. There are also a number of on-going and soon to start NCHRP projects that involve or could involve RSAP and the research teams could be invited.

The workshop would focus on hands-on training in the software. The meeting would be a two-day meeting, probably at the NAS facility in Washington, D.C.. The research team would assist the alpha testers in installing and setting up the software on their own laptops. The team would go through one or two examples to show how to use the software in a tutorial type of presentation. Once the users are comfortable navigating the software, the group will be split into three or four teams of two or three people. Each team will work collaboratively on a problem. The research team will circulate among the teams assisting them and gaining feedback on the software and its features. Problems encountered, situations that are difficult to model and software errors will all be carefully documented for later resolution. At the end of the workshop, the alpha testers will be given a survey which collects feedback from them based on their experience during the workshop.

Once the research team has resolved all the issues that came up during the alpha testing, a second group of testers, the beta testers, will be identified and a second workshop scheduled. The intent is to bring back the alpha testers and add several more people to the beta test. A package of materials similar to the one provided to the alpha testers will be available (i.e., the code, the data tables, the manuals and the benchmark problems) to the beta testers prior to the meeting. The beta test workshop will proceed in a similar manner to the alpha test although the focus will be even more on working with individuals. The meeting will also likely be a two-day meeting in Washington D.C.

When the alpha and beta tests are complete and all issues have been resolved, the software will be considered complete. The software, manuals and benchmark problems will then be submitted to the AASHTO Technical Committee for Roadside Safety (TCRS) for consideration for inclusion in the next edition of the Roadside Design Guide. The panel and TCRS may want to consider maintaining some sort of website and program support after this contract is complete to both address user questions about RSAP as well as distribute new data tables that arise from future NCHRP, FHWA or user research. This would provide a way of getting the most up-to-date data out to the practitioners in the field.

For budgetary purposes it is assumed that the project will not pay alpha or beta testers to attend the workshops or for any other costs of the workshop other than the project team's travel expenses. The travel expenses of the testers and workshop (i.e., meeting space) will have to either be covered by NCHRP outside of the project or by the testers themselves.

TASK 8: Final Report

Original Statement of Work: -- Submit a final report documenting the entire research effort with appendices that include the user's manual, revised RDG Appendix A, and appropriate sections of RDG Chapter 2. The user's manual shall include several example problems with various levels of complexity. The executable software shall be submitted free of defects and viruses on DVD- or CD-ROM, with documentation and user's manual, and all source code in text file format.

Budgeted Cost: $41,816

A final report documenting the entire project will be written and delivered to the panel. The first part of the final report will be substantially the same as the interim report. The results of Phase II of the project will also be documented in the final report and the user's manual, engineer's manual and programmer's manual will be included as stand-alone appendices in the report. The User's Manual will have a section with complete and detailed descriptions of the benchmark problems developed in Task 7A and the Engineer's Manual will have a description of the validation and debugging processes. A revised version of RDG Chapter 2 and Appendix A suitable for submission to the AASHTO TCRS will be included in the appendix as well. A CD or DVD will be assembled with the final report, the input files for the benchmark cases, the source code, the executable code and all data tables. This material should also be made available on the web, perhaps at either the AASHTO or NCHRP websites.

<u>Contractual</u>

The original proposal set aside $181,340 and eight months to accomplish Tasks 6 through 8. As shown in the sections above, there is a great deal of work that needs to be accomplished to complete the remaining tasks and the research team does not believe that everything can be accomplished with the funds and time currently budgeted. The re-programming, data re-analysis and validation tasks can all proceed concurrently but will require more time than currently budgeted. The alpha and beta tests have been structured as workshops in order to reduce the amount of additional time required.

Figure 21 showed an approach for incorporating all the tasks and a revised project budget and schedule are included below in Figure 22 and 23. The revised budget adds another $200,000 to the project bringing the project total to $600,000. All the additional funding is added to Task 6 bringing the total for Task 6 (i.e., execute the plan) to $297,288. Figure 6.2 also includes a sub-budget for Task 6 showing the expected expenditures on each of the subtasks. Figure 23 is the revised project schedule. The original end-date was August 30, 2010. This has been revised by adding another 10 months to the schedule making the end-date June 30, 2011 in order to accomplish the required reviews of the final report. The program, user's manual and example problems, however, could be available to the TCRS as early as the beginning of February 2011 if the TCRS and panel wanted to expedite the process for including them into the new version of the RDG.

Figure 22. Revised Project Budget

National Cooperative Highway Research Program

ROADSIDE SAFETY ANALYSIS PROGRAM (RSAP) UPDATE

NCHRP 22-27

Malcolm H. Ray, P.E., Ph.D.
188 Staples Hill Road
Canton Maine

TOTAL BUDGET

Salaries and Wages

Name	Role	Monthly Salary	Tasks 1	2	3	4	5	6	7	8	Total Months	Total Amount	First Year Total
Malcolm H. Ray	Principal Investigator	$24,566	1.00	1.00	1.00	1.00	1.00	4.00	1.00	1.00	11.00	$270,226	
Sub-total – Salaries and Wages			24,566	24,566	24,566	24,566	24,566	98,264	24,566	24,566	11.00		$ 270,226
Fringe Benefits	(0% see note 1)		-	-	-	-	-	-	-	-			$ -
Other Direct Costs													
Travel							2,500					2,500	
AutoDesk AND license fee			3,000									3,000	
Postage/Freight/Materials/Supplies			250	250	250	250	250	250	250	250		2,000	
Subcontract to Shaw-Pin Miaou			10,000	10,000	10,000	10,000	5,000	80,000	5,000	10,000		140,000	
Subcontract to Christine Conron			7,000	7,000	12,000	7,000	10,000	43,774	5,000	7,000		98,774	
Subcontract to Stefan Nikolic			0	0	1,000	2,500	0	75,000	5,000	0		83,500	
Sub-total – Other Direct Costs													329,774
Total Direct Cost (TDC)			44,816	41,816	47,816	44,316	42,316	297,288	39,816	41,816			600,000
Modified Total Direct Cost (MTDC)			44,816	41,816	47,816	44,316	42,316	297,288	39,816	41,816			600,000
Indirect Cost	(0 % see note 2)		-	-	-	-	-	-	-	-			-
Total Annual Project Cost by Task			44,816	41,816	47,816	44,316	42,316	297,288	39,816	41,816			$ 600,000

1 All participants in this research are independent consultants so no fringe benefits are calculated.
2 All participants in this research are independent consultants so no indirect costs are calculated.

TASK 6 SUB-BUDGET

Sub-Task	Title	Amount
6A1	Program Architecture	$5,000
6A2	Data Table Specifications	$10,000
6A3	Pseudo-Code	$10,000
6A4	Re-Write Code	$60,288
6A5	Verification	$10,000
6B1	Convert Existing Tables	$10,000
6B2	Encroachment Modeling	$50,000
6B3	Multilane Adjustment Factor	$10,000
6B4	Severity Modeling	$50,000
6B5	Penetration Modeling	$25,000
6B6	Driver Input	$25,000
6C1	Benchmark Cases	$12,000
6C2	Validation	$15,000
6C3	Compare RSAP and HSM	$5,000
	Total	$297,288

Figure 23. Revised Project Schedule

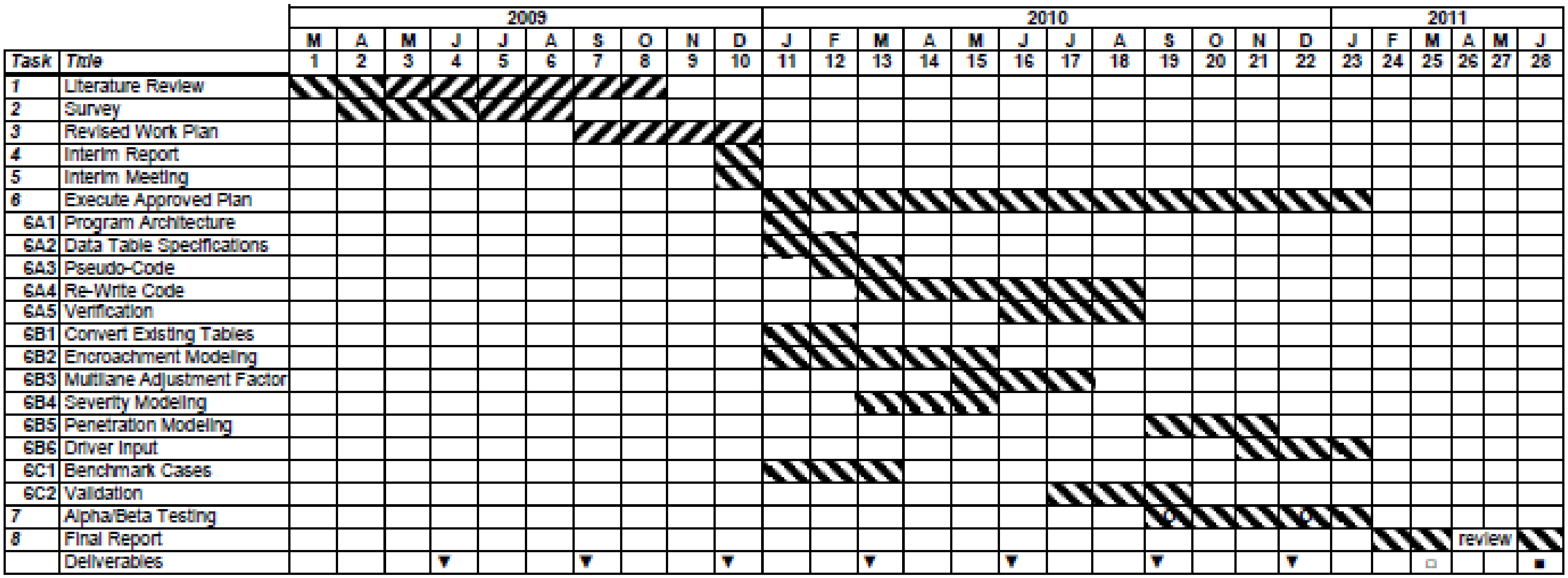
National Cooperative Highway Research Program

ROADSIDE SAFETY ANALYSIS PROGRAM (RSAP) UPDATE

NCHRP 22-27

Malcolm H. Ray, P.E., Ph.D.
186 Staples Hill Road
Canton Maine

Assumed Start Date: 1 March 2009
Assumed End Date: 30 June 2011



▼ Quarterly Report (Via e-mail, due the first week of the month)
□ Draft Final Report (due at the end of the month shown)
■ Final Report (due at the end of the month shown)
O Work shop

REFERENCES

AASHTO77 American Association of State Highway and Transportation Officials, "Guide for Selecting, Locating, and Designing Traffic Barriers," Washington, D.C., 1977.

AASHTO88 Task Force for Roadside Safety, "Roadside Design Guide," American Association of State Highway and Transportation Officials, Washington, D.C., 1988.

AASHTO89 American Association of State Highway and Transportation Officials, "Roadside Design Guide," Washington, D.C., 1989.

AASHTO96 American Association of State Highway and Transportation Officials, "Roadside Design Guide," Washington, D.C., 1996.

AASHTO01 "A Policy on Geometric Design of Highways and Streets", 4th edition", American Association of State Highway and Transportation Officials (AASHTO), Washington D.C., 2001.

AASHTO02 Task Force for Roadside Safety, "Roadside Design Guide," American Association of State Highway and Transportation Officials, Washington, D.C., 2002.

AASHTO06 Task Force for Roadside Safety, "Roadside Design Guide, 3rd edition", American Association of State Highway and Transportation Officials, Washington D.C., 2006.

AASHTO09 American Association of State Highway and Transportation Officials, " The Draft Highway Safety Manual," Washington, D.C., current as of April 6, 2009.

Agresti96 Agresti, A. *An Introduction to Categorical Data Analysis*, Wiley, New York, 1996.

Bellomo02 Bellomo-McGee and Midwest Research Institute. *Highway Safety Manual Prototype Chapter:, Two-Lane Highways.* Draft report from NCHRP Project 17-18(4). June 2002.

Bligh04 Bligh, R.P., Miaou, S-P., and Mak, K.K. Recovery Area Distance Relationships for Highway Roadside. Preliminary Draft Final Report. Prepared for National Cooperative Highway Research Program, Transportation Research Board, National Research Council, 2004.

Bligh08 Roger Bligh and Shaw-Pin Miaou, "Determination of Safe/Cost Effective Roadside Slopes and Associated Clear Distances," NCHRP Project 17-11(2), National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C., 2008.

CADALYST08 Cadalyst, http://aec.cadalyst.com/aec/News/Bentley-and-Autodesk-Join-Hands-to-Bridge-DGN-and-/ArticleStandard/Article/detail/529085, Accessed July 11, 2008

Civil3D08 http://usa.autodesk.com/adsk/servlet/index?siteID=123112&id=8777353

Cooper80 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

Council96 Council, F.M., and Stewart, J.R. Severity Indices for Roadside Objects, Transportation Research Record: Journal of the Transportation Research Board, Volume 1528, p. 87-96, 1996.

Council97 Council, F.M., Mohamedshah, Y.M., and Stewart, J.R. Effects of Air Bags on Severity Indices for Roadside Objects, Transportation Research Record: Journal

of the Transportation Research Board, Volume 1581, p. 66-71, 1997.
Crandall01 Crandall, C.S., L.M. Olson, and D. P. Sklar. Mortality Reduction with Air Bag and Seat Belt Use in Head-on Passenger Car Collisions. American Journal of Epidemiology, Vol. 153, No. 3: 219-224, 2001.
DefineThat08 http://www.definethat.com/define/113.htm
DeLeuw78 De Leuw Cather, Canada Ltd, in association with ADI Ltd., *Study of Single-Vehicle Off-Road Accidents*. Final Report. Dec. 1978.
Eastmand07 Eastman, C. M. (2007) *What is BIM?*, AEC Integration Lab, Georgia Tech, updated November 2007, [Electronic version]. Retrieved October 12, 2008 from http://bim.arch.gatech.edu/?id=402
FHWA91 *Supplemental Information for Use with the ROADSIDE Computer Program*, Federal Highway Administration,, Washington, DC, August 1991
FHWA01 Federal Highway Administration (FHWA), Roadway Shoulder Rumble Strips, Technical Advisory T 5040.35, Dec. 20, 2001. (http://www.fhwa.dot.gov/legsregs/directives/techadvs/t504035.htm)
FHWA08a http://www.fhwa.dot.gov/legsregs/directives/techadvs/t75702.htm.
FHWA08b http://safety.fhwa.dot.gov/facts/index.htm.
FHWA08c http://www.fhwa.dot.gov/VE .
FHWA08d FHWA Safety, http://safety.fhwa.dot.gov/state_program/hsip/hsip_over.htm, accessed April 17, 2008
Gaddis09 Gaddis, T., Irvine, K., *Starting Out with Visual Basic 2008*, Fourth Edition, Pearson, Addison-Wesley, Boston, MA, 2009.
Glennon74 John C. Glennon, "Roadside Safety Improvement Programs on Freeways," National Cooperative Highway Research Program Report 148, Highway Research Board, Washington, D.C., 1974.
Gabauer05 Gabauer, D.J., and H. C. Gabler. Evaluation of Threshold Values of Acceleration Severity Index by Using Event Data Recorder Technology. Paper No. 05-2220, Transportation Research Board 84^{th} Annual Meeting, Jan. 2005.
Gabauer07 Gabauer, D.J., and H. C. Gabler. Comparison of Roadside and Vehicle Crash Test Injury Criteria in Frontal Crash Tests. Paper No. 07-0975, Transportation Research Board 86^{th} Annual Meeting, Jan. 2007.
Gabauer08 Gabauer, D.J., and H. C. Gabler. Comparison of roadside and vehicle crash test injury criteria in frontal crash tests, International Journal of Vehicle Safety, Vol. 3, Number 1, 2008, p.1 – 13.
HSA66 Highway Safety Act of 1966, online version, http://www.nhtsa.dot.gov/nhtsa/whatsup/TEA21/GrantMan/ HTML/07_Sect402Leg23USC_Chap4.html, accessed October 15, 2009.
HSA73 Highway Safety Act of 1973, online version, http://www.iihs.org/research/paper_pdfs/test_19730313.pdf, accessed October 15, 2009.
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.tfhrc.gov/safety/pubs/99207/appd.htm, December 2000, accessed August 23, 2009

Harwood07 Harwood et al. *Methodology to Predict the Safety Performance of Urban and Suburban Arterials.* Final report for NCHRP Project 17-26. March 2007.

HO08 Ho, C. and C. Spence. *The Multisensory Drivers: Implications for Ergonomic Car Interface Design*. Ashgate Publishing Co. ISBN-13: 9780754670681, 2008.

HSM08 The Highway Safety Manual, http://www.wsdot.wa.gov/partners/hsm/public/ResearchProjects/ResearchProjects.html , 2008.

HSM08a Generic HSM Presentation, http://www.highwaysafetymanual.org/, November, 2008

Hughes97 Hughes, W., et al. Improved Guidelines for Median Safety. Interim Report for NCHRP Project 17-14. BMI in association with UNC-HSRC. October 1997.

Hutchinson62 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.

Hutchinson66 John W. Hutchinson and T. W. Kennedy, "Medians of divided highways – frequency and nature of vehicle encroachments," Technical Report No. 487, University of Illinois, 1966.

IHSDM08 http://www.tfhrc.gov/safety/ihsdm/ihsdm.htm

IHSDM09 Interactive Highway Safety Design Module, Crash Prediction Module Beta Version 5.3.0 (Jun 30, 2009).

Igharo04 Igharo, P.O., E. Munger, and R.W. Glad. In-Service Performance of Guardrail Terminals in Washington State. Research Report WA-RD 580.1, Washington State Department of Transportation. June 2004.

InRoads08 InRoads, http://www.bentley.com/en-US/Products/InRoads/Tech+Reqs.htm, May 3, 2008

Jaselskis04 Jaselskis, E. J., Walters, R.C., Andrle, S. J., and Harrington, D. S. (2004) *Development Of Object-Oriented Design And Specifications For Iowa Dot And Urban Standards: Phase I* , Iowa DOT Project TR-487 October, 2004.

Krammes03 Krammes, R.A., Hayden, C., "Making Two-Lane Roads Safer", *Public Roads*, US Department of Transportation, Volume 66, No 4, January/February 2003

LandXML08 http://www.landxml.org/

Lamm99 Lamm, R., Psarianos, B., Mailaender, T., *Highway Design and Traffic Safety Engineering Handbook*, McGraw-Hill, New York, 1999

Lord08 Lord et al. *Methodology to Predict the Safety Performance of Rural Multilane Highways*. Final report for NCHRP Project 17-29. Feb. 2008.

MHD08 http://www.mhd.state.ma.us/PE/WeightedAverageBook.aspx

Mak86 King Mak, Hayes E. Ross, Jr., and Eugene Buth, "Severity Measures for Roadside Objects and Features," Federal Highway Administration, Report FHWA-RD-86-019, Washington, D.C., April 1986.

Mak98 Mak, K. K., Sicking, D. L, and Zimmerman, K., "Roadside Safety Analysis Program: A Cost-Effectiveness Analysis Procedure," Transportation Research Record 1647, Transportation Research Board, Washington, D. C., 1998.

Mak02 Mak, K.K. and Sicking, D.L. Roadside Safety Analysis Program (RSAP)—User's Manual. Prepared for NCHRP Project 22-9, National Cooperative Highway Research Program, Transportation Research Board, National Research Council, 2002.

Mak03 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.

Mak09 Mak, K.K., D.L. Sicking, B.A. Coon, and F.D.B. de Albuquerque, Identification of Vehicle Impact Conditions Associated with Serious Ran-Off-Road Crashes, Draft Final Report for NCHRP Project 17-22, May 2009.

McGinnis99 McGinnis, R.G., “Reexamination of Roadside Encroachment Data,” *Transportation Research Record* 1690, Transportation Research Board, National Research Council, pp. 42-58, 1999.

McGinnis04 McGinnis, R.G. *Runout Length for Roadside Barrier Design*, Final Report for NCHRP Project 17-13 Strategic Plan for Roadside Safety. Dec. 2004.

Miaou92 Miaou, S-P., Hu, P.S., Wright, T., Rathi, A.K., and Davis, S.C. “Relationship Between Truck Accidents and Geometric Design: A Poisson Regression Approach.” *Transportation Research Record* 1376, Transportation Research Board, National Research Council, pp. 10-18, Oct. 1992.

Miaou93 Miaou, S-P., and Lum, H. “Modeling Vehicle Accidents and Highway Geometric Design Relationships.” *Accident Analysis and Prevention*, Vol. 25, No. 6, pp. 689-709, Nov. 1993.

Miaou94 Miaou, S-P. “The Relationship Between Truck Accidents and Geometric Design of Road Sections: Poisson versus Negative Binomial Regressions.” *Accident Analysis and Prevention*, Vol. 26, No. 4, pp. 471-482, Aug. 1994.

Miaou96 Miaou, S-P. ,Measuring the Goodness-of-Fit of Accident Prediction Models. FHWA-RD-96-040, Federal Highway Administration, U.S. Department of Transportation, 121pp, 1996.

Miaou97 Miaou, S-P. Estimating Vehicle Roadside Encroachment Frequencies Using Accident Prediction Models. Transportation Research Record 1599, Transportation Research Board, National Research Council, pp. 64-71., 1997

Miaou01 Miaou, S-P., Estimating Roadside Encroachment Rates with the Combined Strengths of Accident and Encroachment-Based Approaches. FHWA-RD-01-124. Federal Highway Administration, 93pp, 2001.

Miaou04 Miaou, S-P. (ed.) Rollover Causation and Mitigation Study: Phase I Report. Prepared for Federal Highway Administration, 2004.

Miaou05 Miaou, S-P., Bligh, R.P., and Lord, D. “Developing Median Barrier Installation Guidelines: A Benefit/Cost Analysis Using Texas Data.” Paper No. 05-2786. Transportation Research Record 1904**,** Transportation Research Board, National Research Council, pp.3-19, 2005.

Myer08 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

Moskowitz61 Moskowitz, K. and Schaefer, W.E., “California Highway and Public Works.” *Barrier Report*, Vol. 40, Nos. 9-10, Sept-Oct, 1961.

NCHRP17-22 NCHRP Project 17-22, “Identification of Vehicular Impact Conditions Associated with Serious Ran-Off-Road Crashes,” http://www.trb.org, (in progress).

NCHRP22-12 NCHRP Project 22-12, “Selection Criteria and Guidelines for Highway Safety Features,” http://www.trb.org, (in progress).

NCHRP17-45 NCHRP Project 17-45: Developing an enhanced safety prediction methodology and analysis tool for Freeways and Interchanges. (Effective Date: 5/11/2009 and expected completion date: 11/10/2011).

NHS95 NHS Designation Act Of 1995, online version, http://www.fhwa.dot.gov/legsregs/nhs_sec.html, accessed October 15, 2009

NHTSA07 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.

NHTSA08 National Highway Traffic Safety Administration (NHTSA), *Traffic Safety Facts 2008*, Traffic Safety Facts, Research Note DOT HS 811 100, Sept. 2009.

Philbrik08 Personal Communication, Dan Philbrick, AutoDesk, May 8, 2008

RSAP09 Roadside Safety Analysis Program, Version 2.0.3

Ray92 Malcolm H. Ray, "Conceptual Requirements for an Interactive highway Design Model," FHWA-9291-3, Federal Highway Administration, Washington, D.C., June 1992.

Ray93 Malcolm H. Ray, "Quantifying the safeness of highway design," Ph.D. dissertation, Vanderbilt University, Nashville, TN 1993.

Ray00 Ray, M.H., and J. Hopp. Performance of Breakaway Cable and Modified Eccentric Loader Terminals in Iowa and North Carolina: In-Service Evaluation. Transportation Research Record 1720, Transportation Research Board, 2000, p.44-51.

Ray01 Ray, M.H., and J.Weir. Unreported Collisions with Post-and-Beam Guardrails in Connecticut, Iowa, and North Carolina. Transportation Research Record 1743, Transportation Research Board, 2001, p.111-119.

Ray02 Ray, M.H., and Weir, J.A. Expansion and Analysis of In-Service Barrier Performance Data and Planning for Establishment of a Database. NCHRP Project 22-13(2), 2002.

Ray03 Ray, M.H., J.Weir, and J. Hopp. In-Service Performance of Traffic Barriers. NCHRP Report 490. National Cooperative Highway Research Program, Transportation Research Board, 2003.

Rodgman89 Rodgman, E., Zegeer, C., and Hummer, J. Safety Effects of Cross-Section Design for Two-Lane Roads - Data Base User's Guide. Report submitted to FHWA, Revised, November 1989.

Ross77 Hayes E. Ross, Jr., "Guide for Selecting, Locating and Designing Traffic Barrier," American Association of State Highway and Transportation Officials, Washington, D.C., 1977.

Ross91 Ross, H.E., Jr., et al., *Traffic Barriers and Control Treatments for Restricted Work Zones, Volumes I – Main Report*, NCHRP Project 17-8, Texas Transportation Institute, November 1991.

Ross93 Ross, H.E., Jr., Bligh, R.P., and Liu, J., Evaluating the Benefits of Slope Rounding. TTI Report 0468F, Final Report prepared for Minnesota Department of Transportation, Texas Transportation Institute, Texas A&M University, June 1993.

SA08 SafetyAnalyst, http://www.safetyanalyst.org/

Sicking86 Sicking, D. L., and Ross, H. E., Jr., "Benefit/Cost Analysis of Roadside Safety Alternatives," Transportation Research Record 1065, Transportation Research Board, 1986.

Sicking08 Sicking, D. L., Albuqurque, F. D. B., and Lechtenberg, K. A. Cable Median Barrier Guidelines, Final Report to the Midwest State's Regional Pooled Fund Program, Report No. TRP-03-206-08, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, December, 2008.

Sicking09 Sicking, D.L., K.A. Lechtenberg, and S. Peterson. Guidelines for Guardrail Implementation. NCHRP Report 638, prepared for NCHRP Project 22-12(2), 2009.

Sturt09 Sturt, R. and C. Fell._The relationship of injury risk to accident severity in impacts with roadside barriers, International Journal of Crashworthiness, 14(2), p.165-172, April, 2009.

Sun 06 Sun, X., Li, Y., Magri, D., Shirazi, H.H., "Application of the *Highway Safety Manual* Draft Chapter, Louisiana Experience" Transportation Research Record No. 1950, Transportation Research Board, Washington, D.C., 2006

TRIP08 http://www.tripnet.org/national/RuralRoadsPR030305.pdf

Turner94 Daniel Turner, "Severity Indices of Roadside Features," NCHRP Synthesis Report 202, National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C., 1994.

VE08 Value Engineering, http://www.fhwa.dot.gov/VE/, accessed April 21, 2008

vanSchalk04 van Schalkwyk, I., Bligh, R.P. , Alberson, D.C., Bullard, D.L., Lord, D., Miaou, S-P., Developing an In-Service Performance Evaluation (ISPE) for Roadside Safety Features in Texas. Report 0-4366-1. Texas Transportation Institute, College Station, Texas, Dec. 2004.

Washington06 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.

Weaver72 Weaver, G.D. Marquis, E.L., and Luedecke, A.R. Jr. "The Relationship of Side Slope Design to Highway," NCHRP Project 20-7, Final report on Task Order No. 2/1, Report No. 626A-1, Texas Transportation Institute, March 1972.

Wikipedia08 "Computer Aided Drafting" http://www.webopedia.com/TERM/C/CAD.html. June, 2008

Wiki09 "Program Bugs" http://en.wikipedia.org/wiki/Software_bug, July, 2009

Wooldridge03 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.

Wright76 Wright, P.H., and Robertson, L., "Priorities for Roadside Hazard Modification: A Study of 300 Fatal Roadside Object Crashes." *Traffic Engineering*, Vol. 46, No. 8, August 1976.

Zegeer81 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.

Zegeer83 Zegeer, C.V. and M.R. Parker, *Cost-Effectiveness of Counter-Measures for Utility Pole Accidents*, Federal Highway Administration Report No. FHWA-RD-83-063, Washington, DC, 1983.

Zegeer88 Zegeer, C.V., D.W. Reinfurt, J. Hummer, L. Herf, and W. Hunter, "Safety Effects of Cross-Section Design for Two-Lane Roads," *Transportation Research Record* 1195, TRB, 1988.

APPENDIX A
SEVERITY INDICES – VEHICLE SPEED RELATIONSHIPS FOR EIGHT TYPES OF ROADSIDE FEATURES IN THE RSAP 2.0.3

The impact speed-severity index (SI) relationships incorporated into the current RSAP (i.e., RSAP version 2.0.3) are presented in the following figures:

Figures A.1-1 to A.1-4: Type 1 Features, Fore-slopes (4 Charts)
Figure A.2: Type 2 Feature, Back-slopes (1 Chart)
Figure A.3: Type 3 Feature, Parallel Ditches (1 Chart)
Figures A.4-1 to A.4-3: Type 4 Features, Intersecting Slopes (3 Charts)
Figures A.5-1 to A.5-2: Type 5 Features, Fixed Objects (2 Charts)
Figure A.6: Type 6 Features, Culvert End (1 Chart)
Figure A.7-1 to A.7-2: Type 7 Features: Longitudinal Barriers (2 Chart)
Figure A.8: Type 8 Features, Terminals and Crash Cushions (1 Chart)

Figure A.7-2 is a separate set of SI values for longitudinal barriers covered in Figure A.7-1 when encroached vehicles penetrate, roll over the top of, or roll in front of the barrier. In these figures, when applicable, containment (or performance) limits and repair cost per impact for the feature are indicated. Note that trapezoidal ditches are not covered by the Type 3 features and a method to estimate crash severity for these ditches is provided in Figure A.3.

Figure A.1-1

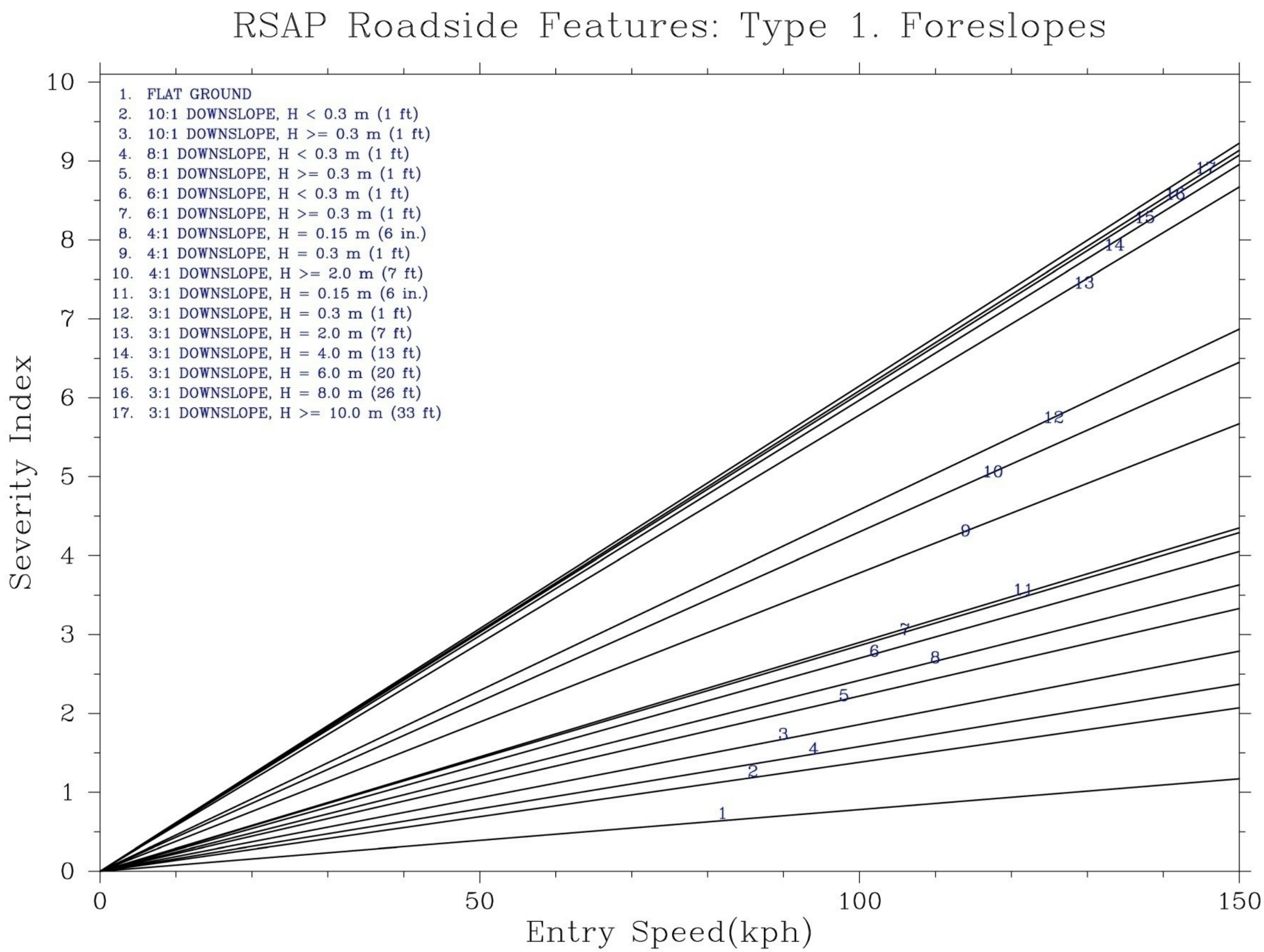

RSAP Roadside Features: Type 1. Foreslopes
1. FLAT GROUND
2. 10:1 DOWNSLOPE, H < 0.3 m (1 ft)
3. 10:1 DOWNSLOPE, H >= 0.3 m (1 ft)
4. 8:1 DOWNSLOPE, H < 0.3 m (1 ft)
5. 8:1 DOWNSLOPE, H >= 0.3 m (1 ft)
6. 6:1 DOWNSLOPE, H < 0.3 m (1 ft)
7. 6:1 DOWNSLOPE, H >= 0.3 m (1 ft)
8. 4:1 DOWNSLOPE, H = 0.15 m (6 in.)
9. 4:1 DOWNSLOPE, H = 0.3 m (1 ft)
10. 4:1 DOWNSLOPE, H >= 2.0 m (7 ft)
11. 3:1 DOWNSLOPE, H = 0.15 m (6 in.)
12. 3:1 DOWNSLOPE, H = 0.3 m (1 ft)
13. 3:1 DOWNSLOPE, H = 2.0 m (7 ft)
14. 3:1 DOWNSLOPE, H = 4.0 m (13 ft)
15. 3:1 DOWNSLOPE, H = 6.0 m (20 ft)
16. 3:1 DOWNSLOPE, H = 8.0 m (26 ft)
17. 3:1 DOWNSLOPE, H >= 10.0 m (33 ft)
Severity Index
Entry Speed(kph)
0
50
100
150
0
1
2
3
4
5
6
7
8
9
10

Figure A.1-2

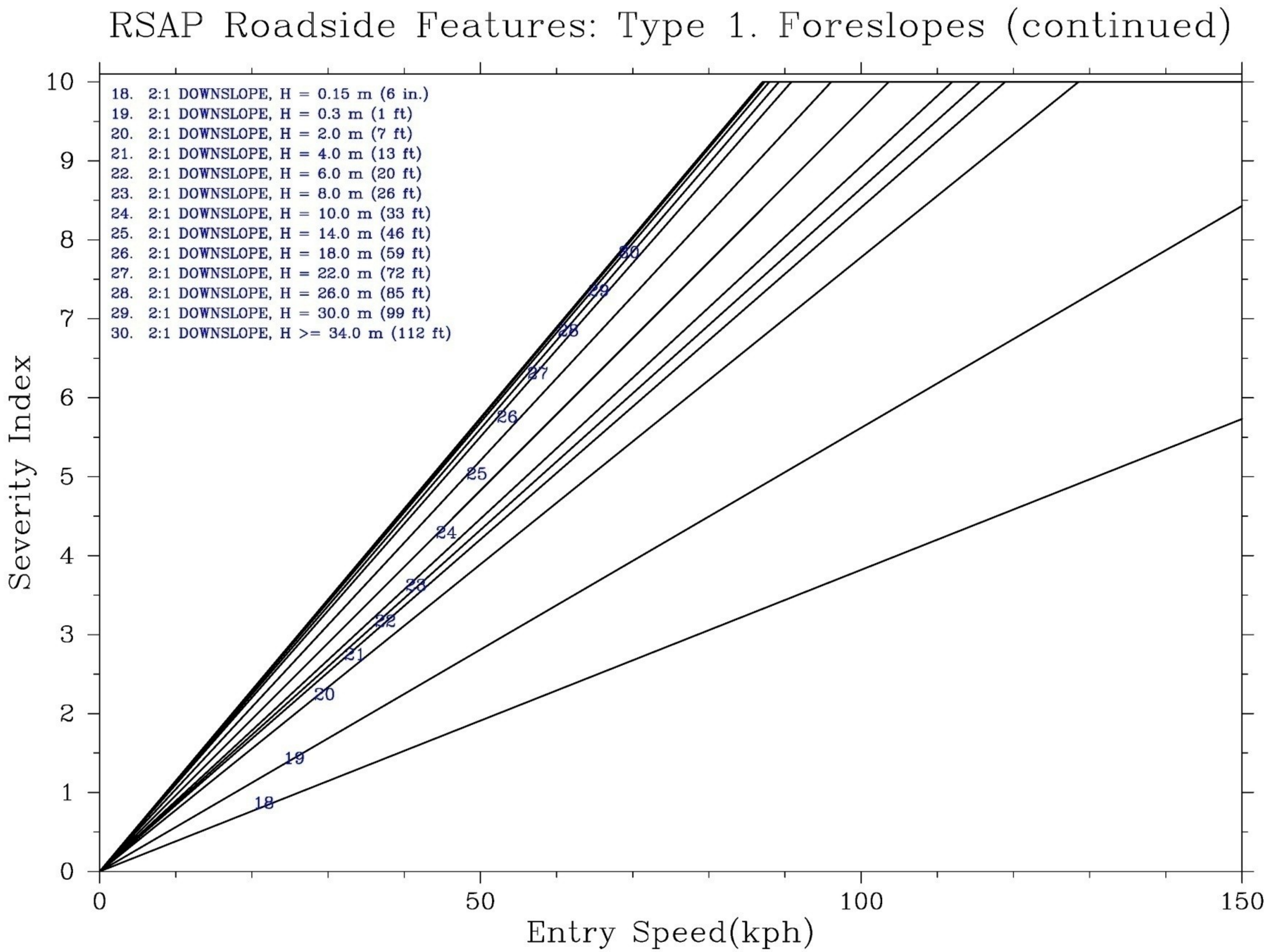
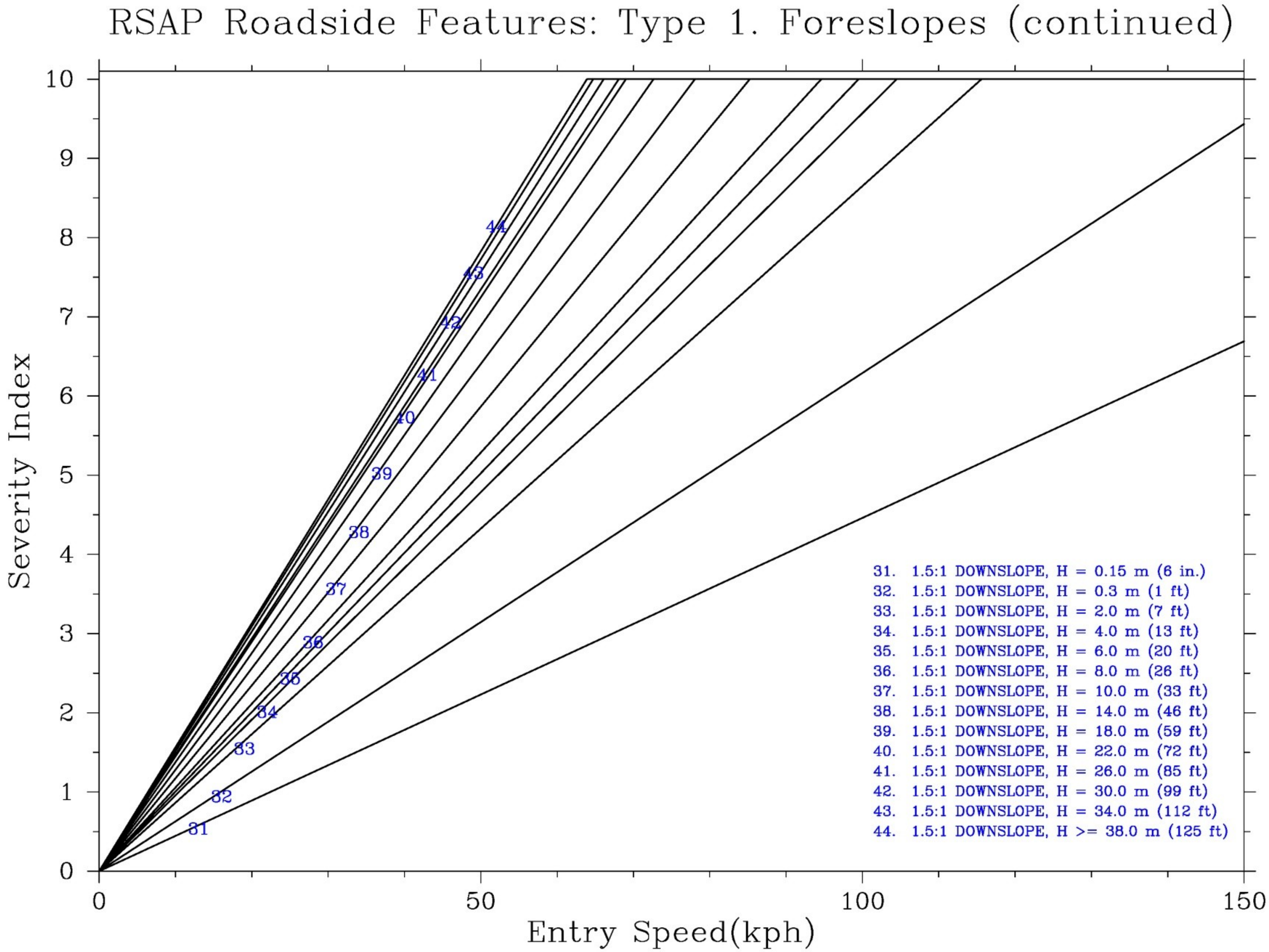

RSAP Roadside Features: Type 1. Foreslopes (continued)
18. 2:1 DOWNSLOPE, H = 0.15 m (6 in.)
19. 2:1 DOWNSLOPE, H = 0.3 m (1 ft)
20. 2:1 DOWNSLOPE, H = 2.0 m (7 ft)
21. 2:1 DOWNSLOPE, H = 4.0 m (13 ft)
22. 2:1 DOWNSLOPE, H = 6.0 m (20 ft)
23. 2:1 DOWNSLOPE, H = 8.0 m (26 ft)
24. 2:1 DOWNSLOPE, H = 10.0 m (33 ft)
25. 2:1 DOWNSLOPE, H = 14.0 m (46 ft)
26. 2:1 DOWNSLOPE, H = 18.0 m (59 ft)
27. 2:1 DOWNSLOPE, H = 22.0 m (72 ft)
28. 2:1 DOWNSLOPE, H = 26.0 m (85 ft)
29. 2:1 DOWNSLOPE, H = 30.0 m (99 ft)
30. 2:1 DOWNSLOPE, H >= 34.0 m (112 ft)
Severity Index
Entry Speed(kph)
0
1
2
3
4
5
6
7
8
9
10
0
50
100
150
18
19
20
21
22
23
24
25
26
27
28
29
30

Figure A.1-3



RSAP Roadside Features: Type 1. Foreslopes (continued)
Severity Index
Entry Speed(kph)
0
1
2
3
4
5
6
7
8
9
10
0
50
100
150
31
32
33
34
35
36
37
38
39
40
41
42
43
44
31. 1.5:1 DOWNSLOPE, H = 0.15 m (6 in.)
32. 1.5:1 DOWNSLOPE, H = 0.3 m (1 ft)
33. 1.5:1 DOWNSLOPE, H = 2.0 m (7 ft)
34. 1.5:1 DOWNSLOPE, H = 4.0 m (13 ft)
35. 1.5:1 DOWNSLOPE, H = 6.0 m (20 ft)
36. 1.5:1 DOWNSLOPE, H = 8.0 m (26 ft)
37. 1.5:1 DOWNSLOPE, H = 10.0 m (33 ft)
38. 1.5:1 DOWNSLOPE, H = 14.0 m (46 ft)
39. 1.5:1 DOWNSLOPE, H = 18.0 m (59 ft)
40. 1.5:1 DOWNSLOPE, H = 22.0 m (72 ft)
41. 1.5:1 DOWNSLOPE, H = 26.0 m (85 ft)
42. 1.5:1 DOWNSLOPE, H = 30.0 m (99 ft)
43. 1.5:1 DOWNSLOPE, H = 34.0 m (112 ft)
44. 1.5:1 DOWNSLOPE, H >= 38.0 m (125 ft)

Figure A.1-4

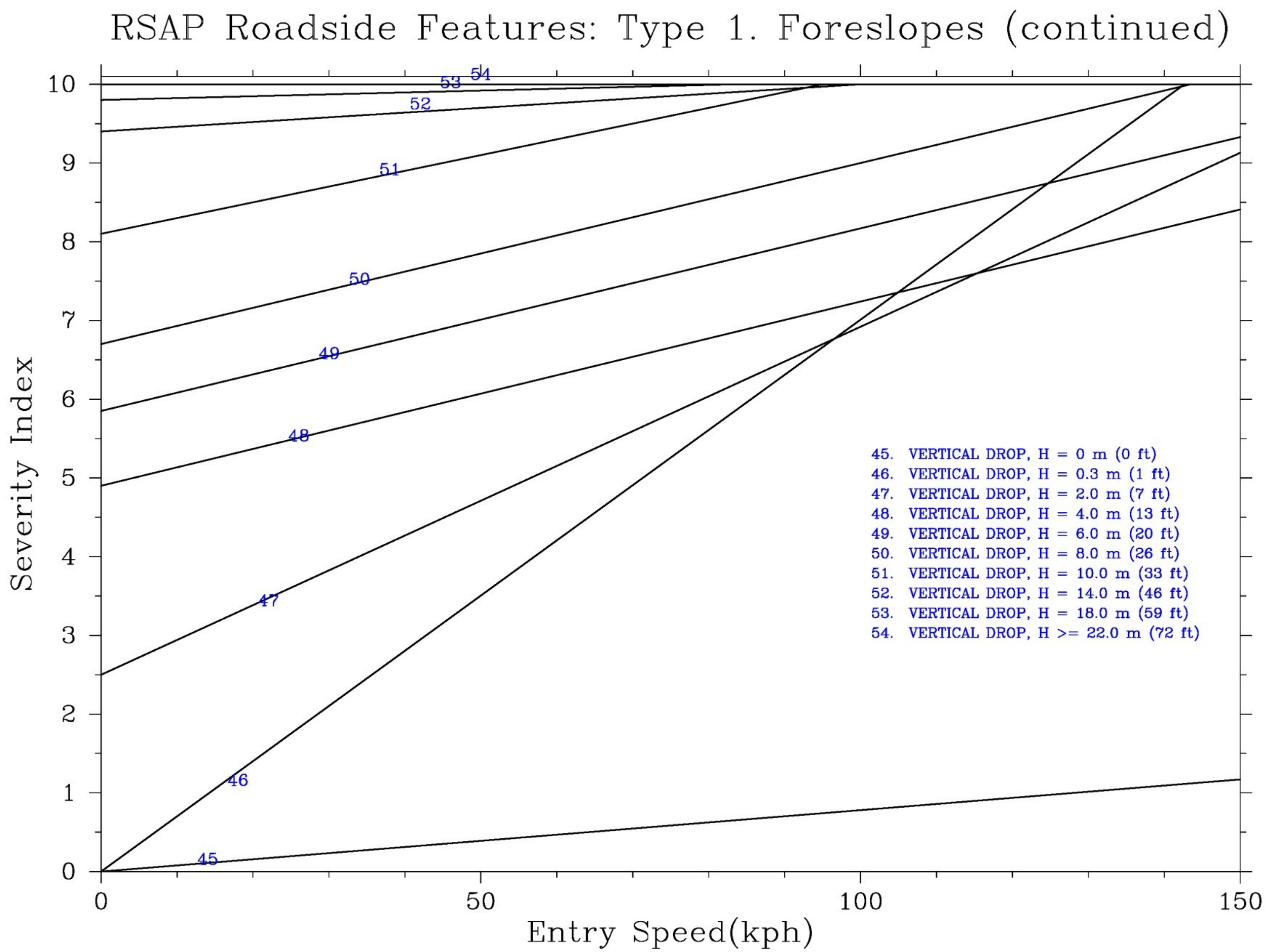

RSAP Roadside Features: Type 1. Foreslopes (continued)
Severity Index
Entry Speed(kph)
0
1
2
3
4
5
6
7
8
9
10
0
50
100
150
45
46
47
48
49
50
51
52
53
54
45. VERTICAL DROP, H = 0 m (0 ft)
46. VERTICAL DROP, H = 0.3 m (1 ft)
47. VERTICAL DROP, H = 2.0 m (7 ft)
48. VERTICAL DROP, H = 4.0 m (13 ft)
49. VERTICAL DROP, H = 6.0 m (20 ft)
50. VERTICAL DROP, H = 8.0 m (26 ft)
51. VERTICAL DROP, H = 10.0 m (33 ft)
52. VERTICAL DROP, H = 14.0 m (46 ft)
53. VERTICAL DROP, H = 18.0 m (59 ft)
54. VERTICAL DROP, H >= 22.0 m (72 ft)

Figure A.2

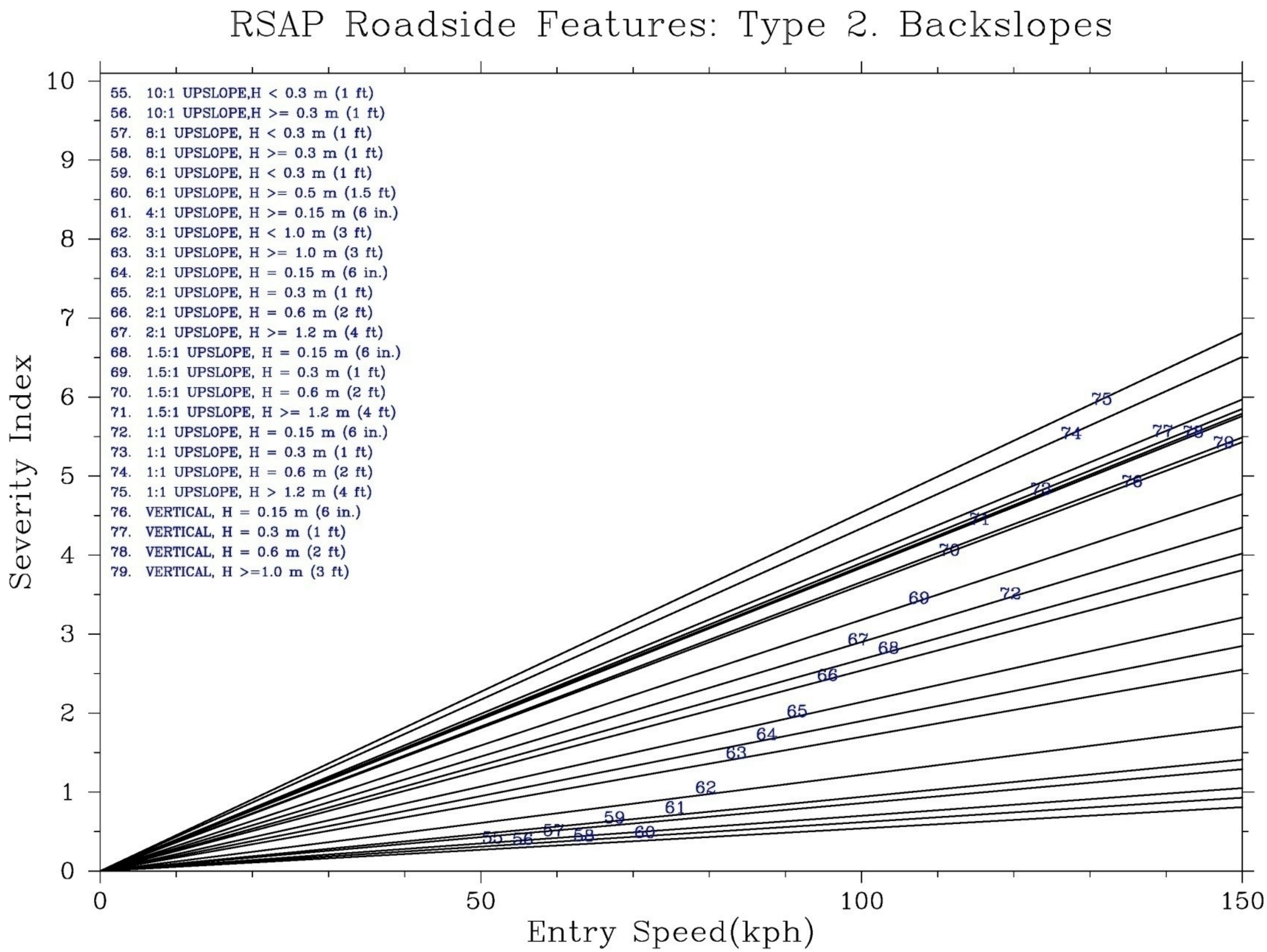

RSAP Roadside Features: Type 2. Backslopes
55. 10:1 UPSLOPE,H < 0.3 m (1 ft)
56. 10:1 UPSLOPE,H >= 0.3 m (1 ft)
57. 8:1 UPSLOPE, H < 0.3 m (1 ft)
58. 8:1 UPSLOPE, H >= 0.3 m (1 ft)
59. 6:1 UPSLOPE, H < 0.3 m (1 ft)
60. 6:1 UPSLOPE, H >= 0.5 m (1.5 ft)
61. 4:1 UPSLOPE, H >= 0.15 m (6 in.)
62. 3:1 UPSLOPE, H < 1.0 m (3 ft)
63. 3:1 UPSLOPE, H >= 1.0 m (3 ft)
64. 2:1 UPSLOPE, H = 0.15 m (6 in.)
65. 2:1 UPSLOPE, H = 0.3 m (1 ft)
66. 2:1 UPSLOPE, H = 0.6 m (2 ft)
67. 2:1 UPSLOPE, H >= 1.2 m (4 ft)
68. 1.5:1 UPSLOPE, H = 0.15 m (6 in.)
69. 1.5:1 UPSLOPE, H = 0.3 m (1 ft)
70. 1.5:1 UPSLOPE, H = 0.6 m (2 ft)
71. 1.5:1 UPSLOPE, H >= 1.2 m (4 ft)
72. 1:1 UPSLOPE, H = 0.15 m (6 in.)
73. 1:1 UPSLOPE, H = 0.3 m (1 ft)
74. 1:1 UPSLOPE, H = 0.6 m (2 ft)
75. 1:1 UPSLOPE, H > 1.2 m (4 ft)
76. VERTICAL, H = 0.15 m (6 in.)
77. VERTICAL, H = 0.3 m (1 ft)
78. VERTICAL, H = 0.6 m (2 ft)
79. VERTICAL, H >=1.0 m (3 ft)
Severity Index
Entry Speed(kph)
0
1
2
3
4
5
6
7
8
9
10
0
50
100
150

Figure A.3

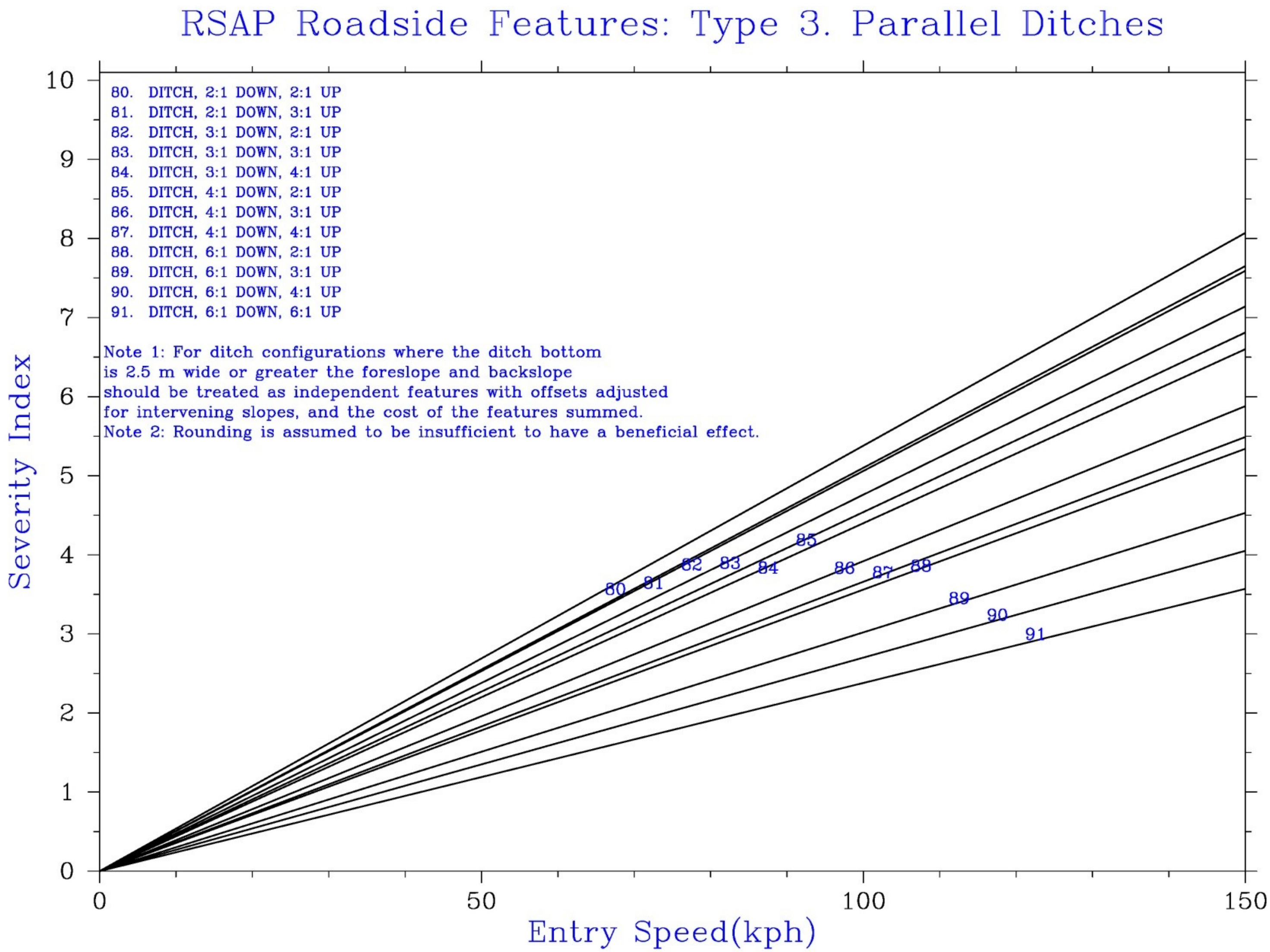

RSAP Roadside Features: Type 3. Parallel Ditches
80. DITCH, 2:1 DOWN, 2:1 UP
81. DITCH, 2:1 DOWN, 3:1 UP
82. DITCH, 3:1 DOWN, 2:1 UP
83. DITCH, 3:1 DOWN, 3:1 UP
84. DITCH, 3:1 DOWN, 4:1 UP
85. DITCH, 4:1 DOWN, 2:1 UP
86. DITCH, 4:1 DOWN, 3:1 UP
87. DITCH, 4:1 DOWN, 4:1 UP
88. DITCH, 6:1 DOWN, 2:1 UP
89. DITCH, 6:1 DOWN, 3:1 UP
90. DITCH, 6:1 DOWN, 4:1 UP
91. DITCH, 6:1 DOWN, 6:1 UP
Note 1: For ditch configurations where the ditch bottom
is 2.5 m wide or greater the foreslope and backslope
should be treated as independent features with offsets adjusted
for intervening slopes, and the cost of the features summed.
Note 2: Rounding is assumed to be insufficient to have a beneficial effect.
Severity Index
Entry Speed(kph)
0
1
2
3
4
5
6
7
8
9
10
0
50
100
150
80
81
82
83
84
85
86
87
88
89
90
91

Figure A.4-1

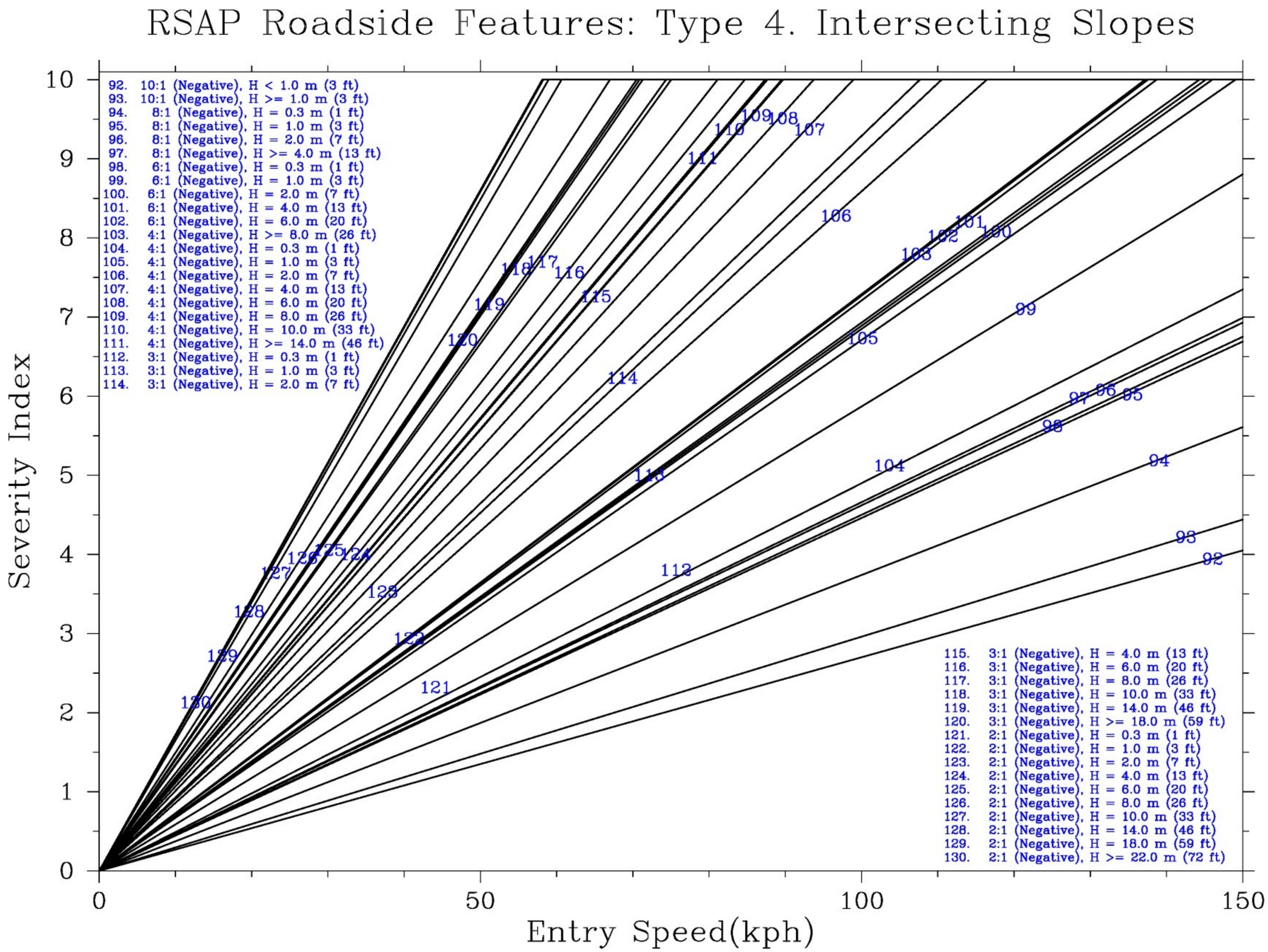
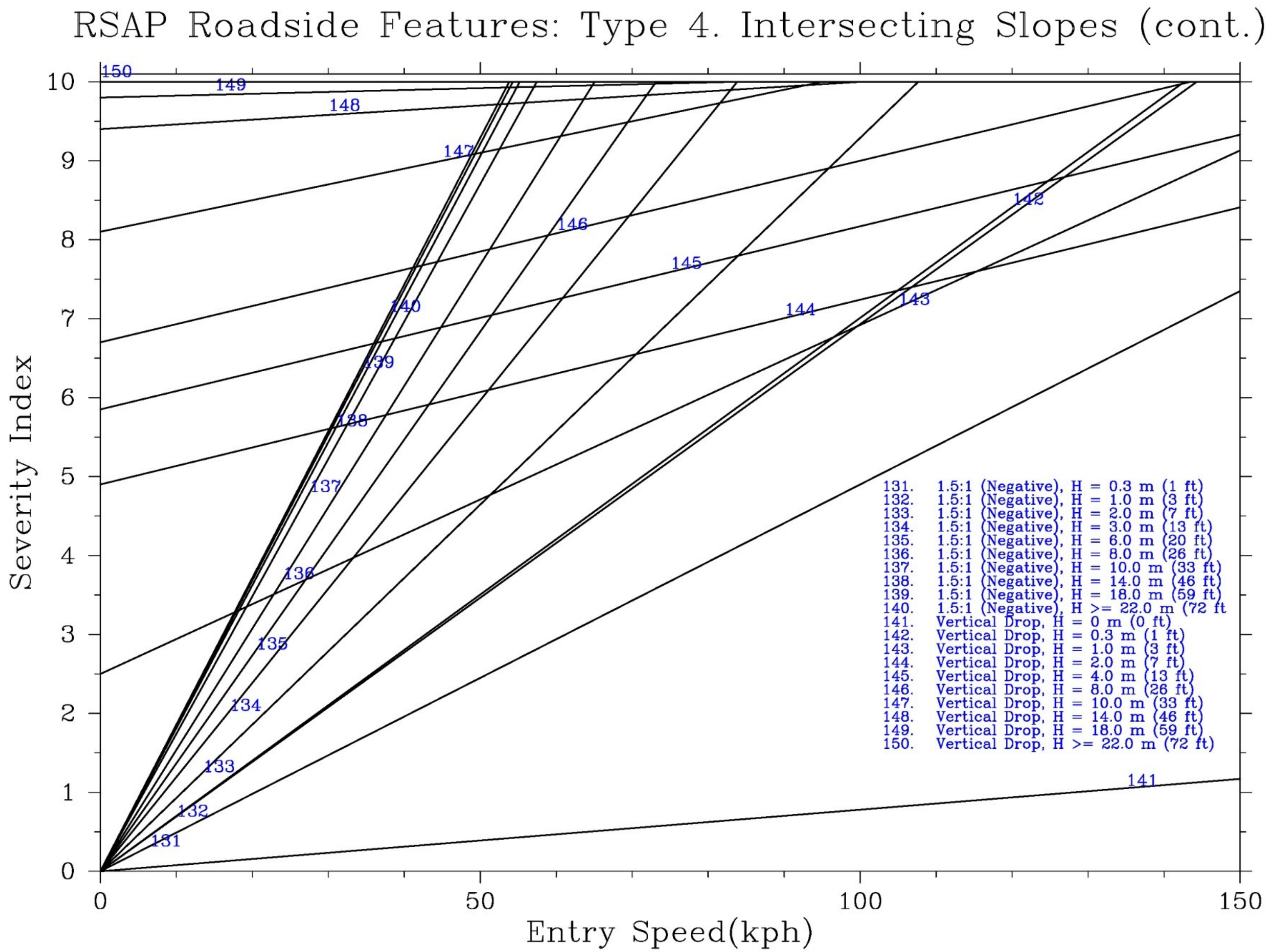

RSAP Roadside Features: Type 4. Intersecting Slopes
Severity Index
Entry Speed(kph)
0
1
2
3
4
5
6
7
8
9
10
0
50
100
150
92. 10:1 (Negative), H < 1.0 m (3 ft)
93. 10:1 (Negative), H >= 1.0 m (3 ft)
94. 8:1 (Negative), H = 0.3 m (1 ft)
95. 8:1 (Negative), H = 1.0 m (3 ft)
96. 8:1 (Negative), H = 2.0 m (7 ft)
97. 8:1 (Negative), H >= 4.0 m (13 ft)
98. 6:1 (Negative), H = 0.3 m (1 ft)
99. 6:1 (Negative), H = 1.0 m (3 ft)
100. 6:1 (Negative), H = 2.0 m (7 ft)
101. 6:1 (Negative), H = 4.0 m (13 ft)
102. 6:1 (Negative), H = 6.0 m (20 ft)
103. 4:1 (Negative), H >= 8.0 m (26 ft)
104. 4:1 (Negative), H = 0.3 m (1 ft)
105. 4:1 (Negative), H = 1.0 m (3 ft)
106. 4:1 (Negative), H = 2.0 m (7 ft)
107. 4:1 (Negative), H = 4.0 m (13 ft)
108. 4:1 (Negative), H = 6.0 m (20 ft)
109. 4:1 (Negative), H = 8.0 m (26 ft)
110. 4:1 (Negative), H = 10.0 m (33 ft)
111. 4:1 (Negative), H >= 14.0 m (46 ft)
112. 3:1 (Negative), H = 0.3 m (1 ft)
113. 3:1 (Negative), H = 1.0 m (3 ft)
114. 3:1 (Negative), H = 2.0 m (7 ft)
115. 3:1 (Negative), H = 4.0 m (13 ft)
116. 3:1 (Negative), H = 6.0 m (20 ft)
117. 3:1 (Negative), H = 8.0 m (26 ft)
118. 3:1 (Negative), H = 10.0 m (33 ft)
119. 3:1 (Negative), H = 14.0 m (46 ft)
120. 3:1 (Negative), H >= 18.0 m (59 ft)
121. 2:1 (Negative), H = 0.3 m (1 ft)
122. 2:1 (Negative), H = 1.0 m (3 ft)
123. 2:1 (Negative), H = 2.0 m (7 ft)
124. 2:1 (Negative), H = 4.0 m (13 ft)
125. 2:1 (Negative), H = 6.0 m (20 ft)
126. 2:1 (Negative), H = 8.0 m (26 ft)
127. 2:1 (Negative), H = 10.0 m (33 ft)
128. 2:1 (Negative), H = 14.0 m (46 ft)
129. 2:1 (Negative), H = 18.0 m (59 ft)
130. 2:1 (Negative), H >= 22.0 m (72 ft)

Figure A.4-2



RSAP Roadside Features: Type 4. Intersecting Slopes (cont.)
Severity Index
Entry Speed(kph)
131. 1.5:1 (Negative), H = 0.3 m (1 ft)
132. 1.5:1 (Negative), H = 1.0 m (3 ft)
133. 1.5:1 (Negative), H = 2.0 m (7 ft)
134. 1.5:1 (Negative), H = 3.0 m (13 ft)
135. 1.5:1 (Negative), H = 6.0 m (20 ft)
136. 1.5:1 (Negative), H = 8.0 m (26 ft)
137. 1.5:1 (Negative), H = 10.0 m (33 ft)
138. 1.5:1 (Negative), H = 14.0 m (46 ft)
139. 1.5:1 (Negative), H = 18.0 m (59 ft)
140. 1.5:1 (Negative), H >= 22.0 m (72 ft
141. Vertical Drop, H = 0 m (0 ft)
142. Vertical Drop, H = 0.3 m (1 ft)
143. Vertical Drop, H = 1.0 m (3 ft)
144. Vertical Drop, H = 2.0 m (7 ft)
145. Vertical Drop, H = 4.0 m (13 ft)
146. Vertical Drop, H = 8.0 m (26 ft)
147. Vertical Drop, H = 10.0 m (33 ft)
148. Vertical Drop, H = 14.0 m (46 ft)
149. Vertical Drop, H = 18.0 m (59 ft)
150. Vertical Drop, H >= 22.0 m (72 ft)

Figure A.4-3

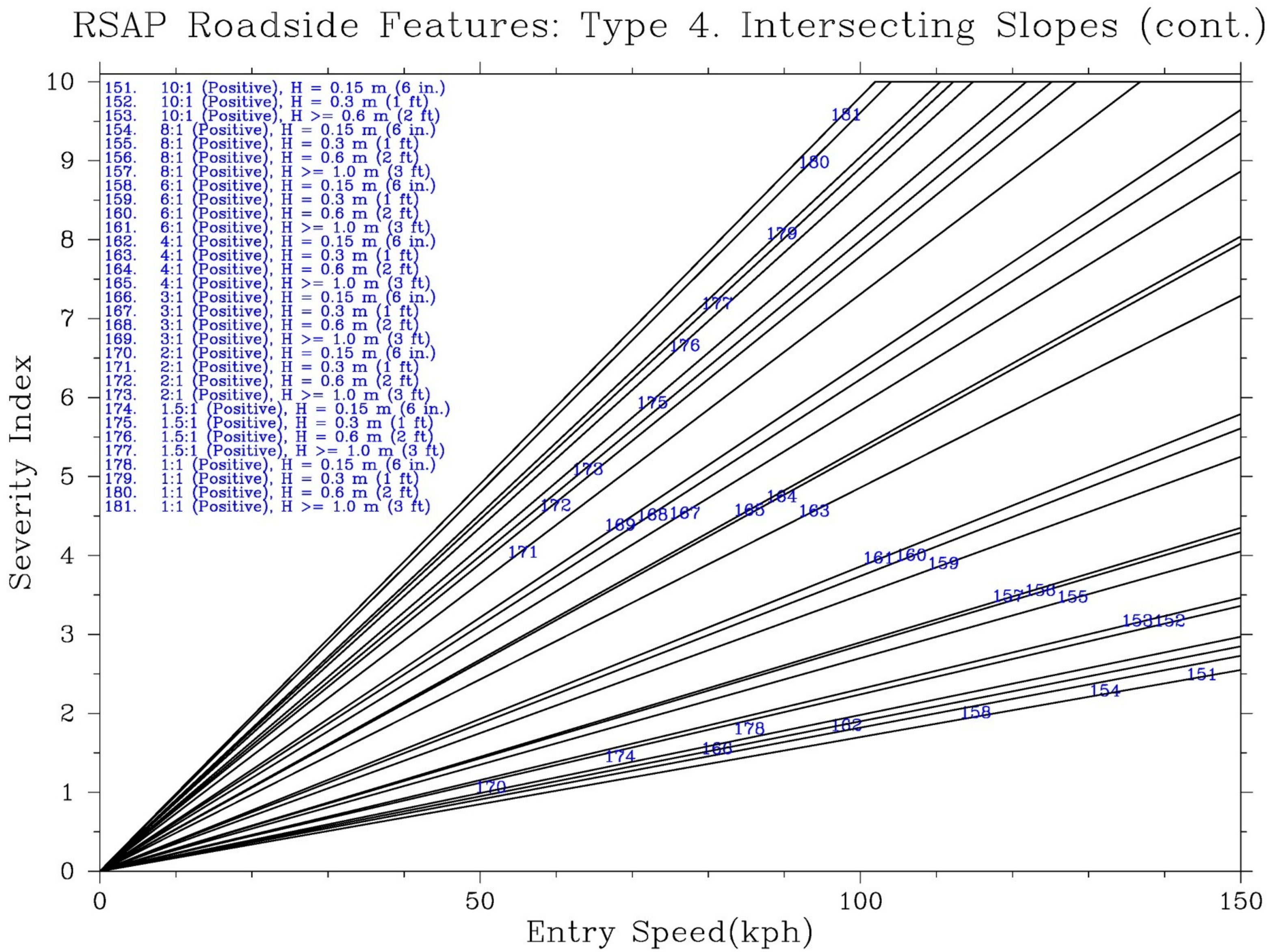

RSAP Roadside Features: Type 4. Intersecting Slopes (cont.)
151. 10:1 (Positive), H = 0.15 m (6 in.)
152. 10:1 (Positive), H = 0.3 m (1 ft)
153. 10:1 (Positive), H >= 0.6 m (2 ft)
154. 8:1 (Positive), H = 0.15 m (6 in.)
155. 8:1 (Positive), H = 0.3 m (1 ft)
156. 8:1 (Positive), H = 0.6 m (2 ft)
157. 8:1 (Positive), H >= 1.0 m (3 ft)
158. 6:1 (Positive), H = 0.15 m (6 in.)
159. 6:1 (Positive), H = 0.3 m (1 ft)
160. 6:1 (Positive), H = 0.6 m (2 ft)
161. 6:1 (Positive), H >= 1.0 m (3 ft)
162. 4:1 (Positive), H = 0.15 m (6 in.)
163. 4:1 (Positive), H = 0.3 m (1 ft)
164. 4:1 (Positive), H = 0.6 m (2 ft)
165. 4:1 (Positive), H >= 1.0 m (3 ft)
166. 3:1 (Positive), H = 0.15 m (6 in.)
167. 3:1 (Positive), H = 0.3 m (1 ft)
168. 3:1 (Positive), H = 0.6 m (2 ft)
169. 3:1 (Positive), H >= 1.0 m (3 ft)
170. 2:1 (Positive), H = 0.15 m (6 in.)
171. 2:1 (Positive), H = 0.3 m (1 ft)
172. 2:1 (Positive), H = 0.6 m (2 ft)
173. 2:1 (Positive), H >= 1.0 m (3 ft)
174. 1.5:1 (Positive), H = 0.15 m (6 in.)
175. 1.5:1 (Positive), H = 0.3 m (1 ft)
176. 1.5:1 (Positive), H = 0.6 m (2 ft)
177. 1.5:1 (Positive), H >= 1.0 m (3 ft)
178. 1:1 (Positive), H = 0.15 m (6 in.)
179. 1:1 (Positive), H = 0.3 m (1 ft)
180. 1:1 (Positive), H = 0.6 m (2 ft)
181. 1:1 (Positive), H >= 1.0 m (3 ft)
Severity Index
Entry Speed(kph)
0
1
2
3
4
5
6
7
8
9
10
0
50
100
150

Figure A.5-1

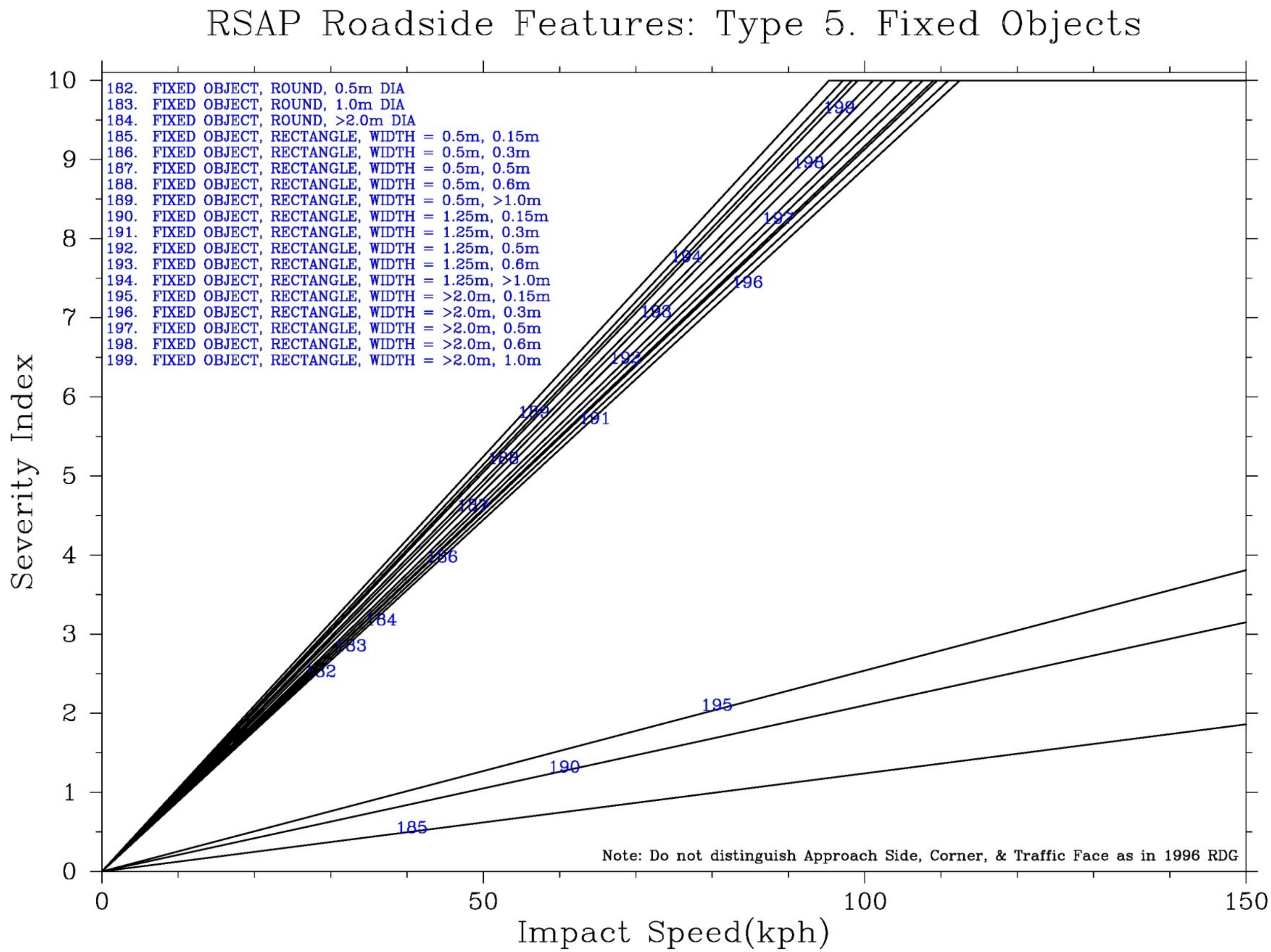
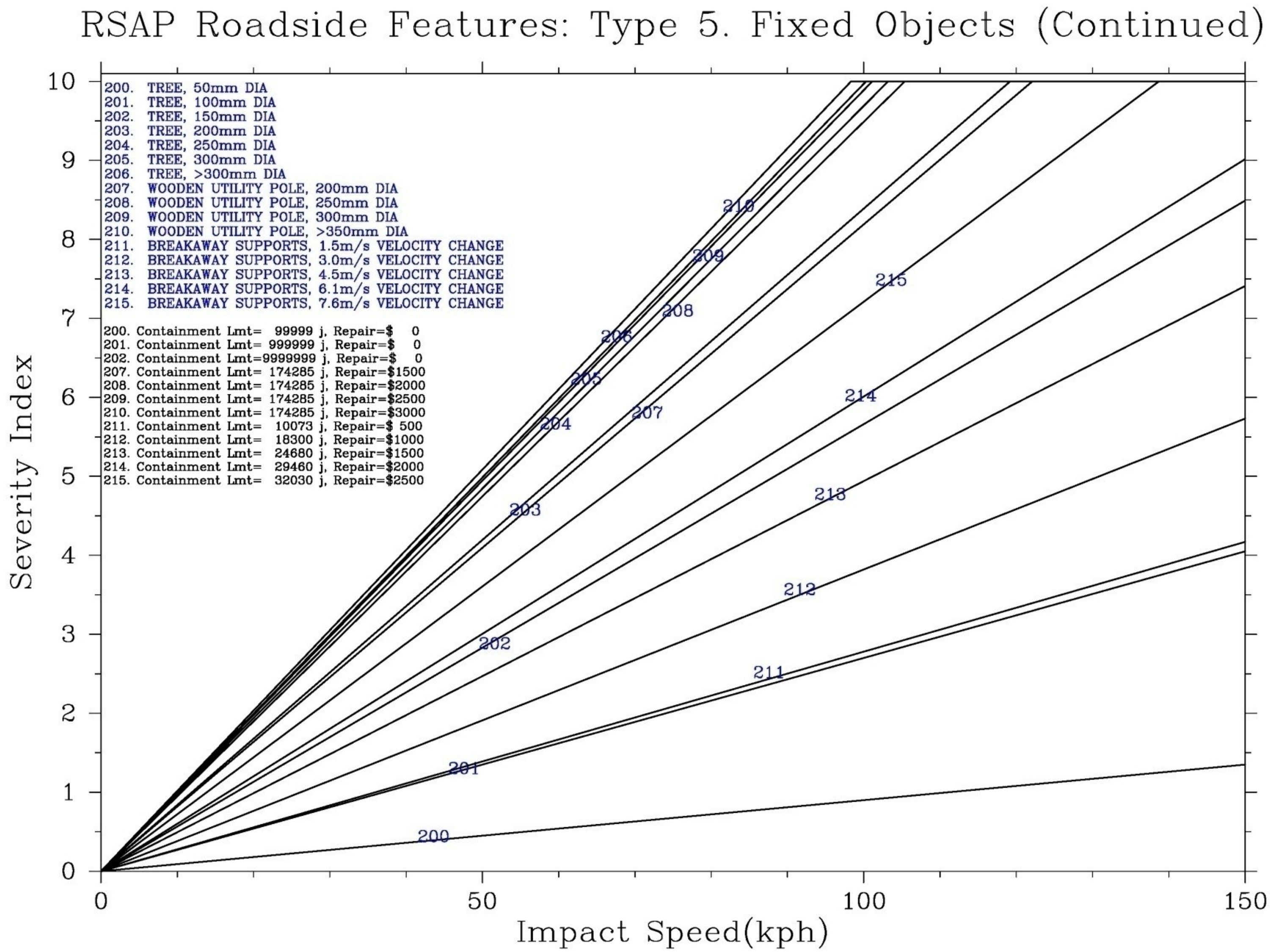

RSAP Roadside Features: Type 5. Fixed Objects
182. FIXED OBJECT, ROUND, 0.5m DIA
183. FIXED OBJECT, ROUND, 1.0m DIA
184. FIXED OBJECT, ROUND, >2.0m DIA
185. FIXED OBJECT, RECTANGLE, WIDTH = 0.5m, 0.15m
186. FIXED OBJECT, RECTANGLE, WIDTH = 0.5m, 0.3m
187. FIXED OBJECT, RECTANGLE, WIDTH = 0.5m, 0.5m
188. FIXED OBJECT, RECTANGLE, WIDTH = 0.5m, 0.6m
189. FIXED OBJECT, RECTANGLE, WIDTH = 0.5m, >1.0m
190. FIXED OBJECT, RECTANGLE, WIDTH = 1.25m, 0.15m
191. FIXED OBJECT, RECTANGLE, WIDTH = 1.25m, 0.3m
192. FIXED OBJECT, RECTANGLE, WIDTH = 1.25m, 0.5m
193. FIXED OBJECT, RECTANGLE, WIDTH = 1.25m, 0.6m
194. FIXED OBJECT, RECTANGLE, WIDTH = 1.25m, >1.0m
195. FIXED OBJECT, RECTANGLE, WIDTH = >2.0m, 0.15m
196. FIXED OBJECT, RECTANGLE, WIDTH = >2.0m, 0.3m
197. FIXED OBJECT, RECTANGLE, WIDTH = >2.0m, 0.5m
198. FIXED OBJECT, RECTANGLE, WIDTH = >2.0m, 0.6m
199. FIXED OBJECT, RECTANGLE, WIDTH = >2.0m, 1.0m
Severity Index
Impact Speed(kph)
0
50
100
150
0
1
2
3
4
5
6
7
8
9
10
Note: Do not distinguish Approach Side, Corner, & Traffic Face as in 1996 RDG

Figure A.5-2



RSAP Roadside Features: Type 5. Fixed Objects (Continued)
200. TREE, 50mm DIA
201. TREE, 100mm DIA
202. TREE, 150mm DIA
203. TREE, 200mm DIA
204. TREE, 250mm DIA
205. TREE, 300mm DIA
206. TREE, >300mm DIA
207. WOODEN UTILITY POLE, 200mm DIA
208. WOODEN UTILITY POLE, 250mm DIA
209. WOODEN UTILITY POLE, 300mm DIA
210. WOODEN UTILITY POLE, >350mm DIA
211. BREAKAWAY SUPPORTS, 1.5m/s VELOCITY CHANGE
212. BREAKAWAY SUPPORTS, 3.0m/s VELOCITY CHANGE
213. BREAKAWAY SUPPORTS, 4.5m/s VELOCITY CHANGE
214. BREAKAWAY SUPPORTS, 6.1m/s VELOCITY CHANGE
215. BREAKAWAY SUPPORTS, 7.6m/s VELOCITY CHANGE
200. Containment Lmt= 99999 j, Repair=$ 0
201. Containment Lmt= 999999 j, Repair=$ 0
202. Containment Lmt=9999999 j, Repair=$ 0
207. Containment Lmt= 174285 j, Repair=$1500
208. Containment Lmt= 174285 j, Repair=$2000
209. Containment Lmt= 174285 j, Repair=$2500
210. Containment Lmt= 174285 j, Repair=$3000
211. Containment Lmt= 10073 j, Repair=$ 500
212. Containment Lmt= 18300 j, Repair=$1000
213. Containment Lmt= 24680 j, Repair=$1500
214. Containment Lmt= 29460 j, Repair=$2000
215. Containment Lmt= 32030 j, Repair=$2500
Severity Index
Impact Speed(kph)
0
1
2
3
4
5
6
7
8
9
10
0
50
100
150
200
201
202
203
204
205
206
207
208
209
210
211
212
213
214
215

Figure A.6

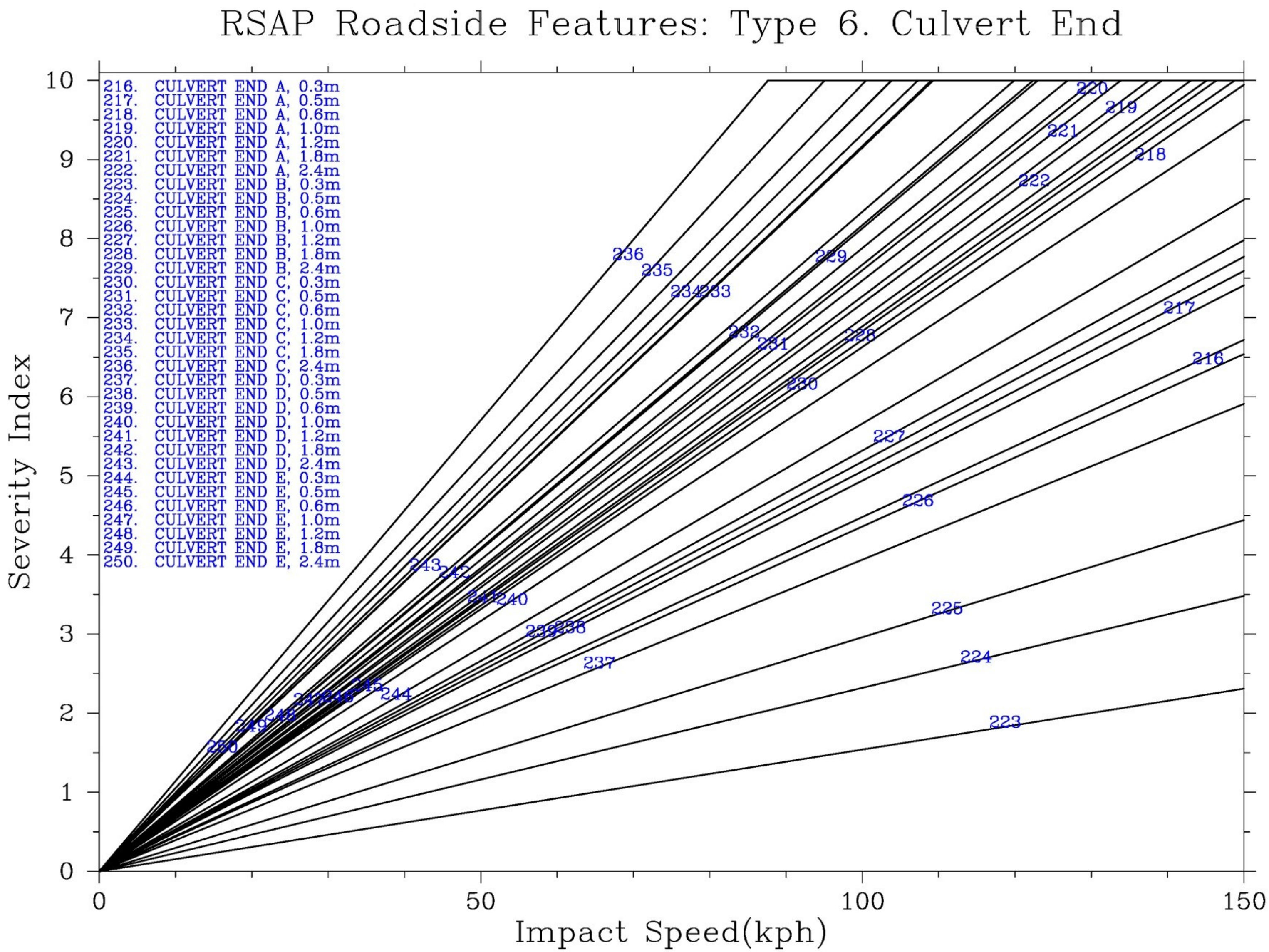

RSAP Roadside Features: Type 6. Culvert End
216. CULVERT END A, 0.3m
217. CULVERT END A, 0.5m
218. CULVERT END A, 0.6m
219. CULVERT END A, 1.0m
220. CULVERT END A, 1.2m
221. CULVERT END A, 1.8m
222. CULVERT END A, 2.4m
223. CULVERT END B, 0.3m
224. CULVERT END B, 0.5m
225. CULVERT END B, 0.6m
226. CULVERT END B, 1.0m
227. CULVERT END B, 1.2m
228. CULVERT END B, 1.8m
229. CULVERT END B, 2.4m
230. CULVERT END C, 0.3m
231. CULVERT END C, 0.5m
232. CULVERT END C, 0.6m
233. CULVERT END C, 1.0m
234. CULVERT END C, 1.2m
235. CULVERT END C, 1.8m
236. CULVERT END C, 2.4m
237. CULVERT END D, 0.3m
238. CULVERT END D, 0.5m
239. CULVERT END D, 0.6m
240. CULVERT END D, 1.0m
241. CULVERT END D, 1.2m
242. CULVERT END D, 1.8m
243. CULVERT END D, 2.4m
244. CULVERT END E, 0.3m
245. CULVERT END E, 0.5m
246. CULVERT END E, 0.6m
247. CULVERT END E, 1.0m
248. CULVERT END E, 1.2m
249. CULVERT END E, 1.8m
250. CULVERT END E, 2.4m
Severity Index
Impact Speed(kph)
0
50
100
150
1
2
3
4
5
6
7
8
9
10

Figure A.7-1

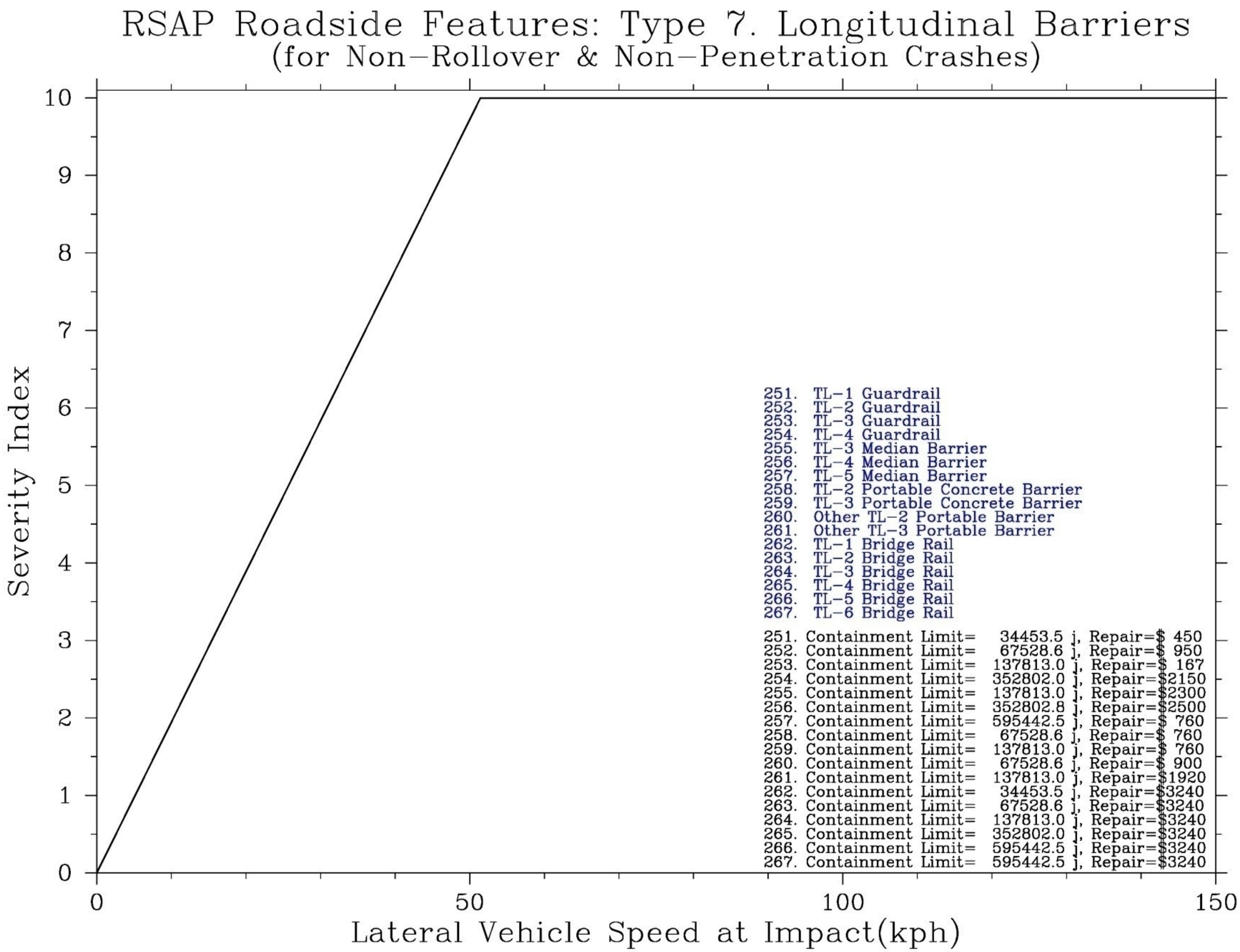

RSAP Roadside Features: Type 7. Longitudinal Barriers
(for Non−Rollover & Non−Penetration Crashes)
Severity Index
0
1
2
3
4
5
6
7
8
9
10
0
50
100
150
Lateral Vehicle Speed at Impact(kph)
251. TL−1 Guardrail
252. TL−2 Guardrail
253. TL−3 Guardrail
254. TL−4 Guardrail
255. TL−3 Median Barrier
256. TL−4 Median Barrier
257. TL−5 Median Barrier
258. TL−2 Portable Concrete Barrier
259. TL−3 Portable Concrete Barrier
260. Other TL−2 Portable Barrier
261. Other TL−3 Portable Barrier
262. TL−1 Bridge Rail
263. TL−2 Bridge Rail
264. TL−3 Bridge Rail
265. TL−4 Bridge Rail
266. TL−5 Bridge Rail
267. TL−6 Bridge Rail
251. Containment Limit= 34453.5 j, Repair=$ 450
252. Containment Limit= 67528.6 j, Repair=$ 950
253. Containment Limit= 137813.0 j, Repair=$ 167
254. Containment Limit= 352802.0 j, Repair=$2150
255. Containment Limit= 137813.0 j, Repair=$2300
256. Containment Limit= 352802.8 j, Repair=$2500
257. Containment Limit= 595442.5 j, Repair=$ 760
258. Containment Limit= 67528.6 j, Repair=$ 760
259. Containment Limit= 137813.0 j, Repair=$ 760
260. Containment Limit= 67528.6 j, Repair=$ 900
261. Containment Limit= 137813.0 j, Repair=$1920
262. Containment Limit= 34453.5 j, Repair=$3240
263. Containment Limit= 67528.6 j, Repair=$3240
264. Containment Limit= 137813.0 j, Repair=$3240
265. Containment Limit= 352802.0 j, Repair=$3240
266. Containment Limit= 595442.5 j, Repair=$3240
267. Containment Limit= 595442.5 j, Repair=$3240

Figure A.7-2

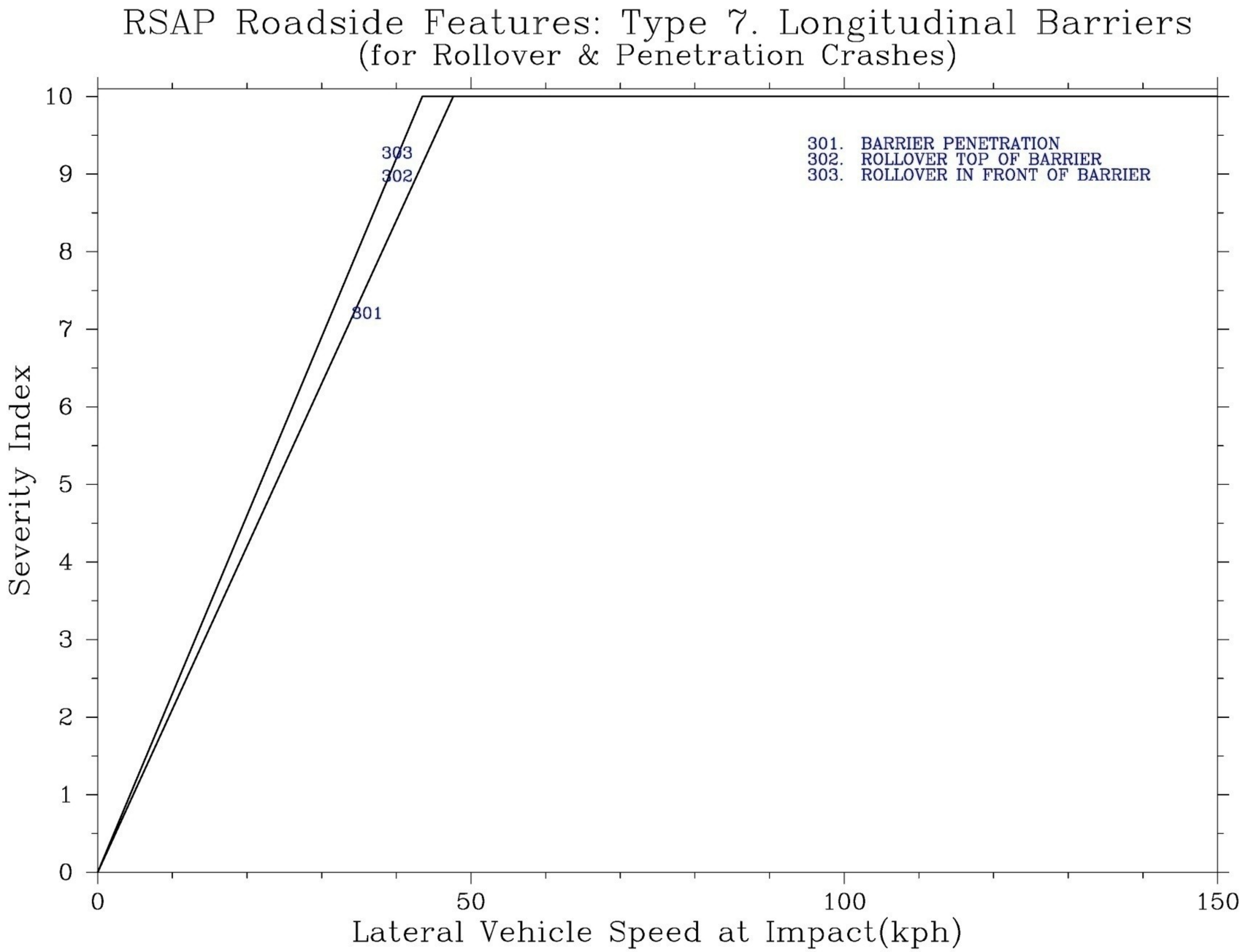
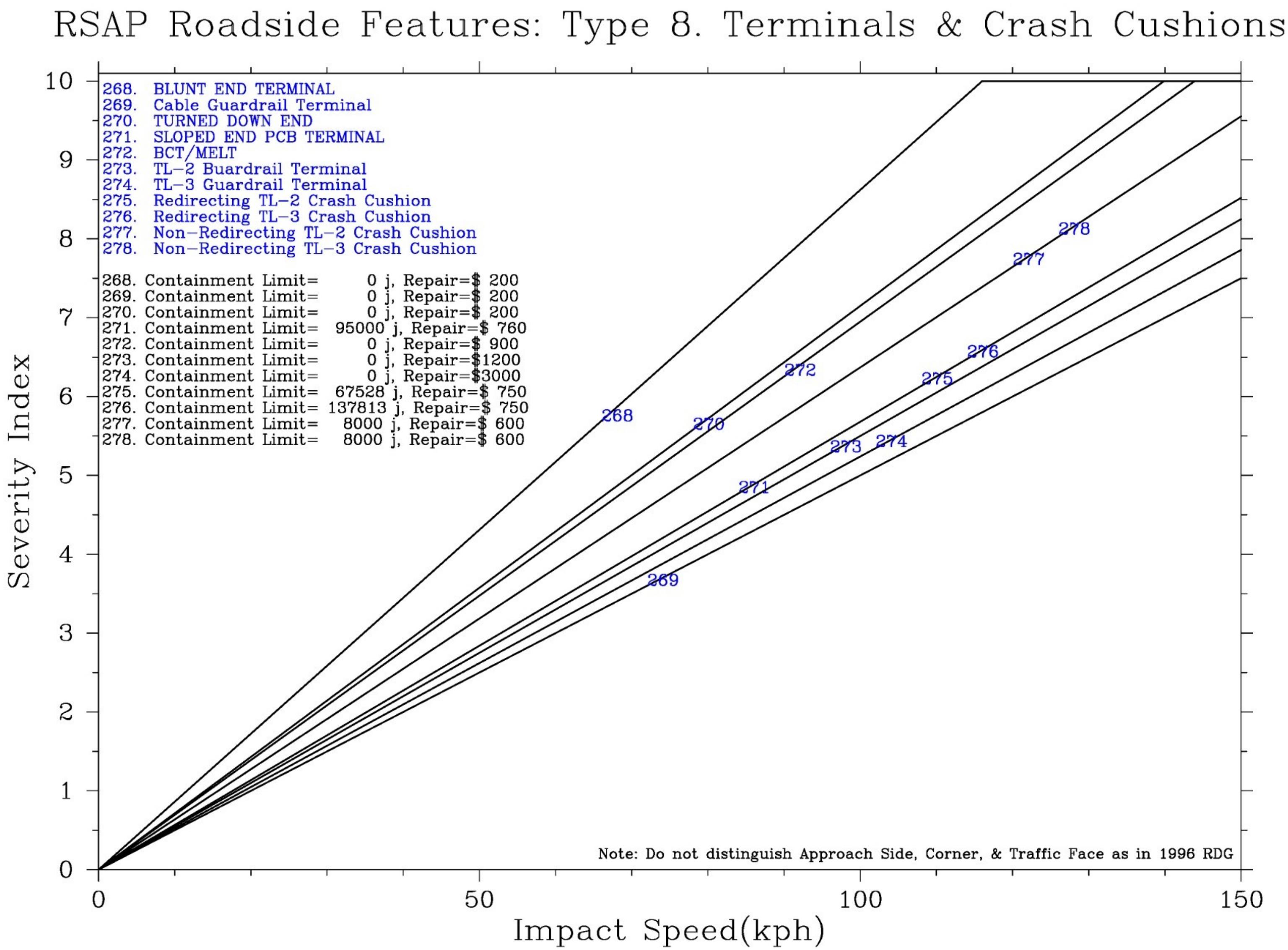

RSAP Roadside Features: Type 7. Longitudinal Barriers
(for Rollover & Penetration Crashes)
Severity Index
Lateral Vehicle Speed at Impact(kph)
0
1
2
3
4
5
6
7
8
9
10
0
50
100
150
303
302
301
301. BARRIER PENETRATION
302. ROLLOVER TOP OF BARRIER
303. ROLLOVER IN FRONT OF BARRIER

Figure A.8


RSAP Roadside Features: Type 8. Terminals & Crash Cushions
268. BLUNT END TERMINAL
269. Cable Guardrail Terminal
270. TURNED DOWN END
271. SLOPED END PCB TERMINAL
272. BCT/MELT
273. TL–2 Buardrail Terminal
274. TL–3 Guardrail Terminal
275. Redirecting TL–2 Crash Cushion
276. Redirecting TL–3 Crash Cushion
277. Non–Redirecting TL–2 Crash Cushion
278. Non–Redirecting TL–3 Crash Cushion
268. Containment Limit= 0 j, Repair=$ 200
269. Containment Limit= 0 j, Repair=$ 200
270. Containment Limit= 0 j, Repair=$ 200
271. Containment Limit= 95000 j, Repair=$ 760
272. Containment Limit= 0 j, Repair=$ 900
273. Containment Limit= 0 j, Repair=$1200
274. Containment Limit= 0 j, Repair=$3000
275. Containment Limit= 67528 j, Repair=$ 750
276. Containment Limit= 137813 j, Repair=$ 750
277. Containment Limit= 8000 j, Repair=$ 600
278. Containment Limit= 8000 j, Repair=$ 600
Note: Do not distinguish Approach Side, Corner, & Traffic Face as in 1996 RDG
Severity Index
Impact Speed(kph)
0
1
2
3
4
5
6
7
8
9
10
0
50
100
150
268
269
270
271
272
273
274
275
276
277
278

APPENDIX B
SURVEY FORM AND RESPONSE DATA

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/expections/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

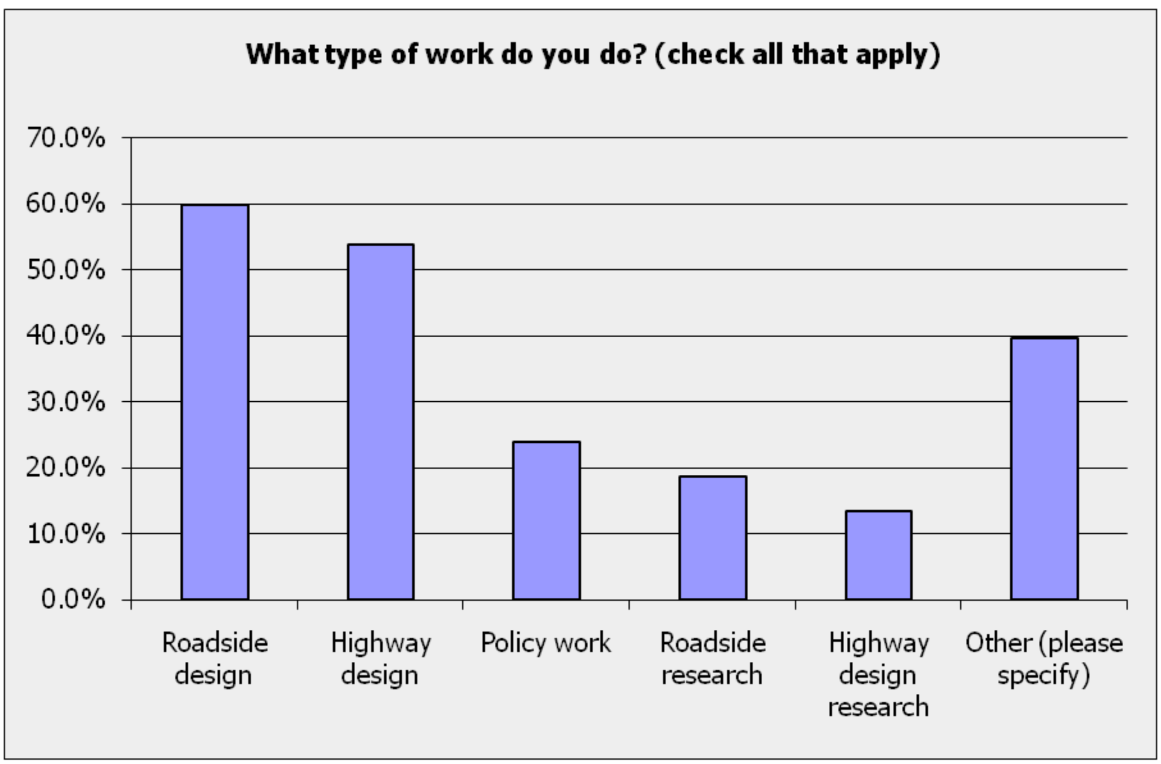
NCHRP Project 22-27

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
	answered question	**101**
	skipped question	**35**

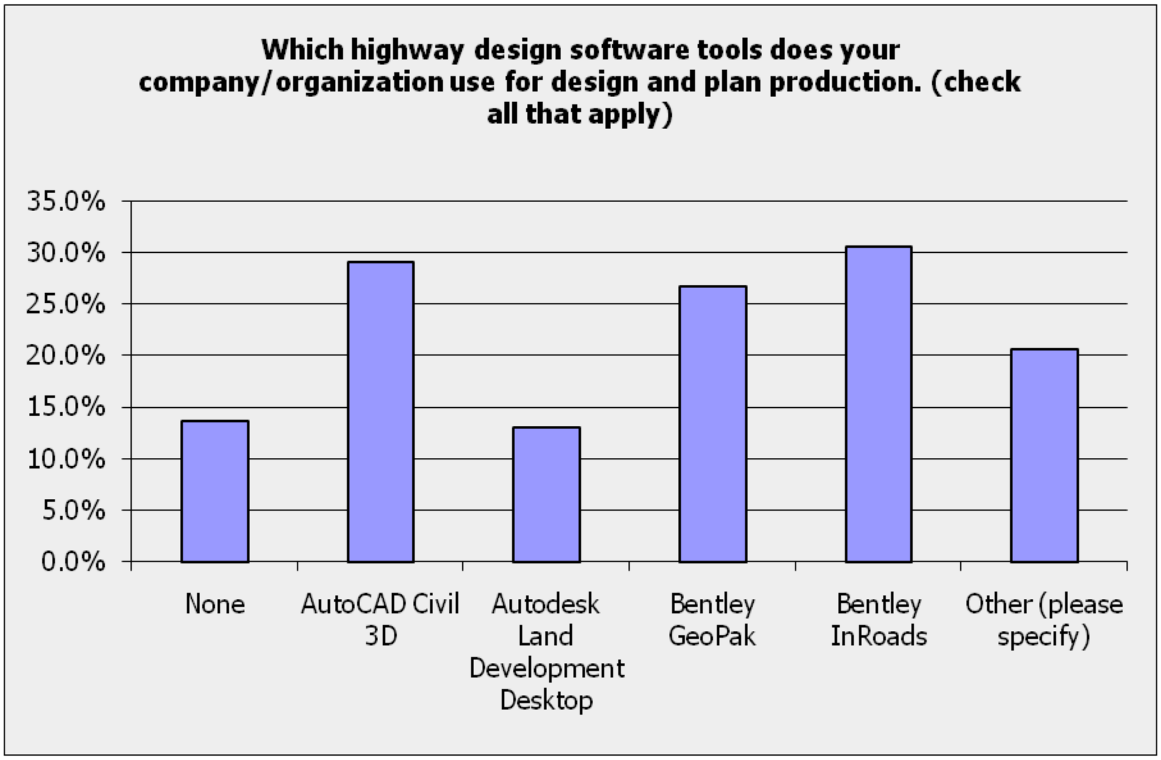
SR.2 What type of work do you do? (check all that apply)



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 constractor 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)



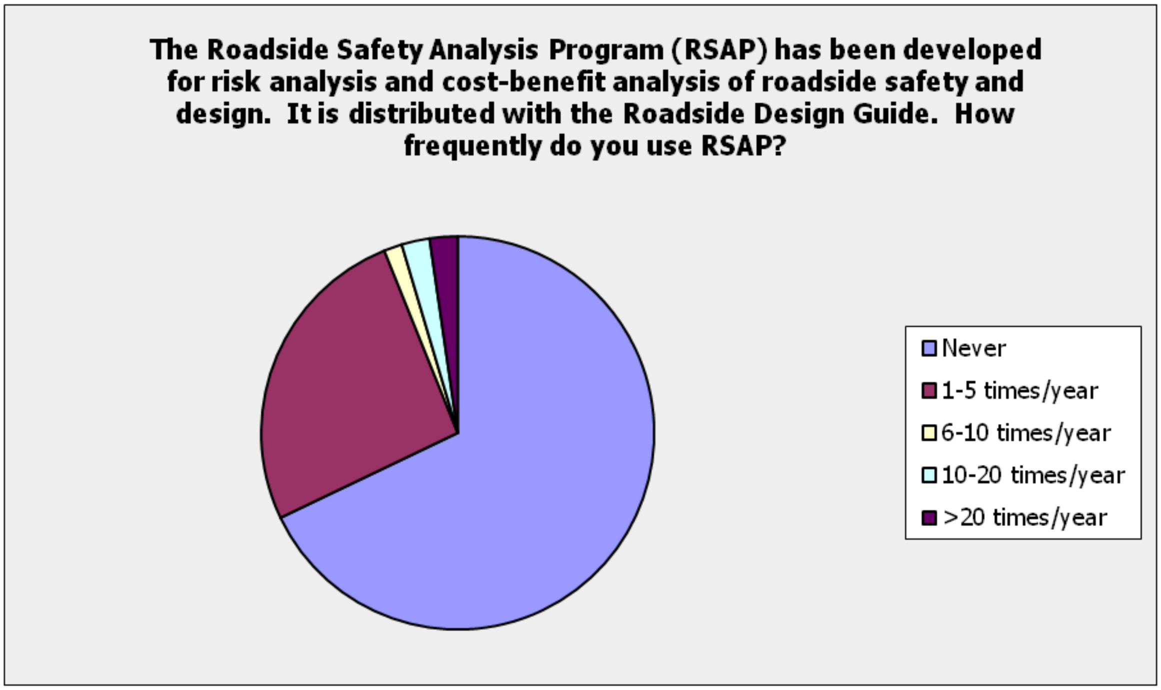
Other (please specify):

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

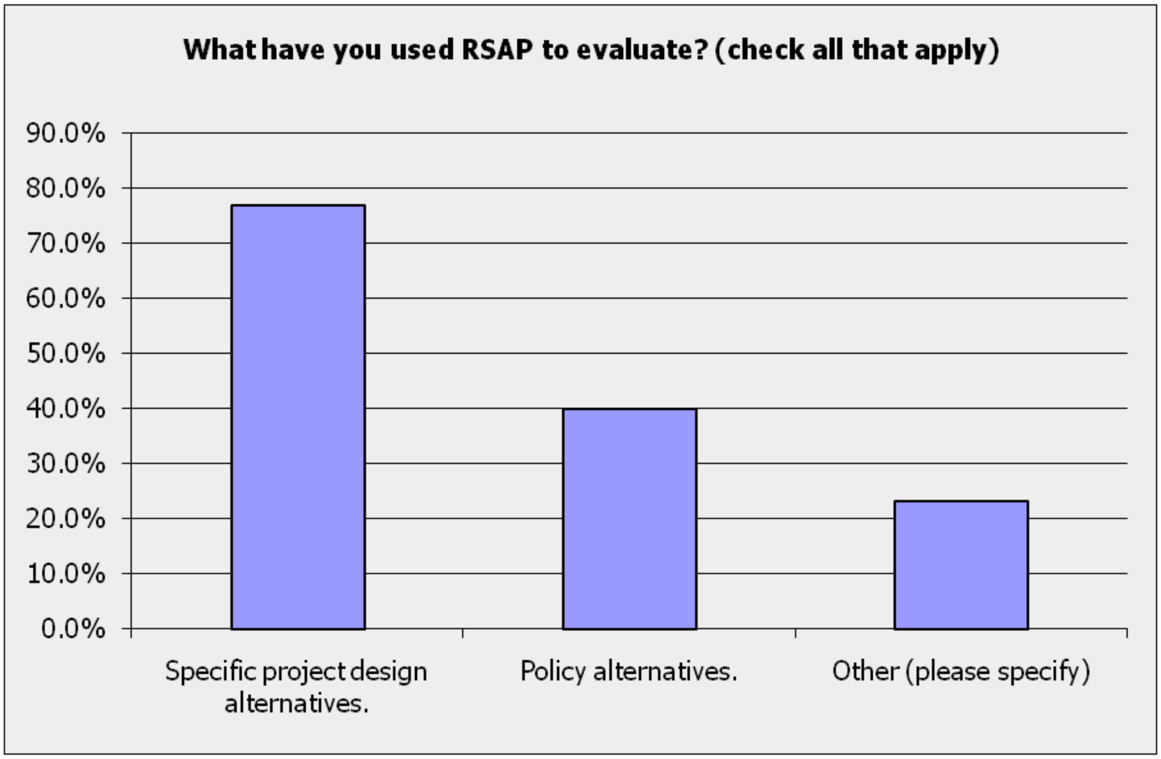
SR.4 Please list other software tools you use to assist with design decisions and cost analysis.

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

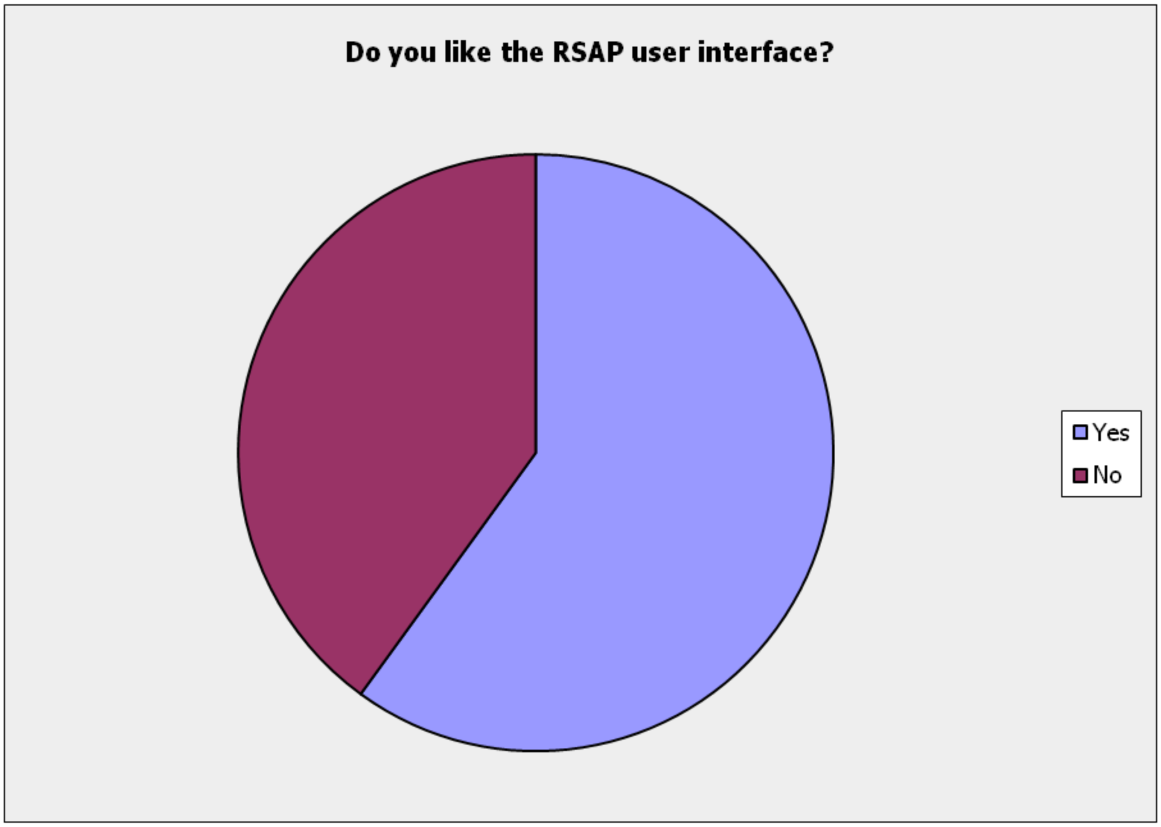
Instructing others on how to perform B/C analyses

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?

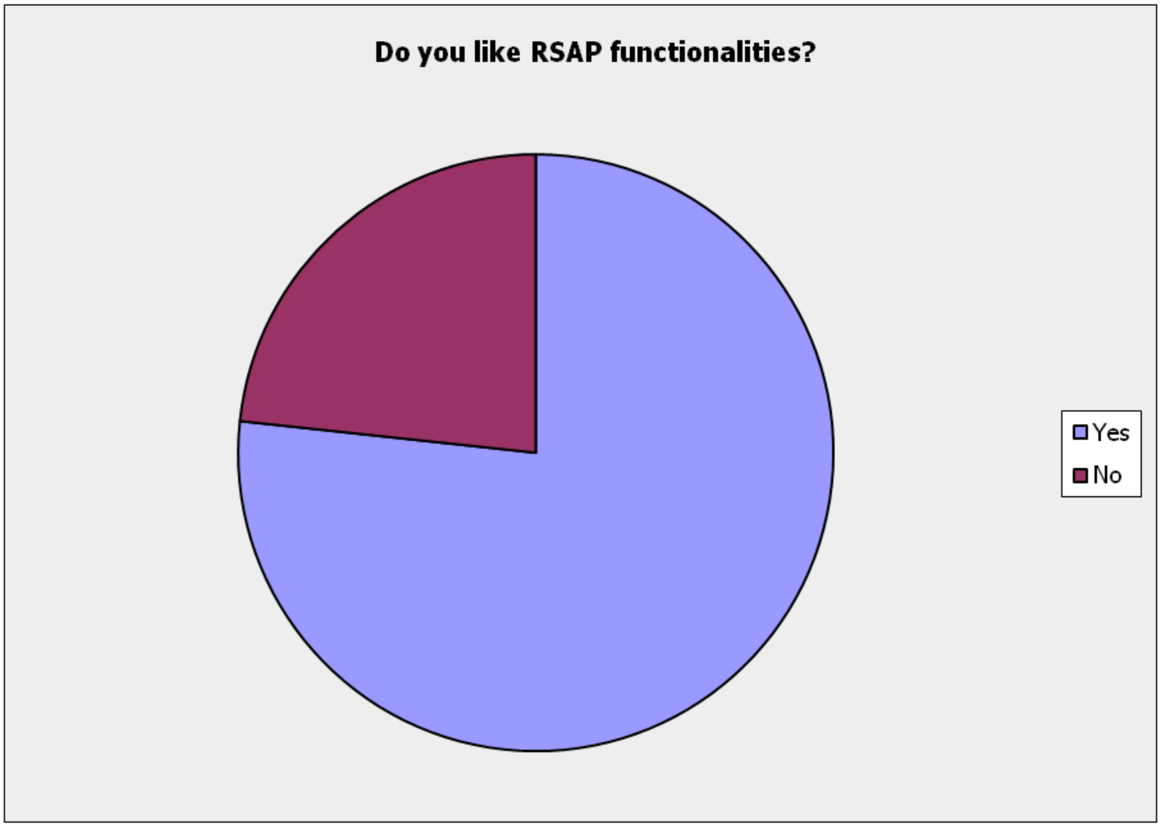


Suggestions for improvements or comment:

- 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 dont save, it defaults back to SI units making things frusterating.
- 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 its 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 automatially 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 accendent cost is easy to understand -- the benifit 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

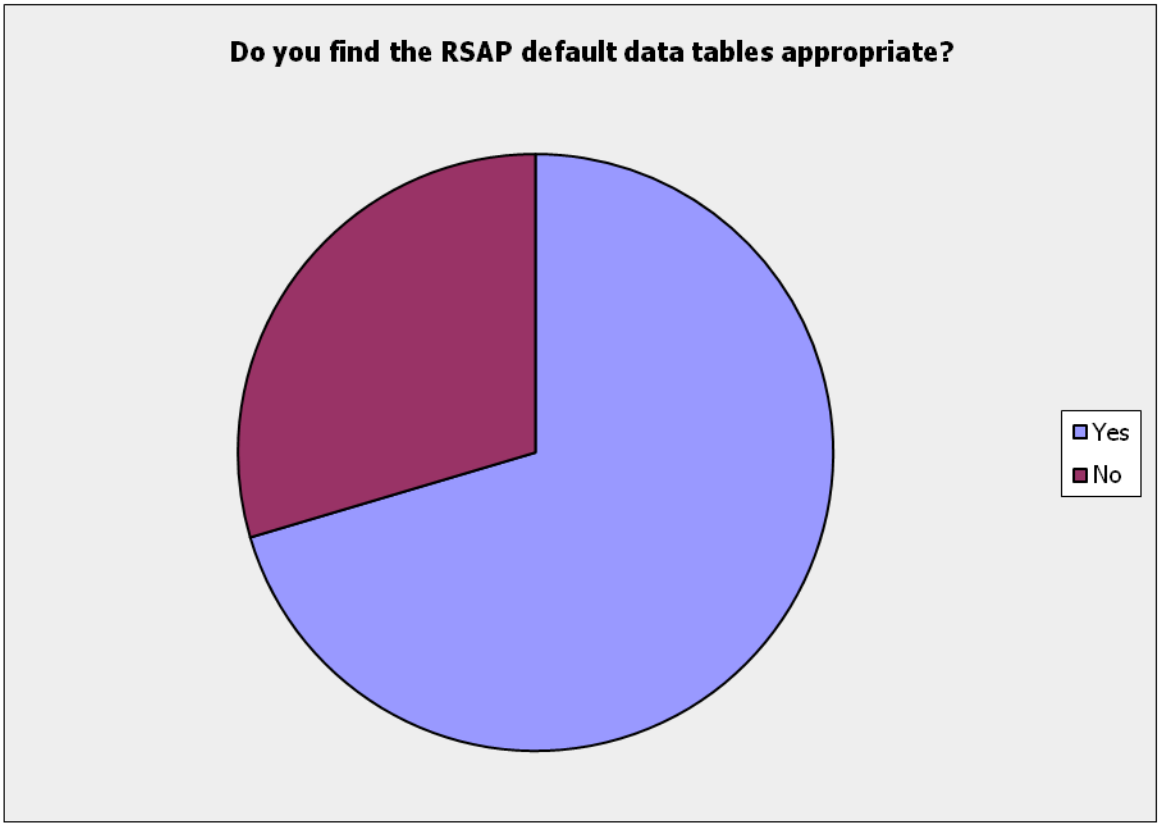
encroachment of the trajectory on the slope rather than an often arbitrary "slope height". Since the steepest slopes are not very hazardous if a vehicle only encroaches 1 ft onto the slopes, inclusion of lateral encroachment effects increases accuracy. Either that, or with the visual aspect, when introducing 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.

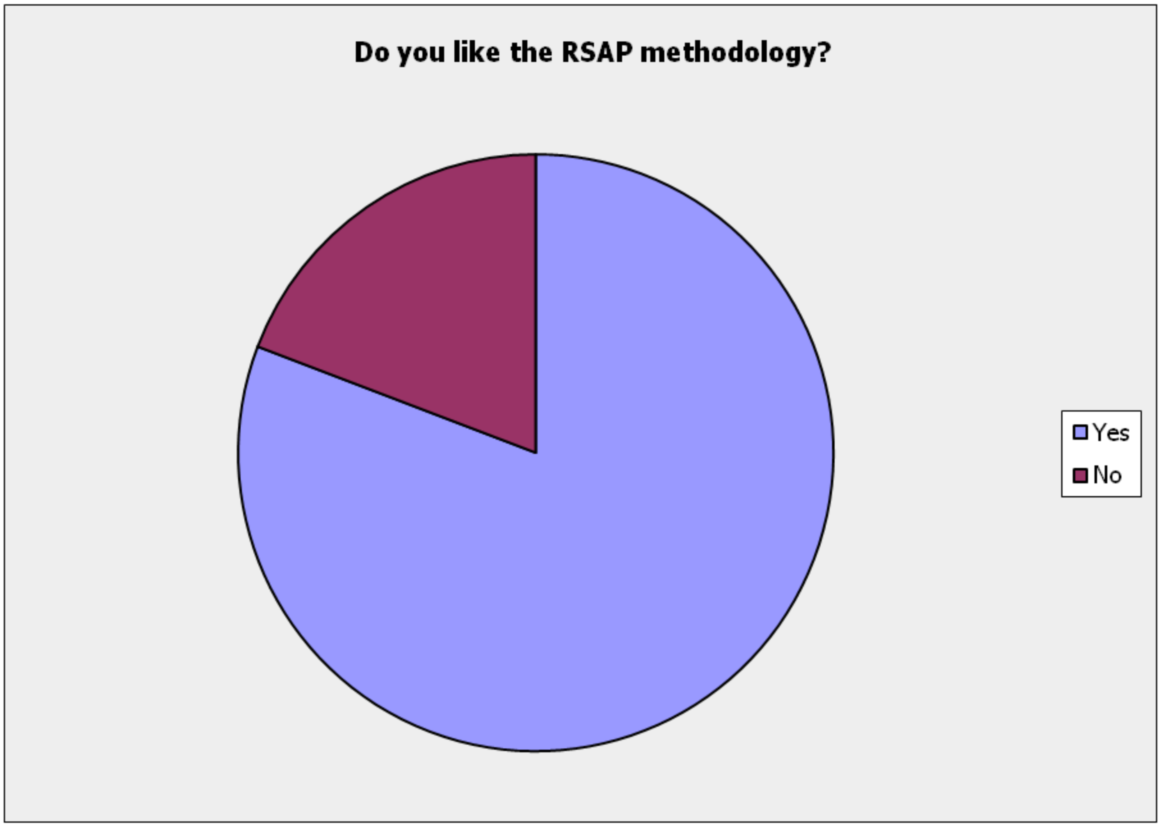
  4. Tree severities are likely overstated. However, this does lead to a conservative analysis, and

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:

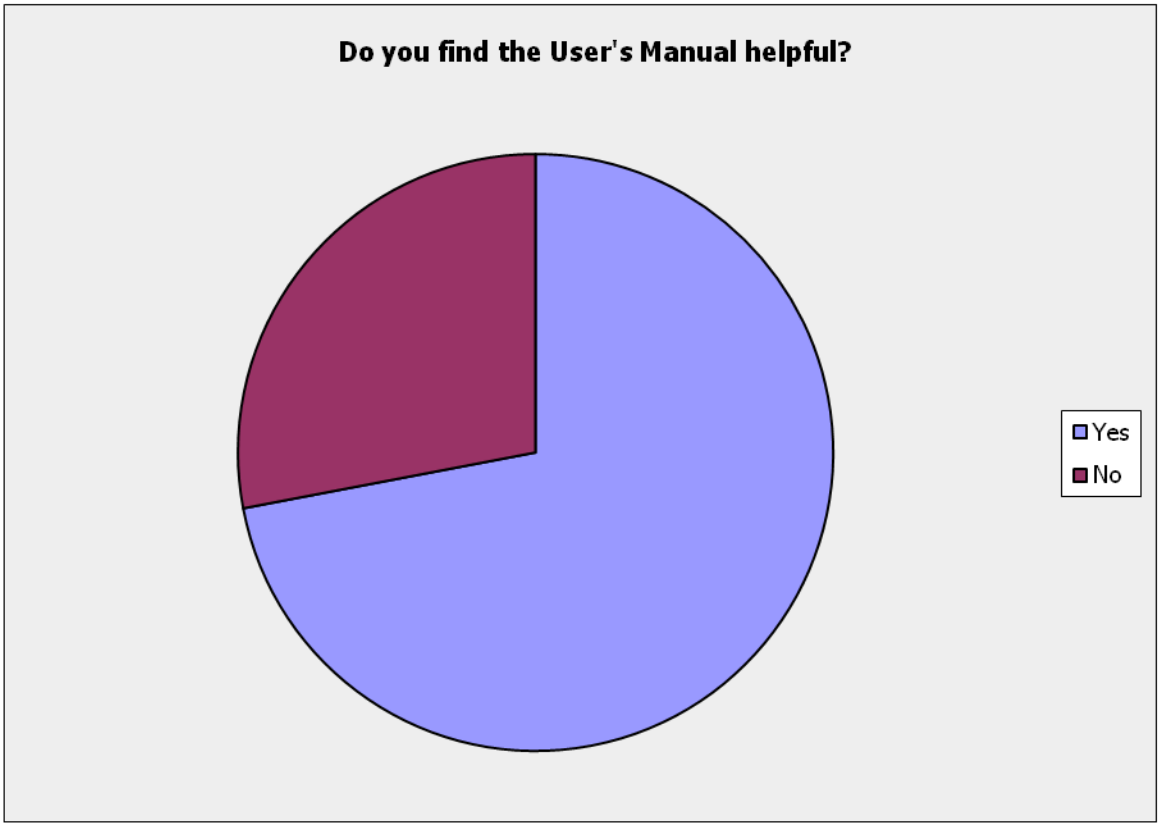
- Make it clearer in the reports section in the ranking of alternatives as they are compared to each other.
- You could do a better job explaining the methodology so that the results can be relayed to others.
- it's a bit of a secret, too black box. need to be more transparent to the user
- I think the 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 vehice 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?



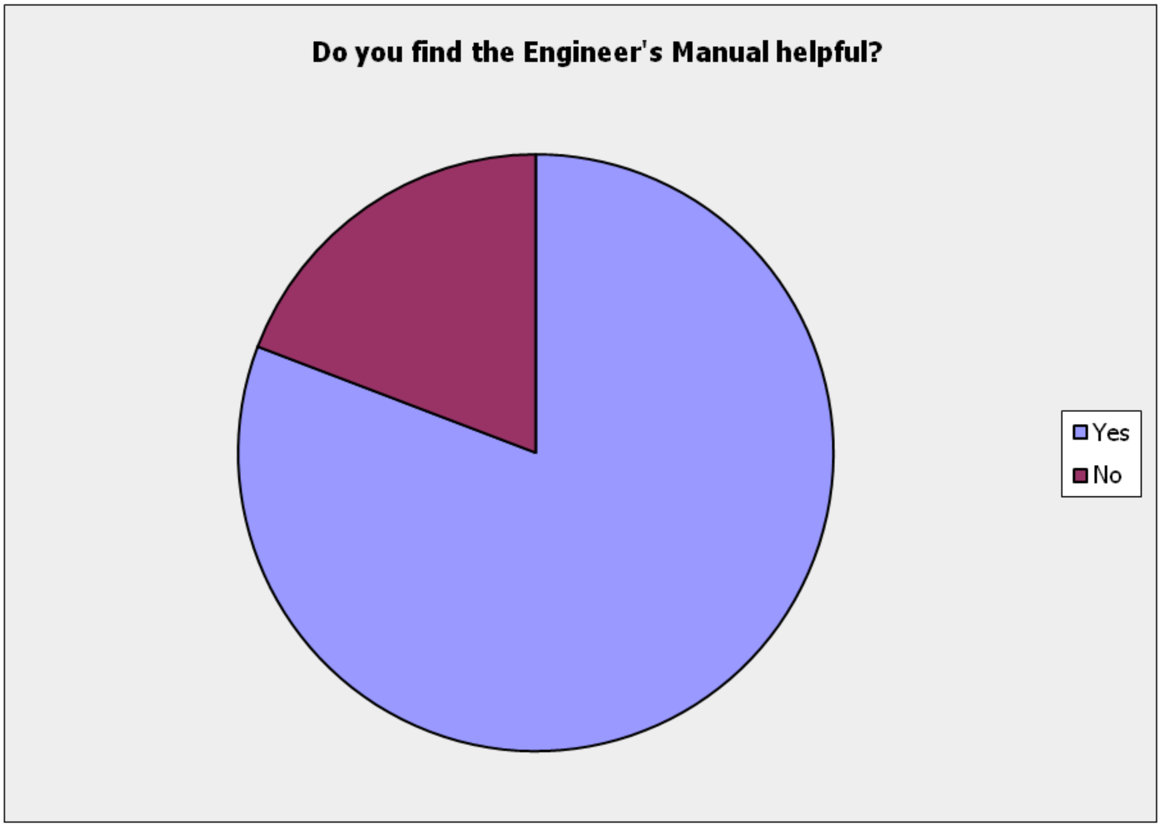
Suggestions for improvements or comment:

- More information as to how crash costs are determined would be helpful.
- Only marginaly helpful. I have had to bug MwRSF to understand how to use the software.
- Pictures associated with different hazard/guardrail treatments would be helpfull 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 copius notes as they work through the program using the manual. Then udpate 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 incorportated 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 marginaly 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 devided 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/judgment?

- 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 decission. 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
- Yes
- No

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

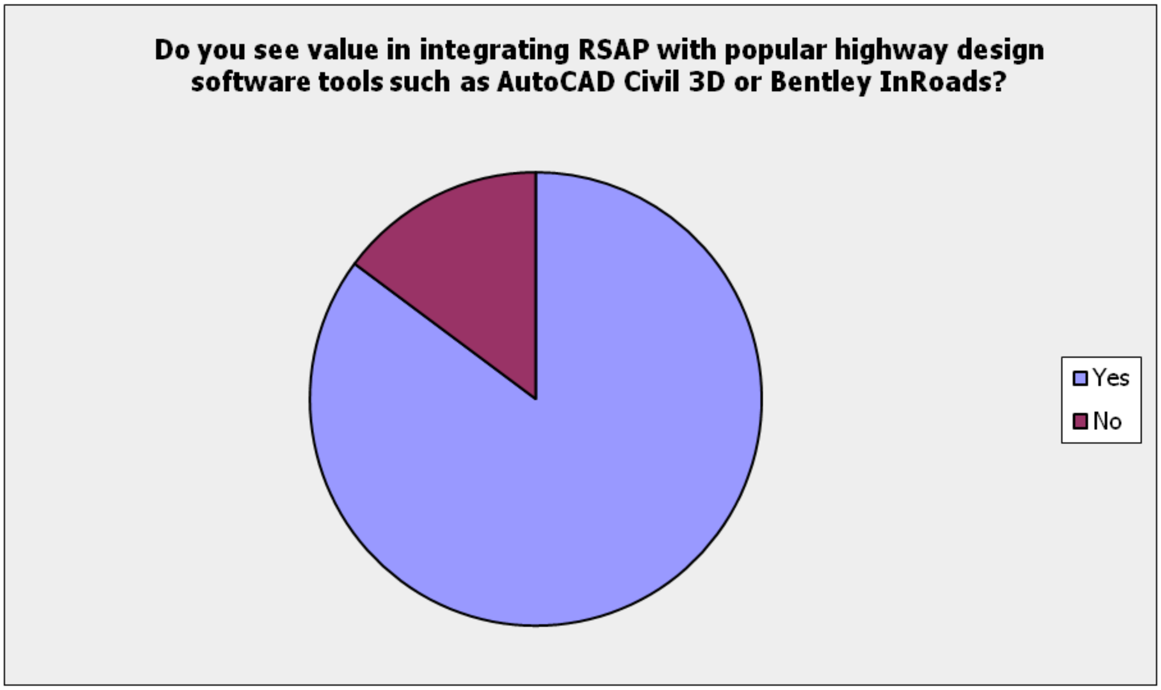
- Report functionality; ability to produce PDF's of reprots;
- More detail, its a very basic program, if you could model situations with more detail it would produce more accurate results.
- Make the inputing of cross section data more graphical
- Better examples with diagrams/pictures. A break down 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

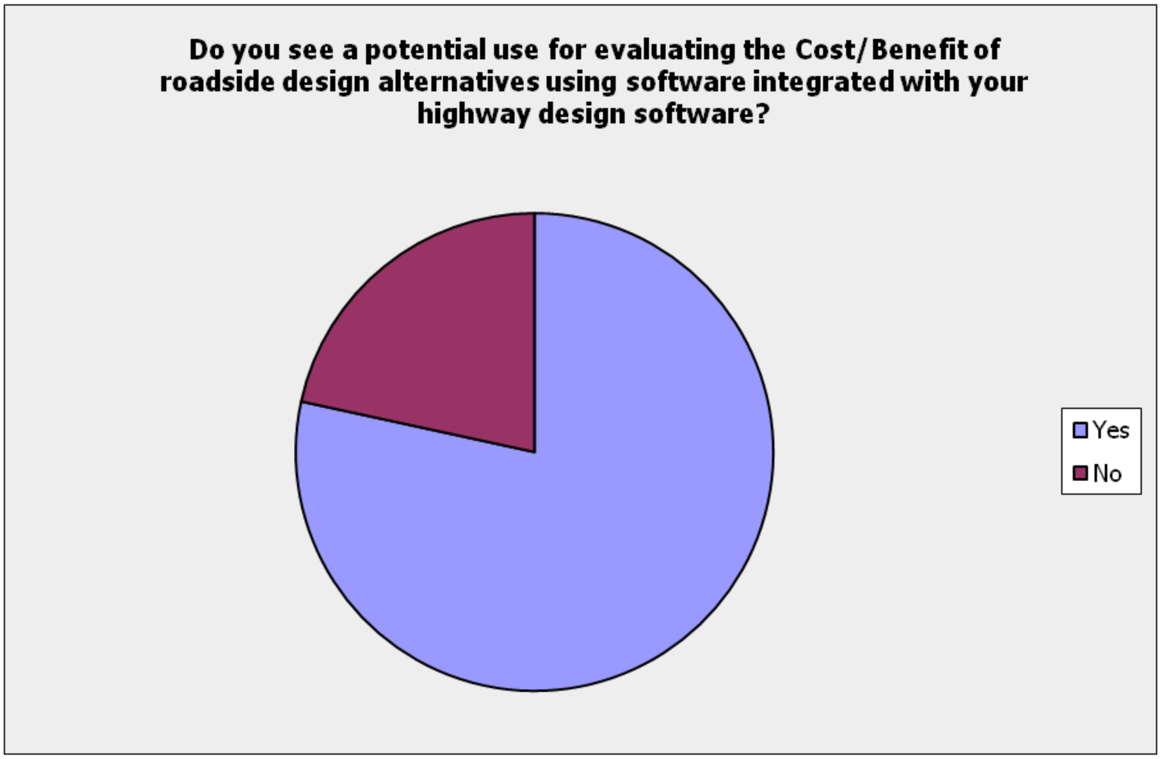
SR.17 Do you see value in integrating RSAP with popular highway design software tools such as AutoCAD Civil3D or Bentley InRoads?



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.

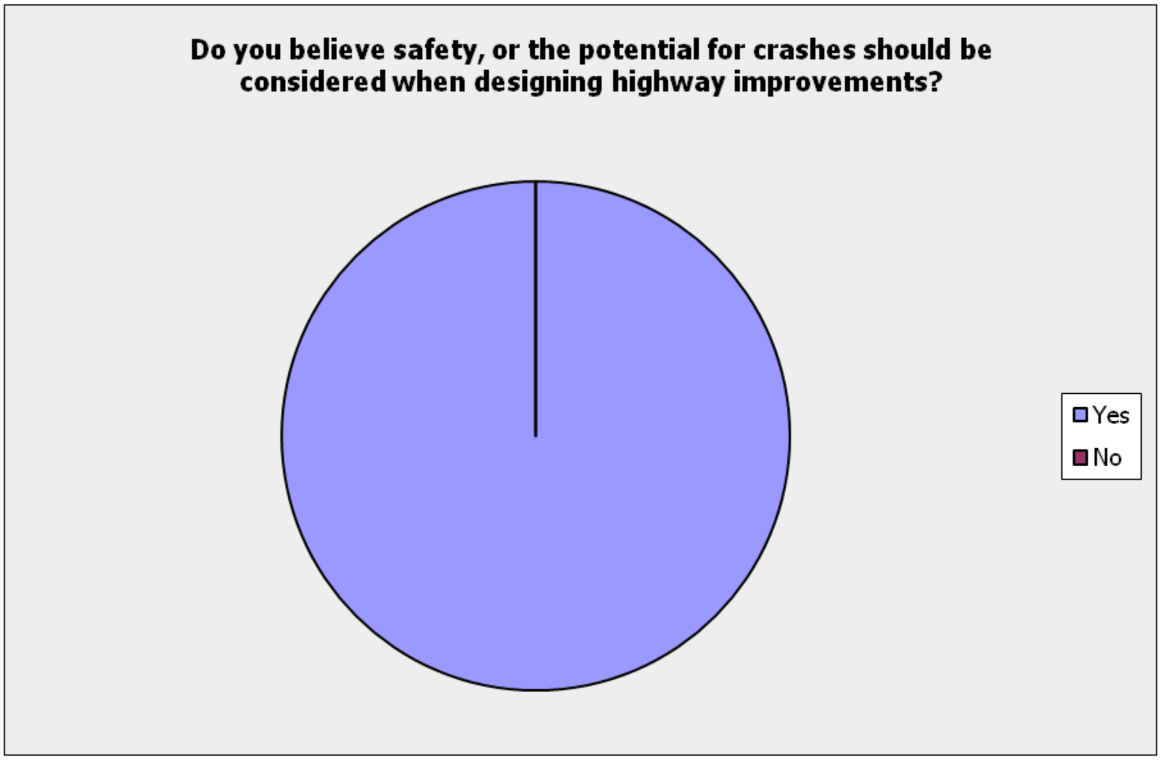
SR.18 Do you see a potential use for evaluating the Cost/Benefit of roadside design alternatives using software integrated with your highway design software?



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".

SR.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 provided contact information and volunteered to be beta testers for the RSAP2010 software.