APPENDIX A

A Cost-Effectiveness Selection Procedure

The Roaside Safety Analysis Program (RSAP) software was developed under National Cooperative Highway Research Program (NCHRP) Project 22-9 and represents one approach to using the *Roadside Design Guide*, as described in this appendix. It carries no guarantees or warranties from the American Association of State Highway and Transportation Officials (AASHTO). The RSAP program is intended as a tool for economic analysis and should not supersede the guidelines presented in the *Roadside Design Guide* or sound engineering judgment.

A1.0 OVERVIEW

This appendix provides a summary of the conceptual framework and algorithms contained in the RSAP computer program, which has been created to assist in the economic analysis of existing or proposed roadside conditions. The RSAP program has its genesis in the analysis procedure presented in Chapter VII of AASHTO's 1977 *Guide for Selecting, Locating, and Designing Traffic Barriers* (1), the ROADSIDE computer program presented in previous versions of the *Roadside Design Guide* (2) (3), and the Benefit-Cost Analysis Program (BCAP) (4) used in the development of the AASHTO's 1989 *Guide Specifications for Bridge Railings* (5).

Additional copies of the RSAP program and the associated documentation, *Engineer's Manual* and *User's Manual*, may be obtained from:

Transportation Research Board
National Cooperative Highway Research Program
2101 Constitution Avenue, NW
Washington, DC 20418

or ordered through the internet at http://www.nationalacademies.org/trb/bookstore.

The *Engineer's Manual* contains detailed descriptions of the conceptual framework and algorithms used with the cost-effectiveness analysis procedure. The *User's Manual* contains detailed descriptions of the operations of the RSAP program and is also available through the on-line help of the program.

The RSAP program is comprised of two separate but integrated programs: the User Interface Program and the Main Analysis Program. The Main Analysis Program contains the cost-effectiveness procedure itself and performs all the necessary calculations. The Main Analysis Program is written in the FORTRAN language because of its efficiency in performing scientific calculations. The User Interface Program is written in the C++ language, which is more adept at providing a user-friendly environment through the use of windows, screens, and menus.

The User Interface Program provides the users with a simple and structured means to input data into the RSAP program. The program generates input data files and transfer data files, which, together with the default and temporary data files, serve as inputs to the Main Analysis Program. After processing by the Main Analysis Program, the User Interface Program takes the outputs from the Main Analysis Program and presents the results to the user. The transfer of data files between the User Interface Program and the Main Analysis Program is conducted in ASCII format for simplicity and ease of file transfer.

To install and run the RSAP program, your computer must be an IBM PC or 100 percent compatible, and have the following:

1. A Pentium III or equivalent based platform
2. Memory—128 MB minimum
3. Disk space
    - Hard disk with at least 8.5 MB free for the program files
    - Additional disk space of at least 1 MB for storage of project input and output files, and temporary data files
4. Mouse—Recommended
5. Operating system—WINDOWS 98, NT, Me, 2000, or XP.

The RSAP installation program and associated documentation is provided on a CD-ROM. Users should have a good understanding of the WINDOWS operating environment and general mouse and keyboard techniques. On most PCs, the installation program can be initiated by inserting the CD-ROM into the drive and following the instructions on the screen. The program will automatically complete the installation of the RSAP program. For PCs with Autorun disabled, users must open the CD-ROM and double-click on the setup program.

A1.1 COST-EFFECTIVENESS ANALYSIS PROCEDURE

The cost-effectiveness analysis procedure in the RSAP program is based on benefit/cost (B/C) analysis. The basic concept behind benefit/cost analysis is that public funds should be invested only in projects where the expected benefits exceed the expected direct costs of the project. Benefits are measured in terms of reductions in crash or societal costs due to decreases in the number and/or severity of crashes. Direct highway agency costs are comprised of initial installation, maintenance, and crash repair costs. An incremental benefit/cost ratio between the incremental benefits and costs associated with an improvement option over the existing conditions or another improvement option is normally used as the primary measure of whether or not a safety improvement investment is appropriate. The incremental benefit/cost ratio is expressed as follows:

$$\text{B/C Ratio}_{2-1} = (AC_1 - AC_2)/(DC_2 - DC_1)$$

where:

B/C Ratio_{2-1} = incremental benefit/cost ratio of Alternative 2 compared to Alternative 1
AC_1, AC_2 = annualized crash or societal cost of Alternatives 1 and 2
DC_1, DC_2 = annualized direct cost of Alternatives 1 and 2

When the incremental benefit/cost ratio comparing safety improvement Alternative 2 to Alternative 1 is greater than 1, the analysis indicates that the increased benefits of Alternative 2 over Alternative 1, i.e., reduction in the crash and societal costs, are greater than the increased costs associated with Alternative 2 over Alternative 1.

Crash cost is estimated using an encroachment probability model, which is unique to roadside safety cost-effectiveness procedures. It is based on the concept that the run-off-the-road crash frequency can be directly related to the encroachment frequency, i.e., the number of vehicles inadvertently leaving the traveled portion of the roadway. The severity of run-off-the-road crashes is related to encroachment characteristics, such as the speed and angle of encroachment. The basic formulation of the encroachment model is expressed by the following equation:

$$E(AC) = \sum_{i=1}^{n} V * P(E) * P(A|E) * P(I_i|A) * C(I_i)$$

where:

$E(AC)$ = Expected crash cost
V = Traffic volume, ADT
$P(E)$ = Probability of an encroachment
$P(A|E)$ = Probability of a crash given an encroachment
$P(I_i|A)$ = Probability of injury severity level “i”, given a crash
$C(I_i)$ = Cost associated with injury severity level “i”
n = Number of injury severity levels

A2.0 RSAP PROGRAM

There are four major modules to the encroachment probability-based cost-effectiveness analysis procedure in the RSAP program:

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

Brief descriptions of each of these modules are presented as follows.

A2.1 ENCROACHMENT MODULE

The encroachment module uses roadway and traffic information to estimate the expected encroachment frequency, V*P(E), along a highway segment. A two-step process is used to estimate encroachment frequencies. The first step involves using highway type and traffic volume to estimate a base or average encroachment frequency. There are two available sources of encroachment data: a study by Hutchinson and Kennedy (6) in the mid-1960s and a study by Cooper (7) in the late 1970s. Both studies involved observations of tire tracks in the medians or on roadsides. The Cooper encroachment data were selected for use in the RSAP program for the encroachment rate-traffic volume relationships because they are more recent, have a larger sample size, and include data from two-lane and other non-freeway facilities as well as from controlled-access highways. Figure A.1 shows the encroachment frequency curves used by the RSAP program. Encroachment rates are expressed as the number of encroachments per km [mi] per year per ADT, broken down by undivided and divided highways.

Two adjustments are made to these encroachment frequency curves:

1. The encroachment frequency is adjusted upward by a ratio of 2.466 for two-lane undivided highways and 1.878 for multi-lane divided highways to account for under-reporting of encroachments due to paved shoulders.

2. The encroachment frequency is multiplied by a factor of 0.6 to account for the lack of ability to detect the difference between controlled and uncontrolled encroachments. The percentage of uncontrolled encroachments is assumed to be 60 percent based on a study of reported vs. unreported crashes involving longitudinal barriers (8).

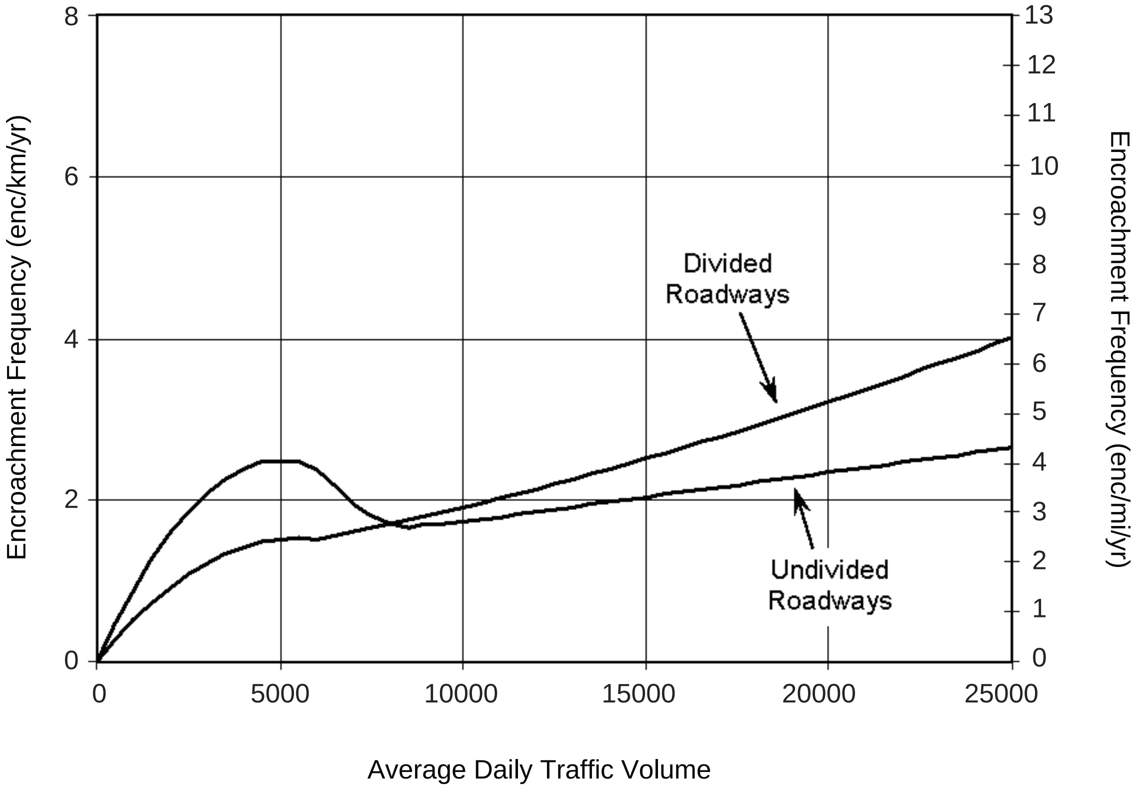

FIGURE A.1 Encroachment frequency curves used by the RSAP Program

Base encroachment rates are then modified to account for specific highway characteristics, including horizontal and vertical alignment and the annual traffic growth factor. The rationale for these adjustment factors is that encroachment rates are affected by these characteristics and the base encroachment rates should therefore be adjusted accordingly.

Crash data studies have indicated that crash rates on horizontal curves and vertical grades are significantly higher than those on tangent sections (9, 10). It is logical to assume that encroachment rates would also be similarly affected by horizontal curves and vertical grades. Thus, the RSAP program incorporates adjustment factors to increase encroachment rates on horizontal curves and vertical grades, as shown in Figure A.2. The adjustment factors are based on research conducted by Wright and Robertson (9).

Note that the adjustment factors for horizontal curvature and vertical grade are determined in relation to the direction of travel and the direction the vehicle ran off the road. A downgrade for one direction of travel would become an upgrade for the opposing direction of travel. Similarly, a vehicle running off to the right would be on the outside of a curve for one direction of travel and on the inside of a curve for the opposing direction of travel.

The traffic volume (ADT) entered into the RSAP program applies to the current year or construction year. To allow for future increases in traffic volume, the RSAP program allows users to input an annual traffic growth in percent. For a given year, n, in the future, the traffic volume is calculated as follows:

$$ADT_n = ADT_1 * (1+ g/100)^n$$

where:

ADT_n = traffic volume in year “n”
ADT_1 = current or base year traffic volume
g = annual percent traffic growth

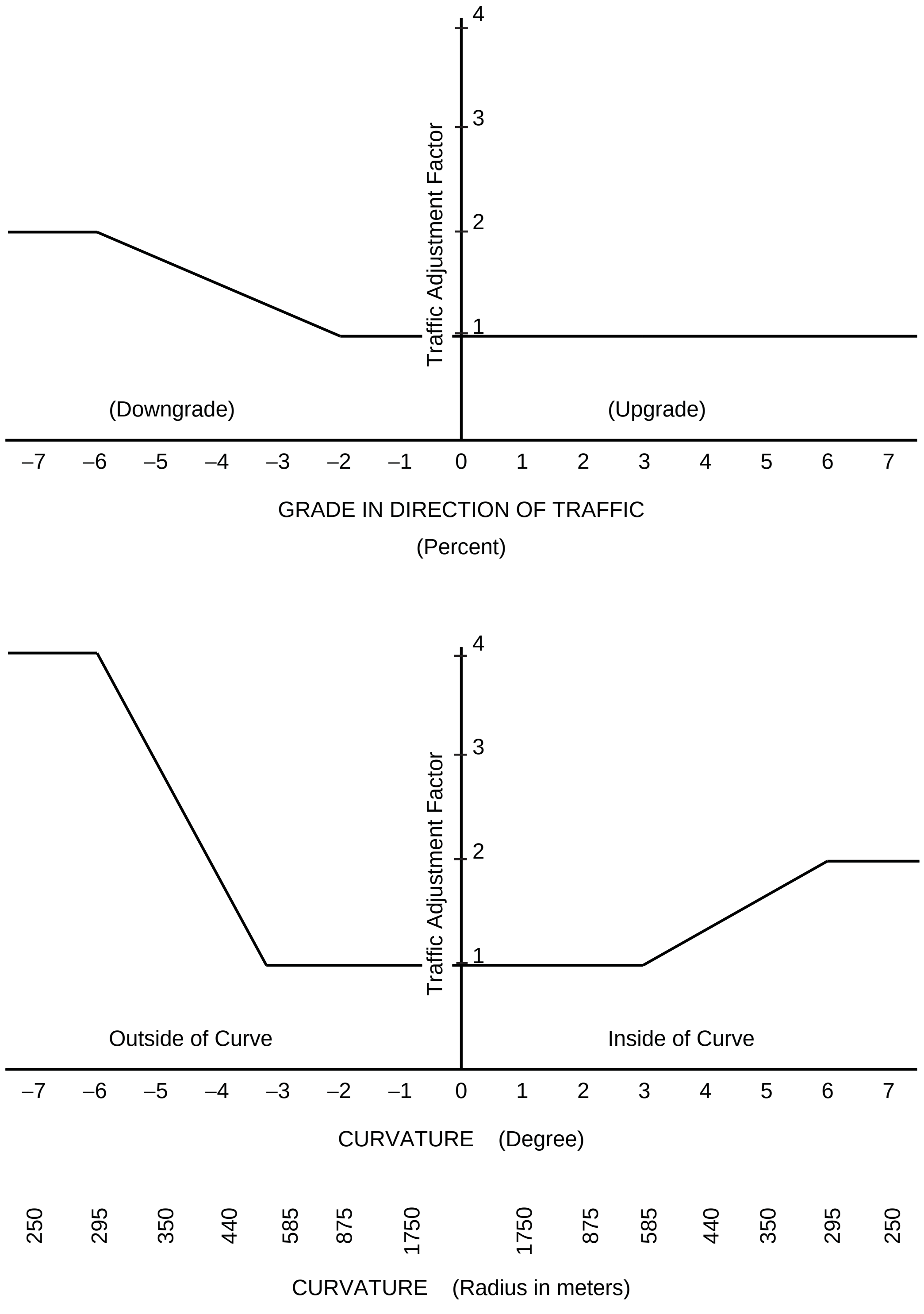

FIGURE A.2 Adjustment factors for encroachment rates on horizontal curves and vertical grades

The traffic growth adjustment factor averages the traffic volume over the life of the project and is calculated as follows:

$$\text{Traffic growth adjustment factor} = \sum_{n=1}^{N} (1 + g/100)^n / N$$

where:

N = project life in years

The RSAP program allows the input of a user-defined adjustment factor to account for special or unusual situations that could affect encroachment frequencies beyond the parameters incorporated into the program. For example, an adjustment factor of greater than 1.0 may be appropriate if the highway section under consideration has a higher than average crash history or encroachment frequencies at night. An adjustment factor of less than 1.0 may be appropriate for a highway section with special safety countermeasures, such as rumble strips on the shoulder or increased law enforcement activities.

The encroachment module will then combine base encroachment rates and adjustment factors to determine encroachment frequencies for the highway section under study.

A2.2 CRASH PREDICTION MODULE

The crash prediction module assesses if an encroachment would result in a crash, P(A|E). A stochastic process using the Monte Carlo simulation technique is used for the crash prediction module, which involves using random selection processes to simulate vehicles running off the road within the highway section under study. One encroachment is simulated each time with the following characteristics randomly assigned to the encroachment: location along the highway, lane of origination, direction of encroachment, vehicle type, vehicle speed and angle, and vehicle orientation.

The random assignment of characteristics is based on distributions built into the program. For example, encroachments are assumed to be evenly distributed within a homogeneous roadway section and are a function of the encroachment frequency (i.e., the encroachments vary among roadway sections with different geometrics and encroachment frequencies). The lane of origination and direction of encroachment are a function of traffic volume distribution by lane. Vehicle type, which has 12 categories ranging from a small passenger car to a tractor-trailer, is a function of the vehicle mix calculated from the nominal truck percentage (user input item). Vehicle speed, angle, and orientation are determined from distributions estimated from real-world crash data (11).

A weighting scheme is used with the random encroachment assignments to ensure that rare events, i.e., combinations of distributions with low probabilities such as a tractor-trailer impact with high impact speed at an angle, will be properly represented in the distributions.

For each encroachment, the path (assumed to be a straight line) and the impact envelope of the vehicle are a function of the encroachment angle and the physical dimensions and orientation of the vehicle, as shown in Figure A.3. The presence of roadside features within the impact envelope of the vehicle is then checked. If there is no roadside feature within the impact envelope, the encroachment would not result in a crash. If there is a roadside feature within the impact envelope, then a crash would occur with the probability determined by the lateral extent of encroachment for the vehicle. The severity of the crash and the associated crash cost are then estimated by the severity prediction module. The crash frequency and crash cost are then multiplied by the probability that the vehicle would travel far enough laterally to reach the hazard. The lateral extent of encroachment distribution, shown in Figure A.4, is based on the Cooper encroachment data (7).

A new encroachment is then randomly generated and the process is repeated. After every 10,000 encroachments, the convergence of the solution is examined. The distributions of the encroachment characteristics for the simulated encroachments are compared to the pre-established distributions to check if they are within the specified level of convergence, which can be set by the user to high (1 percent), medium (5 percent), or low (10 percent). If all of these distributions are within the specified level of convergence, the simulation is terminated and the results are saved in the output files. Otherwise, another 10,000 iterations will be undertaken and the convergence checks outlined above will be repeated.

A2.3 SEVERITY PREDICTION MODULE

After a crash is predicted to occur, the next step is to estimate the severity of the impact using the crash severity prediction module. Crash severity estimation is perhaps the most important step of this cost-effectiveness analysis procedure. For most roadside safety improvements, the benefit, or reduction in crash cost, is derived from lower crash severity with little or no change, and sometimes even an increase, in the crash frequency. The crash cost is principally a function of the crash severity, i.e., the probability of injury and/or fatality, since the associated crash cost is highly non-linear.

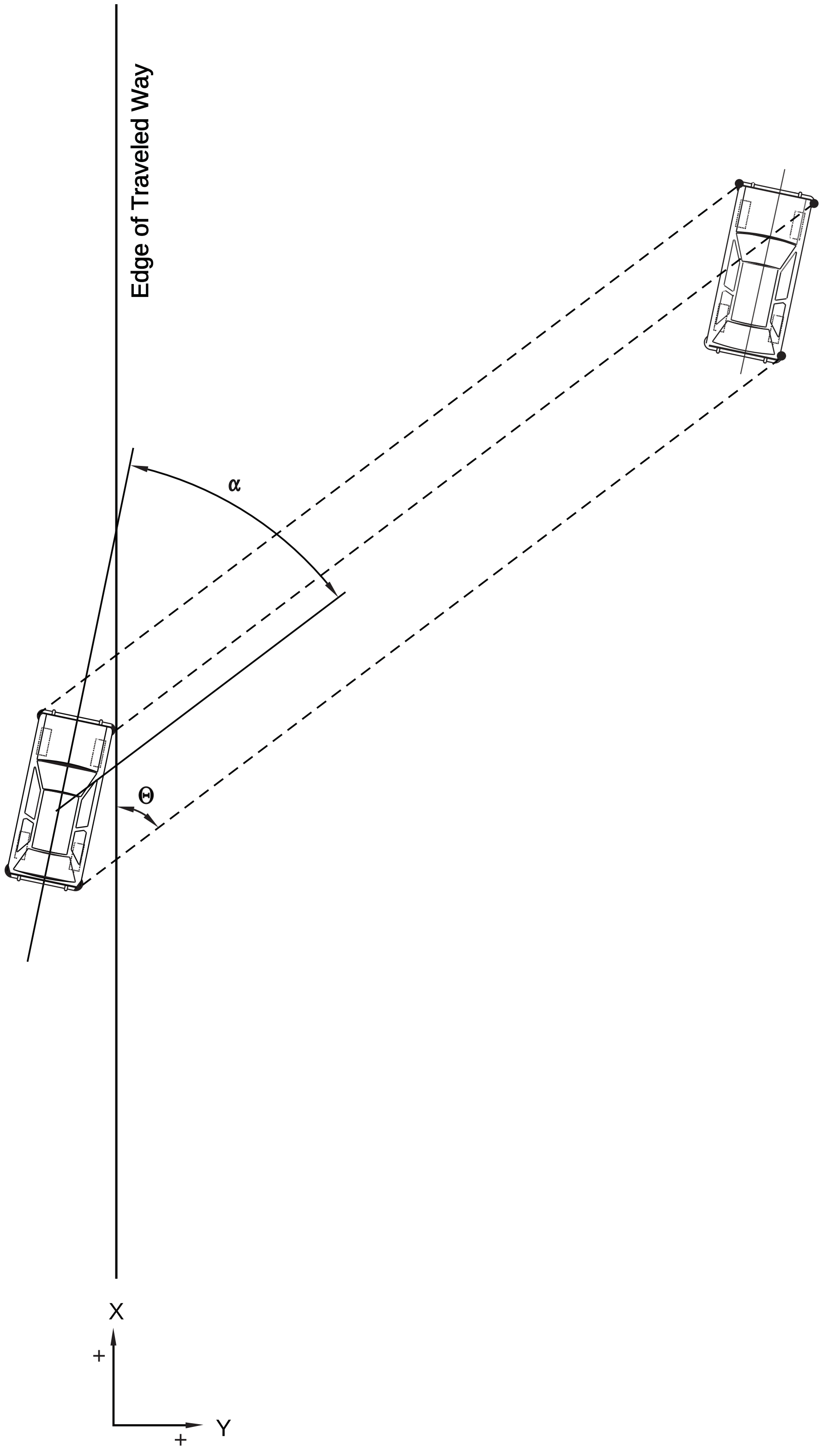

FIGURE A.3 Vehicle path and impact envelope

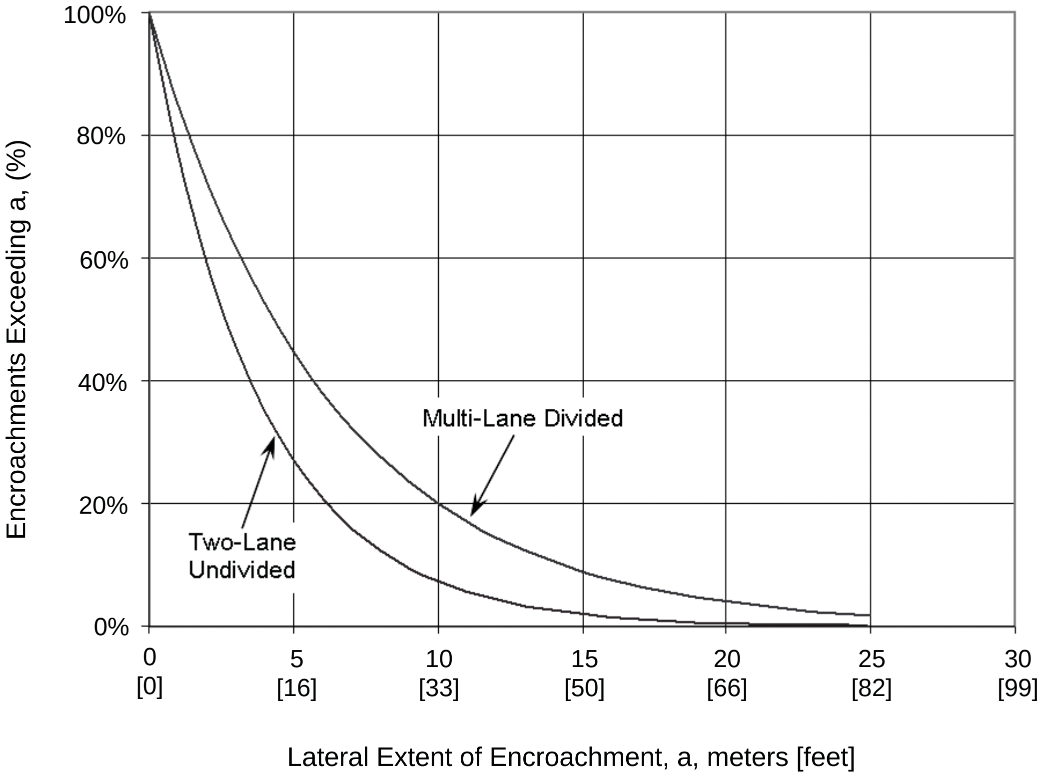

FIGURE A.4 Lateral extent of encroachment distribution

Each crash predicted by the crash prediction module is associated with a particular roadside feature or hazard, vehicle type, impact speed, impact angle, and vehicle orientation. This information is then used by the severity prediction module to estimate the severity, $P(I_i|A)$, and associated costs, E(AC), for the crash. For a given roadside object or feature and impacting vehicle, the conditions under which the vehicle impacts the roadside feature, i.e., speed, angle and vehicle orientation, determine the outcome and severity of the crash. In the case of a roadside safety device, e.g., a guardrail, crash cushion, etc., the performance limit of the safety device should also be taken into account. For example, the severity of an impact involving a longitudinal barrier is much different if the vehicle is successfully redirected than if the vehicle penetrates the barrier or rolls over. Separate procedures for determining impact performance are developed for each roadside hardware feature included in the model. Also, these procedures are vehicle dependent, i.e., different techniques are used to estimate rollover or vaulting potentials for passenger cars and trucks.

Crash severity is expressed in terms of a severity index (SI), which is a surrogate measure for injury probability and severity. Table A.1 illustrates the relationships of severity indices and probability of injury for various injury levels.

The severity indices used in the RSAP program are basically those used in the ROADSIDE program with some modifications. Specifically, severity indices are expressed as a function of impact speed instead of roadway design speed. In the *Roadside Design Guide* (2), average severities or SI values are provided for the various roadside objects and features for design speeds of 50, 70, 90, and 110 km/h [30, 45, 55, and 70 mph], which were assumed to be the design speeds for urban collectors, rural collectors and urban arterials, rural arterials, and freeways and interstate highways, respectively. For each roadside object or feature, a linear regression line was fitted through these SI values as a function of speed. Note that these regression lines would almost always originate from the zero point since an impact speed of zero (0) km/h [0 mph] should not produce any damage to the vehicle or injury to the occupants. Figure A.5 shows an example of this linear relationship between SI and impact speed.

TABLE A.1 Relationship of Severity Indices (SI) and probability of injury

Severity Index (SI)	Injury Level (%)						
	None	PDO1	PDO2	C	B	A	K
0.0	100.0	—	—	—	—	—	—
0.5	—	100.0	—	—	—	—	—
1.0	—	66.7	23.7	7.3	2.3	—	—
2.0	—	—	71.0	22.0	7.0	—	—
3.0	—	—	43.0	34.0	21.0	1.0	1.0
4.0	—	—	30.0	30.0	32.0	5.0	3.0
5.0	—	—	15.0	22.0	45.0	10.0	8.0
6.0	—	—	7.0	16.0	39.0	20.0	18.0
7.0	—	—	2.0	10.0	28.0	30.0	30.0
8.0	—	—	—	4.0	19.0	27.0	50.0
9.0	—	—	—	—	7.0	18.0	75.0
10.0	—	—	—	—	—	—	100.0

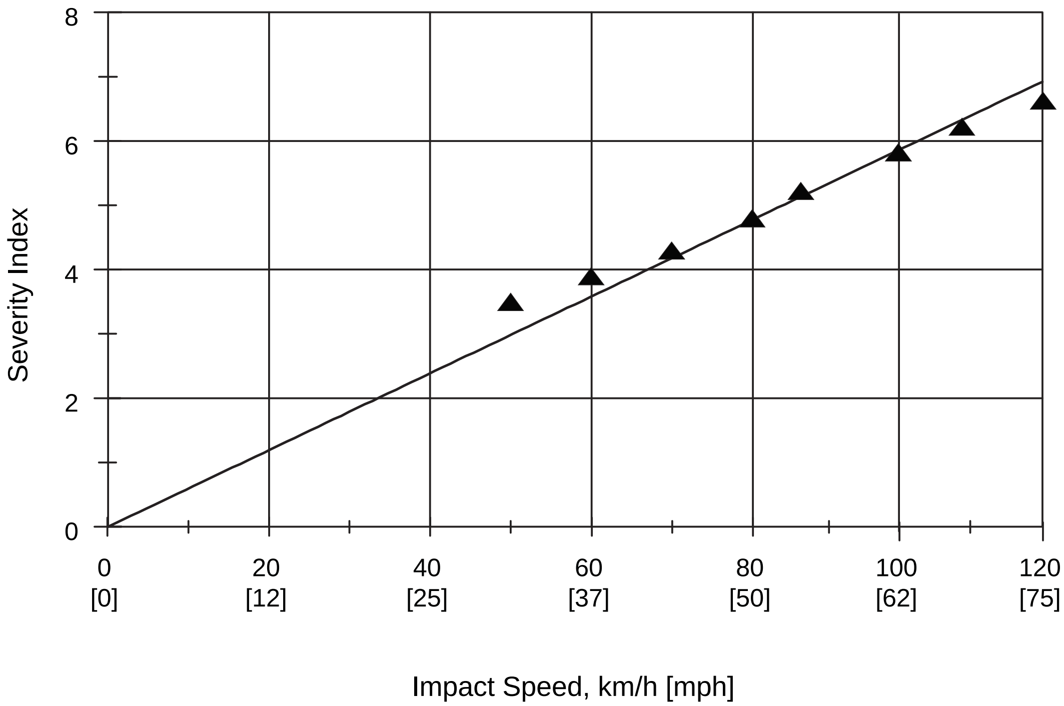

FIGURE A.5 Example of relationship between Severity Index (SI) and impact speed

This simplistic calibration method removed some of the inconsistencies in the earlier ROADSIDE SI tables. More importantly, it relates SI values to specific impact speeds for each roadside object or feature instead of average SI values. There are, however, two exceptions to this procedure. First, large vertical drops would not necessarily have an SI value of zero for an impact speed of zero because gravity would also play a large role in the probability of vehicle damage and occupant injury. Therefore, the regression lines for vertical drops were not fitted through the zero point. Second, lateral speed, V_{lat} , was used instead of impact speed for the SI relationships of longitudinal barriers since the severity of a longitudinal barrier impact is a function of both the impact speed and the impact angle. ($V_{lat} = V*\sin\theta$, where V is the impact speed and θ is the impact angle.)

A2.4 BENEFIT/COST MODULE

After the severity of a crash is estimated by the crash severity prediction module, the crash or societal costs associated with the crash are then calculated by multiplying the probability of each level of injury by the cost associated with that level of injury.

$$AC = \sum_{i=1}^{n} P(I_i) * C(I_i)$$

where:

AC = crash cost

$P(I_i)$ = probability of injury severity level "i"

$C(I_i)$ = cost associated with injury severity level "i"

n = total number of injury severity levels

As previously shown in Table A.1, the severity index (SI) is associated with six injury levels: fatality (K), severe injury (A), moderate injury (B), slight injury (C), property-damage-only level 2 (PDO2), and property-damage-only level 1 (PDO1). The severity estimate of the crash is then converted to crash costs using crash cost figures selected by the user. The program offers the choice of crash cost figures from the AASHTO *Roadside Design Guide* (2) or the FHWA comprehensive cost figures based on the willingness to pay approach, as shown in Table A.2. Alternatively, the user can input values for crash costs for various injury severity levels to suit the particular needs of the agency.

The crash costs are normalized to an annual basis. The normalization process involves two steps:

1. The crash cost is divided by the weighted number of encroachments and then multiplied by the expected number of encroachments per year to convert to an annual basis.

2. The crash cost is unweighted to arrive at the true crash cost. As discussed previously, the probability distributions for various encroachment characteristics are weighted to ensure proper sampling of conditions with very low probabilities to improve the accuracy of the analysis results and the speed at which the RSAP program arrives at a solution.

The direct costs, which include the costs for initial installation of the safety feature, normal maintenance, and repair of damages from crashes, are also normalized to an annual basis. The initial installation is converted to an annual basis using the project life and the discount rate. The normal maintenance cost is already entered on an annual basis. The cost of repairing roadside safety hardware is estimated by correlating repair costs to impact energy terms. For example, results from full-scale crash testing and computer simulations are used to determine the relationship between impact energy terms and length of guardrail damage. The unit repair cost for a typical guardrail, e.g., $50.00 per meter [$15.24 per foot] is then estimated. The total repair cost is therefore the product of the length of damaged rail and the unit cost for repair. Procedures for estimating the extent of hardware damage are developed for each longitudinal barrier design, as well as most common crash cushions, barrier terminals, and other roadside safety devices.

Incremental benefit/cost ratios are then calculated for all alternatives in a pairwise manner. As shown previously, the expression for calculating the incremental benefit/cost ratios is as follows:

$$\text{B/C Ratio}_{2-1} = (AC_1 - AC_2)/(DC_2 - DC_1)$$

where:

B/C Ratio_{2-1} = incremental benefit/cost ratio of Alternative 2 compared to Alternative 1

AC_1, AC_2 = annualized crash or societal cost of Alternatives 1 and 2

DC_1, DC_2 = annualized direct cost of Alternatives 1 and 2

The numerator of this equation is the difference in crash or societal costs between the two alternatives. Since Alternative 2 is being evaluated as a potential safety

TABLE A.2 Crash cost figures*

Crash Severity	*Roadside Design Guide*	FHWA Comprehensive Cost
Fatal Crash	$1,000,000	$2,600,000
Severe Injury Crash	200,000	180,000
Moderate Injury Crash	12,500	36,000
Slight Injury Crash	3,750	19,000
PDO Crash Level 2	3,125	2,000
PDO Crash Level 1	625	2,000

* Crash cost figures are based upon the 1996 edition of the *Roadside Design Guide* and a 1994 FHWA memorandum entitled "Update of Value of Life and Injuries for Use in Preparing Economic Evaluations."

improvement over Alternative 1, the societal or crash costs of Alternative 1 would be expected to be higher than those of Alternative 2. Thus, the numerator is expressed as (AC_1–AC_2). The denominator of the equation represents the differences in direct costs to the transportation agency associated with implementing the safety improvement of Alternative 2 in relation to Alternative 1. Again, since Alternative 2 is being evaluated as a potential safety improvement over Alternative 1, the direct costs of Alternative 2 would be expected to be higher than those of Alternative 1. Hence, the denominator is expressed as (DC_2–DC_1).

A3.0 COMPARISON WITH ROADSIDE PROGRAM

Table A.3 presents the major differences between the RSAP program and the ROADSIDE program, which is the cost-effectiveness analysis procedure presented in previous versions of the *Roadside Design Guide*(2,3). ROADSIDE uses a constant encroachment rate of 0.0003 encroachment per km [0.0005 encroachment per mile] per year per ADT. The lateral extent of encroachment distribution is based on a constant deceleration rate of 3.66 m/sec/sec [12 ft/sec/sec], or 0.4 g, and a sine curve density function for steer back. In comparison, the RSAP program uses the Cooper encroachment data. Adjustments were made to account for encroachments with 4 m [13.1 ft] or less of lateral extent which might not have been detected due to presence of paved shoulders.

ROADSIDE uses a hypothetical distribution for encroachment speed based on design speed and an average encroachment angle based on the point-mass model. A constant deceleration rate of 3.66 m/sec/sec [12 ft/sec/sec], or 0.4 g, is assumed for calculating the impact speed from the encroachment speed. A straight path is assumed so that the impact angle is the same as the encroachment angle. In comparison, RSAP uses impact speed and angle distributions from real-world crash data. A straight path with no braking is assumed so that the encroachment speed and angle are the same as the impact speed and angle.

ROADSIDE uses only a single vehicle type and an average encroachment angle for the hazard imaging. Vehicle orientation is not taken into account. The program can handle only one hazard at a time and shielding of one hazard by another is not incorporated. For multiple hazards, each hazard has to be analyzed individually and the crash costs summed manually. In comparison, RSAP allows for 12 vehicle types. Vehicle orientation is incorporated into the program based on real-world crash data. Hazard imaging is based on the size of the vehicle, encroachment angle, and vehicle orientation. The program can handle multiple hazards with algorithms to account for shielding of one hazard by another and multiple impacts.

ROADSIDE uses an average severity index without accounting for speed. RSAP estimates severity as a function of impact speed instead of an average value. These improvements incorporated into RSAP provide better severity estimates, which is perhaps the most critical element for estimating crash costs. Further, ROADSIDE assumes that all impacts with a hazard shielded by a barrier are eliminated, regardless of barrier length. RSAP allows for impact with a hazard shielded by barrier if the vehicle encroaches upstream of the barrier.

A4.0 SUMMARY

This appendix provides a summary of the conceptual framework and algorithms contained in the RSAP computer program, which has been created to assist in the economic analysis of existing or proposed roadside conditions. For users desiring more detailed information, please refer to the *Engineer's Manual*. Also, for detailed descriptions on the operation of the RSAP program, please refer to the *User's Manual*.

TABLE A.3 Comparison between RSAP and ROADSIDE programs

Data Element	ROADSIDE	RSAP
Encroachment Rate	A constant of 0.0003 encroachments per km per year [0.0005 encroachments per mi per year] per vehicle per day	Cooper encroachment data, adjusted for encroachments with lateral extent $\leq 4\text{ m}\left[13.1\text{ ft}\right]$
Encroachment Speed	Function of design speed	Same as impact speed
Encroachment Angle	Average angle based on point-mass model	Same as impact angle
Impact Speed	= Encroachment speed–speed loss with 3.66 m/sec/sec [12 ft/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
Lateral Extent of Encroachment	Assumes 3.66 m/sec/sec [12 ft/sec/sec] [0.4 g] deceleration rate and sine curve density function for steer back	Cooper encroachment data, lateral extent $\leq 4\text{ m}\left[13.1\text{ ft}\right]$
Vehicle Type	One	12 vehicle types, based on nominal percent trucks
Vehicle Orientation	None	Based on real-world crash data
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
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

The RSAP program presents many new advances and features over its predecessors. Highlights of the improvements incorporated into the RSAP program are summarized as follows:

- A user-friendly interface with WINDOWS-like screens and menus to facilitate easier use of the program by inexperienced users. Features of the User Interface Program include:

  –simplified data input process with multiple choice entries where appropriate,

  –numerous built-in default values to reduce data entry requirements,

  –on-screen instructions and help,

  –built-in edit and consistency checks,

  –options to choose built-in default values or input user-defined values for crash cost figures and vehicle mix, and

  –choice of reports to preview or print to hard copies or electronic files.

- Capability to 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. The program is capable of simultaneously analyzing hazards on either or both sides of the roadway as well as in the median for a divided roadway.

- Use of a stochastic solution method with the Monte Carlo simulation technique to allow for modular design of the Main Analysis Program. The program can be updated in the future without a major rewrite of the source code to incorporate such new features as curvilinear vehicle path, driver inputs, side impacts, etc.

- Use of re-analyzed Cooper encroachment data for encroachment rates and lateral extent of encroachment distributions with adjustments for under-reporting of encroachments with small lateral extent due to presence of paved shoulders and controlled versus uncontrolled encroachments.

- Use of real-world crash data for impact speed and angle distributions instead of theoretical distributions.

- Incorporation of vehicle orientation into the analysis code to better define vehicle swath or impact envelope. More importantly, this would allow for future consideration of non-tracking crashes and side impacts, which account for a significant percentage of run-off-the-road crashes and have been shown to result in higher severities than tracking crashes.

While the RSAP program is an improvement over existing procedures, it also has drawbacks and limitations, most of which are the result of lack of available data or which require a level of effort beyond that available for this study. Some of the limitations and future modifications and refinements are as follows:

- **Applications.** The RSAP program is intended for the evaluation of safety treatments for hazards/ features along the roadside or in the median and cannot handle other applications, such as crossover crashes at narrow median sites.

- **Computational time.** The use of the Monte Carlo simulation technique requires longer computational time.

- **Multiple solutions.** Due to the nature of the stochastic process, the solutions or answers will vary from run to run within a range as determined by the convergence criteria. This variation for a given project can be eliminated by using the same seed number for all the runs, which is an option provided in the program.

- **Encroachment data.** The Cooper encroachment data are almost 30 years old and many improvements to vehicle and highway designs have been implemented in the interim. The encroachment probability model can greatly benefit from better encroachment data.

- **Vehicle path.** The RSAP program does not currently take into account vehicle and driver behavior during encroachments due to lack of available data. The incorporation of curvilinear vehicle paths, vehicle orientation, and slope effects would significantly improve crash prediction and impact severity estimation.

- **Extent of lateral encroachment distributions.** The effects of roadside slopes and geometrics are not adequately addressed in the current distributions for the extent of lateral encroachment.

- **Crash severity.** The severity index approach currently incorporated in the RSAP program has many limitations. A better approach to estimate severity, such as the probability of injury approach, would be highly desirable. In the interim, the severity indices of individual roadside objects or features could benefit from a critical review and then revised as appropriate.

- **Impact models.** The impact models for predicting vehicle penetration and rollover that are incorporated into the RSAP program are relatively simplistic in nature and could benefit from more sophisticated and better validated models.

Finally, it should again be emphasized that the RSAP program is intended as a tool for economic analysis and should not supersede the guidelines presented in the *Roadside Design Guide* or sound engineering judgment.

REFERENCES

1. *Guide for Selecting, Locating, and Designing Traffic Barriers*. American Association of State Highway and Transportation Officials, Washington, DC, 1977.

2. *Roadside Design Guide*. American Association of State Highway and Transportation Officials, Washington, DC, 1996.

3. *Roadside Design Guide*. American Association of State Highway and Transportation Officials, Washington, DC, 1989.

4. "Benefit to Cost Analysis Program," Publication No. FHWA-TS-88. Research, Development, and Technology, Turner-Fairbank Highway Research Center, 6300 Georgetown Pike, McLean, VA, June 1988.

5. *Guide Specifications for Bridge Railings*. American Association of State Highway and Transportation Officials, Washington, DC, 1989. (archived publication)

6. Hutchinson, J. W. and T. W. Kennedy. "Medians of Divided Highways—Frequency and Nature of Vehicle Encroachments," *Engineering Experiment Station Bulletin 487*. University of Illinois, June 1966.

7. Cooper, P. "Analysis of Roadside Encroachments—Single Vehicle Run-Off-Road Accident Data Analysis for Five Provinces," *B. C. Research*. Vancouver, British Columbia, Canada, March 1980.

8. Moskowitz, K. and W. E. Schaefer. "Barrier Report," *California Highways and Public Works*, Vol. 40, Nos. 9–10, September–October, 1961.

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

10. Perchonok, K., T. A. Ranney, A. S. Baum, D. F. Morris, and J. D. Eppich. "Hazardous Effects of Highway Features and Roadside Objects," Vol. 2, Report No. FHWA-RD-78-202, September 1978.

11. Mak, K. K., D. L. Sicking, and H. E. Ross Jr. "Real-World Impact Conditions for Ran-off-the-Road Accidents," *Transportation Research Record 1065*. Transportation Research Board, Washington, DC, 1986.