NCHRP REPORT 486

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systemwide Impact of Safety and Traffic Operations Design Decisions for 3R Projects

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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FOREWORD

By Charles W. Niessner
Staff Officer
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This report presents the findings of a research project to develop a resource allocation process that optimizes systemwide safety for a set of potential resurfacing projects while not exceeding a specified improvement budget. The project objective has been accomplished with the development of the Resurfacing Safety Resource Allocation Program (RSRAP), which is provided on CD-ROM with this report. The report will be of particular interest to planning/design engineers with responsibility for determining the level of safety enhancements that can be included within a specified improvement budget.

Highway agencies face a dilemma in determining the appropriate balance of resurfacing and safety improvements in their programs. From a design perspective, it is becoming increasingly difficult to find an appropriate balance between the need to rehabilitate the pavement structure and the desire to provide the highest possible level of systemwide safety and traffic-operational efficiency given limited resources. Budget limitations may restrict some highway agencies to resurfacing roads without making any geometric improvements. This strategy may miss the opportunity to make cost-effective safety improvements. Other highway agencies have attempted to upgrade every roadway to full geometric design criteria whenever a roadway is resurfaced. This strategy may lead highway agencies to make safety improvements that are not cost-effective.

Under NCHRP Project 3-56, “Systemwide Impact of Safety and Traffic Operations Design Decisions for Resurfacing, Restoration, and Rehabilitation (3R) Projects,” the Midwest Research Institute undertook research to develop a process for allocating resources to maximize the effectiveness of 3R projects in improving safety and traffic operations on the nonfreeway highway network.

RSRAP allows highway agencies to maximize the cost-effectiveness of the funds spent on 3R projects by improving safety on nonfreeway facilities while maintaining the structural integrity and ride quality of the highway pavement. In order to do this, the process considers

- A specific set of highway sections that are in need of resurfacing either at the present time or within the relatively near future;
- A specific set of improvement alternatives for each candidate site including doing nothing, resurfacing only, and various combinations of safety improvements for the site; and
- A limit on the funds available for improvements to the set of highway locations.

The result of the process is a recommended improvement alternative for each highway section that results in the maximum net safety benefit while not exceeding the available budget. The process identifies the highest priority improvements, those that should be made during the next construction season.

The process is structured so that it can be used by highway agencies in two different ways. These are as follows:

- Option 1—Optimize Safety Improvements. The objective of this option is to select the safety or operational improvements that should be implemented at a given set of locations that have already been scheduled for resurfacing during a specific year. This option would be appropriate for those agencies that (a) budget funds for safety improvements separately from resurfacing funds and (b) want to maximize the net benefits from those safety improvements.
- Option 2—Optimize Both Resurfacing and Safety Improvements. The objective of this option is to select both the projects that should be resurfaced and the safety improvements that should be implemented from among a given set of locations for which a decision has not yet been made about resurfacing during a specific year. This option would be appropriate for a highway agency that wants to maximize the net benefits from the combined resurfacing and safety improvement program.

RSRAP is applicable to two-lane highways, multilane undivided highways, and multilane divided highways without control of access. The types of safety improvements that are considered are those that can be accomplished in conjunction with resurfacing projects and that do not require complete reconstruction or replacement of the pavement structure. Major projects, such as realignment of an entire roadway section or adding a lane, were not considered because such projects would typically be designed in accordance with AASHTO Green Book criteria, or equivalent state geometric design criteria, as a matter of policy.

RSRAP has been developed to be applicable to any improvement program that involves resurfacing and safety improvements on nonfreeway facilities. The process is not tied in any way to the federal 3R program. Thus, it is applicable to sites being considered for the federal 3R program, for sites being considered for state programs conducted with 100-percent state funds, or for a mixture of sites considered for both types of programs.

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Note: Part 1 and Part 2 have their own Contents pages.

PART 1:
FINAL REPORT

CONTENTS

SYSTEMWIDE IMPACT OF SAFETY AND TRAFFIC OPERATIONS DESIGN DECISIONS FOR 3R PROJECTS

SUMMARY

Highway agencies face a dilemma in determining the appropriate balance of resurfacing and safety improvements in their programs to maintain the structural integrity and ride quality of highway pavements. Because of budget limitations, some highway agencies may prefer to resurface roads without making any accompanying geometric improvements. This strategy may miss the opportunity to make cost-effective safety improvements. Other highway agencies have been encouraged by safety advocates to upgrade every roadway to full geometric design criteria whenever a roadway is resurfaced. This strategy may lead highway agencies to make safety improvements that are not cost-effective; such improvements require funds that could produce greater safety benefits if they were applied at other sites where a safety improvement would be cost-effective.

Highway agencies currently lack a tool that would allow them to consider the trade-offs between the competing goals described above. Specifically, highway agencies need a tool to determine which sites should be resurfaced without accompanying safety improvements and which sites should be resurfaced and improved in other ways that would enhance safety. A resource allocation process that maximizes the benefits from resurfacing and safety improvements within a specified improvement budget can provide such a tool.

A resource allocation process that accomplishes this goal has been developed and implemented in a software tool known as the Resurfacing Safety Resource Allocation Program, or RSRAP. RSRAP uses an optimization process based on integer programming to determine which improvement alternatives (or combinations of alternatives) would optimize the benefits for a specified set of improvement projects. The goal of the optimization process is not to optimize safety at any particular site but to optimize systemwide safety for a given set of resurfacing projects while not exceeding a user-specified improvement budget.

RSRAP can be used to evaluate trade-offs between expenditures for resurfacing and safety improvements. It can also be used to evaluate trade-offs among alternative safety improvements for a set of projects for which a decision to resurface the pavement has already been made. The RSRAP software is available for use by highway agencies and is provided on CD-ROM with this report.

In developing the resource allocation process and the RSRAP software, several key issues had to be addressed. The safety effectiveness of alternative improvements is estimated from the results of the best available safety research. The priority assigned to resurfacing is based on a user-supplied estimate of the time remaining before resurfacing is necessary to avoid a complete pavement failure (i.e., a failure that requires the pavement structure to be replaced down to the subgrade).

There has been a long-standing debate about whether pavement resurfacing leads to an increase in speeds, which may, in turn, lead to an increase in accidents. Field studies in the research for this report found that resurfacing results in an average increase of approximately 1 mph in mean and 85th-percentile vehicle speeds. However, this effect may vary substantially from site to site and is probably short-lived. Research results on the effect of resurfacing on accidents are inconsistent—resurfacing appears to increase accidents in some cases and to decrease accidents in others. Based on the best available study, the resource allocation process developed in the research for this report assumes an increase in accidents for a period of 12 to 30 months following resurfacing. However, because it is uncertain whether or not resurfacing has this effect on safety, users of RSRAP can elect either to include this effect or not to include it in the resource allocation process.

CHAPTER 1

INTRODUCTION

BACKGROUND

Highway agencies face a dilemma in determining the appropriate balance of resurfacing and safety improvements and the appropriate balance of large and small projects in their programs to maintain the structural integrity and ride quality of highway pavements. Highway agencies have a responsibility to the traveling public to maintain the pavements of all roads under their jurisdiction in serviceable condition. Furthermore, timely resurfacing is essential to prevent degradation of the pavement structure; if resurfacing is postponed too long, it may become necessary to replace the entire pavement structure down to the subgrade, which involves a large and unnecessary cost to the public. On the other hand, highway agencies also have a responsibility to make geometric improvements to enhance both the safety and traffic-operational efficiency of the roads under their jurisdiction. Clearly, there are economies of scale in making geometric improvements in conjunction with resurfacing and restoration projects. Existing knowledge of the safety and traffic-operational effects of geometric improvements has not previously been sufficiently organized and evaluated to assist highway agencies in assessing the trade-offs between these competing goals. The existing knowledge is also insufficient to optimize, on a systemwide basis, the safety and operational benefits of geometric improvements while still meeting the obligations to maintain the pavement structure of the roads under a highway agency's jurisdiction.

Highway agencies have struggled for many years with the trade-offs among the competing goals described above and to square their own perceptions of the interests of the traveling public with conflicting advice and conflicting requirements from the federal government, safety advocates, and other sources. Key questions in the ongoing debate are listed below.

Question 1—What are the effects of various types of geometric improvements on safety?

Question 2—What are the effects of various types of geometric improvements on traffic operations?

Question 3—Does resurfacing of a roadway without accompanying geometric improvements lead to higher speeds, and do those higher speeds, in turn, increase traffic accidents? If so, does the increase in accident frequency with resurfacing occur for all types of sites, or only for sites with particular geometric elements that do not fully comply with the geometric design policies used for new highway construction, particularly the AASHTO *Policy on Geometric Design of Highways and Streets* (also known as the Green Book) (*1*)?

Question 4—What level of investment in safety and traffic-operational improvements should accompany resurfacing programs?

Question 5—Which of the following improvement strategies will provide the maximum net benefits to the traveling and taxpaying public, considering both highway agency and user costs within a given level of available resources:

- Resurfacing roadways without any accompanying geometric improvements?
- Resurfacing roadways while improving all geometric elements to full compliance with AASHTO design policies for new construction?
- Resurfacing roadways while improving all geometric elements to state resurfacing, restoration, and rehabilitation (3R) standards, which typically require fewer modifications than AASHTO policies for new construction?
- Resurfacing roadways while adopting a flexible strategy for geometric improvements in which some sites are improved to full compliance with AASHTO policies, other sites have some, but not all, geometric elements improved; and still other sites are resurfaced without geometric improvements?

Question 5 is equivalent to asking whether a blanket policy on geometric improvements in resurfacing projects should be adopted or whether optimal results would be obtained if geometric improvements were made selectively, based on perceived need and anticipated cost-effectiveness. In other words, will optimal benefits to the traveling public result from a few large projects, or from many smaller projects, or from some mix of small and large projects?

Question 6—What analytical tools (i.e., resource allocation models) can be used to determine the most appropriate mix of geometric improvements in resurfacing projects?

This debate has been ongoing at least since the advent of the Federal-Aid 3R program that was established by the Federal-Aid Highway Act of 1976. With the advent of the 3R program, AASHTO published, in 1977, a *Geometric Design Guide for Resurfacing, Restoration, and Rehabilitation (RRR) of Highways and Streets* (*2*), also known as the Purple Pamphlet. The intent of this guide was to assist highway agencies to identify geometric features that should, and those that need not, be improved in conjunction with 3R projects. Controversy followed, as safety advocates sued the U.S. DOT to prevent the adoption of the AASHTO *Guide*, or similar reduced geometric criteria, as federal policy.

The key focus of the debate has been on nonfreeway facilities—highways with two-lane, multilane undivided, and multilane divided cross sections and without full access control—for several reasons. First, freeway facilities with full access control typically carry higher traffic volumes, making it easier to justify geometric improvements as cost-effective. Second, pavement damage from heavy vehicles often makes reconstruction (rather than just resurfacing) a preferred option for freeways at an earlier date than for nonfreeways. Third, improvements to interstate freeways have been funded under a different federal program that includes funding for reconstruction projects.

Subsequent to the controversy of the late 1970s, most state highway agencies proceeded to manage geometric improvements in conjunction with federal projects by requesting formal design exceptions for projects in which, in the agency's best judgment, it was not necessary to improve geometric elements that did not fully comply with AASHTO policy for new construction. Under this approach, decisions about appropriate geometric policies were made on a case-by-case basis. In recent years, some state agencies have adopted and obtained federal approval for formal policies on acceptable geometric design criteria for 3R projects. For example, both the New York State Department of Transportation (*3,4*) and the Illinois Department of Transportation (*5*) have published 3R geometric design guides. These guides are used to identify geometric elements that should be improved and geometric elements that are "allowed to remain in place" in 3R projects. Some state highway agencies that do not have formal 3R design policies continue to use the design exception process to obtain approval of geometric elements that depart from new construction standards in particular 3R projects.

A fundamental problem in both the design exception approach and the 3R design policy approach has been the lack of accepted research findings on the safety and operational effects of geometric improvements on which to base decisions concerning design exceptions or the adoption of 3R design policies. In the absence of reliable research, such decisions necessarily rely on engineering judgment.

It is clear that, for the six key questions identified above, answers to Questions 1 through 3 should lead directly to answers to Questions 4 through 6. In other words, if reliable data are available on the effects on safety and operations of various geometric improvements and the effects on safety of resurfacing with and without accompanying geometric improvements, resource allocation decisions can be made on the basis of those data. With reliable data on the effects of geometric improvements and resurfacing, it would be possible to determine the appropriate level of investment in safety and operational improvements, to maximize the benefits from funds invested in safety and operational improvements, and to develop formal resource allocation models that address these issues.

In fact, research has been conducted to provide answers to Questions 1 through 3. For example, Question 1 has been addressed in a series of research studies and synthesis efforts, including *NCHRP Report 374: Effect of Highway Standards on Safety* (*6*), and an FHWA report by Harwood et al. (*7*), *Prediction of the Expected Safety Performance of Rural Two-Lane Highways*. Question 2 is addressed in part by the procedures of the *Highway Capacity Manual* (HCM) (*8*), in part by recent and ongoing research on design consistency for two-lane highways (*9,10*), and in part by research presented in this report. Question 3 has been addressed in research by Hauer, Terry, and Griffith (*11*). Many of the available data are uncertain and provide answers that are less than precise, but, given the research efforts that have been devoted in recent years to Questions 1 through 3, it is now feasible to formally investigate Questions 4 through 6 using the best available data for Questions 1 through 3. Part 1 of this report presents the results of such research.

RESEARCH OBJECTIVES AND SCOPE

The objective of the research presented in Part 1 of this report was to develop a process for allocating resources on a systemwide basis to maximize the effectiveness of 3R projects in improving safety and traffic operations on nonfreeway facilities while maintaining the structural integrity and ride quality of highway pavements. The process developed in the research can be used as a tool by highway agencies to allocate resources to specific 3R projects; in addition, the testing of the process during the research helped to illustrate the type of project mix that will maximize the benefits from funds spent on 3R projects, as well as the pitfalls of "suboptimization," when strategies not based on the expected safety and traffic-operational benefits are followed. Although the federal 3R program is the focus of the research, the process developed in the research is applicable to any resurfacing program in which specific projects may be supplemented by geometric improvements, including programs based on a mixture of federal and state funding.

The research focused on nonfreeway facilities because, for reasons stated above, decisions concerning whether to supplement resurfacing projects with geometric improvements are more difficult for projects on nonfreeway facilities than for projects on freeways. The great majority of the nonfreeway mileage for which 3R projects are considered consists of two-lane highways, although multilane undivided highways and multilane divided highways without access control are also within the scope of the research. The project scope included a mix of urban, suburban, and rural locations.

The types of safety improvements that were considered within the scope of the research are those that can be accomplished in conjunction with resurfacing projects and those that do not require complete reconstruction or replacement of the pavement structure. The research also addressed projects involving traveled-way and shoulder widening, shoulder paving, roadway realignments at individual horizontal curves, added turn lanes at intersections, and roadside improvements. Several options for each project were considered, including resurfacing with no other accompanying improvements and resurfacing together with various combinations of safety improvements. Major projects, such as realignment of an entire roadway section or adding a lane, which would typically involve pavement reconstruction throughout the length of the project, were not considered because such projects would typically be designed in accordance with the full AASHTO Green Book criteria, or equivalent state geometric design criteria, as a matter of policy.

ORGANIZATION OF PART 1: FINAL REPORT

Chapter 2 summarizes the results of the literature review that was conducted as part of the research. Chapter 3 presents a review of the 3R policies and practices of highway agencies. Chapter 4 presents the results of the research conducted to determine the effects of resurfacing on safety and traffic operations. Chapter 5 presents the components of the resource allocation process to maximize the cost-effectiveness of resurfacing projects; this resource allocation process was developed as part of the research. Chapter 6 describes the development, demonstration, testing, and evaluation of the RSRAP software developed to implement the resource allocation process and includes application examples that illustrate the resource allocation process. Chapter 6 also demonstrates benefits of the resource allocation process that are not available in other methodologies. Chapter 7 presents the conclusions and recommendations reached during the research project.

CHAPTER **2**

LITERATURE REVIEW

This chapter presents the results of the literature review conducted as part of the research. The topics addressed are safety effects of geometric design features, safety effects of resurfacing, traffic-operational effects of resurfacing, and resource allocation models.

SAFETY EFFECTS OF GEOMETRIC DESIGN FEATURES

An important aspect of the literature review has been documentation of the safety effects of specific geometric design features. Key sources in the literature that have been considered in this effort include

- *NCHRP Report 374: Effect of Highway Standards on Safety* (*6*).
- The work of the TRB Study Committee on 3R Improvements, which resulted in the publication of TRB *Special Report 214: Designing Safer Roads: Practices for Resurfacing, Restoration, and Rehabilitation* (*12*) and TRB's *State-of-the-Art Report 6: Relationship Between Safety and Key Highway Features: A Synthesis of Prior Research* (*13*).
- The six-part FHWA series of chapters entitled *Synthesis of Safety Research* (*14*), which updated a previous FHWA synthesis report and a previous set of chapters published by the Highway Users' Federation.
- The evaluation of the effects of roadway and roadside cross-section design features conducted by Zegeer et al. in the FHWA reports, *Safety Effects of Cross-Section Design for Two-Lane Roads* (*15*) and *Safety Cost-Effectiveness of Incremental Changes in Cross-Section Design* (*16*).
- The extension of the above work to roadway cross-section features for low-volume roads presented in *NCHRP Report 362: Roadway Widths for Low-Traffic-Volume Roads* (*17*).
- The FHWA research report, *Cost-Effective Geometric Improvements for Safety Upgrading of Horizontal Curves* (*18*), and the related publication, *Safety Improvements on Horizontal Curves for Two-Lane Rural Roads—Informational Guide* (*19*).
- The FHWA research report, *Safety Effectiveness of Intersection Left- and Right-Turn Lanes* (*20*).

These sources, and others that have been reviewed, present varied estimates of the safety effectiveness of geometric design elements. To establish an accepted measure of the safety effects of specific geometric features, FHWA convened an expert panel. This panel performed a critical review of the available literature and recommended safety measures of effectiveness for selected geometric features. In some cases, the expert panel selected the results of a particular study as most credible; in other cases, the panel averaged the results of two or more credible studies. In still other cases, the panel used its own best judgment to establish a safety measure of effectiveness in light of the results reported in the literature. The development of the safety measures of effectiveness for two-lane highways is documented by Harwood et al. (*7*). This work was extended as part of the research for this report to include multilane undivided and divided highways.

The safety measures of effectiveness developed by Harwood et al. (*7*) are expressed as accident modification factors (AMFs). The AMF for the nominal or base condition for each specific geometric design or traffic-control feature has a value of 1.0. Any feature associated with higher accident experience than the nominal or base condition has an AMF with a value greater than 1.0; any feature associated with lower accident experience than the base condition has an AMF with a value less than 1.0. For example, an improvement with an AMF of 0.95 would be expected to decrease accident frequency by 5 percent, whereas an improvement with an AMF of 1.05 would be expected to increase accident frequency by 5 percent.

The AMFs for specific geometric and traffic-control improvements are presented in Chapter 5 of this report.

SAFETY EFFECTS OF RESURFACING

A key issue in the debate over the geometric design issues related to 3R projects has been the safety and traffic-operational effects of resurfacing with and without geometric improvements. The hypothesis of many engineers has been that resurfacing increases traffic speeds and, therefore, increases accidents. However, this effect is not well understood, and it is not clear to what extent the quality of roadway geometrics and the coefficient of friction of the pavement surface before and after resurfacing influence the effect of resurfacing on safety.

A paper by Cleveland (*21*) provides a literature review and some original data analysis on the safety effects of resurfacing projects. Cleveland concluded that there was substantial information on the safety effects of pavement skid resistance and pavement roughness but that further study of the safety effects of resurfacing was needed.

A recent study by Hauer, Terry, and Griffith (*11*), using data from the state of New York, used an Empirical Bayes (EB) approach to evaluate the effects of resurfacing. The study concluded that accidents did increase after resurfacing on "fast-track" projects (resurfacing only, with no accompanying geometric improvements), whereas accidents declined at intersections on reconditioning and preservation (R&P) projects that included geometric improvements and were unchanged at nonintersection locations. The results indicate that, for "fast-track" projects, accidents may return to pre-resurfacing levels after 12 to 30 months and may decline later. Thus, the potential increases in accidents associated with resurfacing appear to be short lived. R&P projects appeared to have no effect on nonintersection accidents and to reduce intersection accidents. The results of the study by Hauer, Terry, and Griffith are summarized in Tables 1 and 2. However, the authors concede that the scope of the study limited their ability to investigate anomalies in the analysis results, and lack of speed and friction data prevented verification of the cause-and-effect chain from resurfacing to increased speeds to increased accidents.

A more comprehensive database of the safety effects of resurfacing with and without geometric improvements, based on data from seven states, was assembled in NCHRP Project 179, but no conclusive results were found. A more detailed explanation of the problems encountered in this research is presented in Chapters 4 and 5.

TRAFFIC-OPERATIONAL EFFECTS OF RESURFACING

The traffic-operational effects of geometric features, primarily their effect on vehicle speeds, are well known and have been quantified in the HCM (*8*) and in design consistency research (*9,10*). However, the effect of pavement resurfacing on traffic operations has not been investigated previously.

TABLE 1 Safety effects of resurfacing projects without accompanying geometric improvements (*11*)

Accident type	Time after resurfacing	Percent change in crashes
Non-intersection	0 to 30 months	+21%
	40 to 63 months	0%
	> 63 months	Decline, % unknown
Intersection	0 to 12 months	+35%
	13 to 32 months	0%
	> 32 months	–23%

TABLE 2 Safety effects of resurfacing projects with accompanying geometric improvements (*11*)

Accident type	Time after resurfacing	Percent change in crashes
Non-intersection	0 to 70 months	No change
Intersection	0 to 70 months	–29%

As discussed above, safety analysts have long been concerned that, if an existing highway with restricted geometrics is resurfaced without improving those restrictive geometric features, an increase in traffic accidents might result. The working hypothesis of this view is that the smoother ride surface provided by resurfacing may encourage motorists to travel at higher speeds and, as a result, may lead to an increase in traffic accidents. However, the first portion of this hypothesis—that resurfacing increases vehicle speeds—has not been addressed in past research. However, data to address this issue were collected in the research for this report; the results from analysis of these data are presented in Chapter 4 and Appendix C.

RESOURCE ALLOCATION MODELS

Resource allocation models are used to identify activities or combinations of activities that optimize a program within a given funding level. In the context of this research, resource allocation models can be used to identify optimal combinations of resurfacing projects and geometric improvement alternatives within a specified budget constraint. The following discussion reviews the literature on resource allocation models, including the literature on benefit-cost techniques and optimization techniques.

McFarland et al. (*22*) provide a review of various benefit-cost and optimization techniques for maximizing the cost-effectiveness of highway safety improvement programs. The techniques reviewed include benefit-cost analysis, linear programming, and dynamic programming. The report of McFarland and colleagues has been reviewed as a source of ideas concerning applicable resource allocation techniques.

FHWA developed a resource allocation model for 3R projects in a 1980 report entitled *RRR Alternative Evaluations for Non-Interstate Rural Arterial and Collector Systems* (*23*). This study used a method referred to as the Performance Investment Analysis Process (PIAP) to analyze the effects of several hypothesized strategies for improving the geometrics of 3R projects to "minimum tolerable conditions" (*24*). The scenarios for geometric upgrading to "minimum tolerable conditions" included upgrading to conformance with new construction standards, upgrading to FHWA's proposed 1978 3R standards, and upgrading to a mid-level point between these two sets of standards. The PIAP procedures were subsequently renamed the Highway Investment Analysis Process (HIAP).

Smith et al. (*25*) have applied linear programming to test safety improvement strategies for rural two-lane highways. The objective of this effort was to determine, under various candidate budget levels, the number of miles of two-lane roads that should receive various types of geometric improvements (e.g., traveled-way widening, shoulder widening, or shoulder paving) in order to maximize the safety benefits from the specified level of expenditure.

Bellomo-McGee, Inc., has conducted research for the FHWA Office of Advanced Research to develop a multiobjective resource allocation model for highway improvements (*26*). A multiobjective resource allocation model can consider trade-offs among safety, traffic-operational, and other types of benefits without the need for all of those benefits to be expressed in monetary terms.

Each of these approaches is reviewed below.

Incremental Benefit-Cost Analysis

Benefit-cost analysis is the most traditional approach to resource allocation. This approach requires an estimate of the costs and benefits for each alternative resurfacing or resurfacing-plus-geometrics project that could be considered for each site under consideration. Typically, all costs and benefits, including safety and traffic-operational benefits, are expressed in monetary terms, which requires estimates of the dollar value of each accident reduced and the dollar value of travel time.

The most widely accepted procedures for benefit-cost analyses for highway applications are those found in the AASHTO *Manual on User Benefit Analysis for Highway and Bus Transit Improvements* (*27*). Typically, the most desirable improvements are those with the highest benefit-cost ratio:

$$\text{B/C Ratio} = \text{Benefits/Costs} \tag{1}$$

or the highest net return:

$$\text{Net Return} = \text{Benefits} - \text{Costs} \tag{2}$$

All benefits and costs must be expressed consistently on either an annual or present-value basis. Conversion of costs or benefits between an annualized and a present-value basis requires an estimate of the service life of the improvement and a specified minimum attractive rate of return (also known as the discount rate). The net return approach, illustrated in Equation 2, is generally preferred to the benefit-cost ratio approach, illustrated in Equation 1, because the net return approach avoids a largely meaningless debate about whether particular benefit and cost items belong in the numerator or the denominator of the benefit-cost ratio. Therefore, the net return approach represented by Equation 2 was chosen for use in the resource allocation process developed as part of the research.

When used as a resource allocation tool, rather than simply to assess the cost-effectiveness of a particular project, an incremental approach must be used. In other words, each additional increment of funds expended for any improvement project must be justified as cost-effective, in its own right, and more cost-effective than any alternative expenditure of those funds. The need for incremental analysis requires an iterative approach to project selection.

Linear and Integer Programming Methods

Another approach to resource allocation is mathematical programming, including the techniques of linear and integer programming. Mathematical programming methods are optimization techniques that are intended to maximize or minimize a specified quantity that is subject to specified constraints. This is, of course, precisely the goal of the planned analysis of 3R projects: to maximize the net benefits of 3R projects, which are subject to constraints such as overall cost.

The most common form of mathematical programming is known as linear programming. A typical linear program can be illustrated as follows:

Maximize (or minimize) Y, where

$$Y = c_1 x_1 + c_2 x_2 + \dots + c_n x_n \tag{3}$$

subject to:

$$a_{11} x_1 + a_{12} x_2 + \dots + a_{1n} x_n \leq b_1 \tag{4}$$

$$a_{21} x_1 + a_{22} x_2 + \dots + a_{2n} x_n \leq b_2 \tag{5}$$

$$\vdots$$

$$a_{m1} x_1 + a_{m2} x_2 + \dots + a_{mn} x_n \leq b_m \tag{6}$$

Equation 3 is known as the objective function of the linear program because it is used to determine Y, the objective that is to be maximized or minimized. The variables $c_1, \dots, c_n$ in the objective function are numerical values appropriate to the particular problem being evaluated; for example, $c_1, \dots, c_n$ might represent the costs and benefits of particular improvement types or projects. The variables $x_1, \dots, x_n$ in the objective function are called the decision variables, because assigning values to the variables is the decision that must be made. The decision variable in a linear program might represent, for example, the number of miles of roadway to be improved. All of the decision variables in a linear program are limited to nonnegative values (i.e., greater than or equal to zero). Equations 4 through 6 represent the constraints on the values of the decision variables. The variables $a_{11}, \dots, a_{mn}$ are the coefficients of the decision variables in particular constraints, and the variables $b_1, \dots, b_m$ are the limiting values in those constraints. Such constraints could be used to limit total expenditures to a fixed budget amount and to prevent incompatible or infeasible combinations of alternatives from being implemented. The number and complexity of the constraints considered will vary with the problem being evaluated. The constraints can be either equations (equalities) or inequalities. Because a linear program can address only one objective function, all costs and benefits would need to be put on a common basis, typically by expressing them in monetary terms.

An alternate form of the linear program presented in Equations 3 through 6 that uses summation notation is shown below.

Maximize (or minimize) Y, where

$$Y = \sum_{i=1}^{n} c_i x_i \tag{7}$$

subject to:

$$\sum_{i=1}^{n} a_{1i} x_i \leq b_1 \tag{8}$$

$$\begin{gathered} \sum_{i=1}^{n} a_{2i} x_i \leq b_2 \\ \vdots \end{gathered} \tag{9}$$

$$\sum_{i=1}^{n} a_{mi} x_i \leq b_m \tag{10}$$

In Equations 7 through 10, i is an index variable for the specific terms in the objective function and the constraints, and n is the maximum value of i. The subscript m represents the total number of constraints. The subscripted variables a, b, and c are the same variables used in Equations 3 through 6.

Previous FHWA research by Smith et al. has applied linear programming as a tool to select potential safety improvements for two-lane highways (*25*). In this effort, the safety and operational benefits of different geometric improvements for rural two-lane highways were estimated from the literature, and linear programming was used to estimate the number of miles of highway that should receive each type of improvement within a fixed overall budget.

Linear programming methods generally assume that the decision variables can take on values in any fractional amount. Thus, they are not directly suited to making a build/no-build decision. However, it is possible to structure a linear program so that a fractional value of a decision variable might represent a level of investment that ranges from the no-build decision to use of full new construction standards (for an example of this approach, see Weingartner's *Mathematical Programming and the Analysis of Capital Budgeting Problems* [*28*]).

A more suitable approach to the selection of the optimal set of 3R project alternatives can be accomplished with a variation of linear programming known as integer programming. In integer programming, the decision variables can assume only nonnegative integer values. In the case of a 3R project evaluation, the decision variables might be constrained so that only zero and one are acceptable values: one would be used if a particular design alternative were selected for implementation as part of a particular project, and zero would be used if that design alternative were *not* selected for implementation. If several alternative designs (including the no-build alternative) were considered for a given project, a constraint would be provided for each project to limit the number of alternatives selected for that project to one and only one; this would be a simple constraint in which the sum of the decision variables for all design alternatives for that project must be exactly equal to one.

Linear programs can be solved with mathematical techniques such as the Simplex algorithm and various Branch and Bound algorithms. These algorithms determine the values of the decision variables that produce the maximum (or minimum) value of the objective function, while not violating any of the constraints. Such algorithms can be applied manually, but, for any realistic problem, the computations quickly become quite laborious and repetitive. Computer software to solve linear and integer programs is commercially available.

Dynamic Programming

Dynamic programming provides a mathematical method for solving optimization problems that is applicable when the decision can be broken down into smaller subprograms or stages. When many feasible combinations of alternative solutions must be considered (such as multiple design alternatives for many candidate projects), a linear or integer program may become too large or too inefficient to solve directly. Dynamic programming provides an efficient method for finding an optimal solution to such problems. In applying dynamic programming, the problem is formatted as a decision tree, and the program evaluates portions of that decision tree on an iterative or recursive basis. The efficiency of a dynamic program comes about because once any portion of the decision tree is found to be suboptimal in the analysis of any stage, solutions involving that portion of the decision tree can be disregarded on the grounds that they would be suboptimal for the decision as a whole. Like incremental benefit-cost analysis and linear and integer programming, dynamic programming would necessarily address all costs and benefits in monetary terms. An example of the use of dynamic programming for optimizing highway safety improvements is presented by Pigman et al. (*29*).

Multiobjective Resource Allocation

Both incremental benefit-cost analysis and mathematical programming methods are constrained to the consideration of a single objective. This constraint is typically met by expressing all costs and benefits in dollar terms and then using an optimization technique to minimize costs and/or maximize benefits. In reality, however, there are always multiple objectives to be satisfied in any highway investment decision. Typical objectives of 3R projects include, at a minimum, preservation of the pavement structure, enhancement of safety, and enhancement of traffic operations. The attempt to express safety and traffic operations in dollar terms may lead to an incomplete view of these issues. The results of benefit-cost analyses concerning safety issues may be strongly affected by the values assigned to accident costs, especially when fatal accidents are being considered (*30*). Howard (*31*) has cautioned against the use of benefit-cost risk analyses because of the flaws inherent in the available analysis techniques. These flaws include the difficulty of quantifying benefits (benefits for whom and valued by whom) and quantifying costs for (who is going to pay and how will these costs be measured). Furthermore, there may be issues like environmental quality, historic preservation, and scenic beauty that are important considerations in 3R decisions, but that do not lend themselves to evaluation in dollar terms at all.

Highway agencies and researchers have used cost-effectiveness analysis approaches in safety analyses to avoid the necessity of expressing accident benefits in monetary terms. However, cost-effectiveness values are limited and are useful in only three cases (*32*): (1) when a particular alternative involves both the lowest cost and highest effectiveness, (2) when equal effectiveness is attributed to all alternatives, and (3) when all alternatives have equal costs. Furthermore, cost-effectiveness approaches cannot evaluate multiple objectives; that is, there is no practical method to consider both safety and traffic-operational effects in a cost-effectiveness analysis.

The interactive multiobjective resource allocation (IMRA) methodology can address multiple objectives in which, for example, costs and benefits are addressed in different units. Bellomo-McGee, Inc., has performed research for FHWA on the IMRA methodology (*26*). The FHWA Office of Advanced Research has been working to develop a generic safety resource allocation tool based on the IMRA methodology.

The IMRA methodology generates a set of options or solutions for allocating resources that simultaneously satisfies given objectives and constraints and then provides an interactive process between the analyst and the decision maker to make a final selection from the available options. It also provides a logical base to derive a limited number of most desirable options from a large number of otherwise possible options. The decision maker faces only a limited number of the most desirable options with a knowledge of the trade-offs among these options. This makes the decision-making situation very efficient.

The IMRA methodology was developed on the principles of multiobjective analysis. The fundamental concept of multiobjective analysis is based on nondominated or noninferior solutions (also known as Pareto optimal solutions). In a multiobjective problem, a nondominated, or noninferior, solution is one in which any improvement of one objective function can be achieved only at the degradation of another (*33*). A rational decision maker always chooses the "best" solution from among the set of nondominated or noninferior solutions.

Multiobjective analysis is a practical tool for real world applications as multiple conflicting objectives are encountered in all facets of problem-solving efforts. An example of a multiobjective problem would be a highway agency that is trying to minimize highway crash rates while trying to minimize the cost of crash countermeasures (such as resurfacing and widening) and trying to maximize the speed of traffic. These goals are conflicting in nature. There is no clear, optimal solution to satisfying all these goals simultaneously. With a single objective of minimizing the highway crash rates, or minimizing the cost of crash countermeasures, or maximizing the speed of the traffic, only one optimal solution would be derived. In a situation with more than one objective, all objectives should be satisfied simultaneously in the ultimate solution.

The IMRA methodology appears to be potentially useful as a decision-making tool for 3R projects. The IMRA methodology can be used to generate a set of solutions that will satisfy the multiple objectives of minimizing accidents, maximizing operational efficiency, and minimizing costs of implementation under limited resources. Unlike other resource allocation tools, which provide only one solution (which may not be appropriate when there is more than one objective), the IMRA methodology presents a set of "best" solutions (or best scope of project) based on given objectives and constraints. Each solution in this set meets the objective function criteria and is therefore feasible.

Once a set of "best" solutions is provided, the analyst can let the decision maker select an appropriate solution from among them. Alternatively, the analyst can pursue an interactive approach, guiding the decision maker to select a solution from the set of available solutions by generating trade-offs among different objective functions (termed the "best compromise solution"). The interactive part of the IMRA methodology graphically shows the trade-offs in terms of safety, traffic operations, and costs among different best possible scopes within a particular 3R project and guides decision makers to the best possible scope or the best compromise solution.

Conflicting objectives exist not only within a particular 3R project but also among different 3R projects. The IMRA methodology can also be used to provide the best set of projects to constitute a 3R program under given objectives and budget constraints. Again, the interactive part of the IMRA methodology can further limit the choices (i.e., find the "best of the bests") by showing objective trade-offs among different projects in terms of safety, traffic operations, and costs and by guiding the decision makers to the set of projects (narrowing down from the previous set) that will best satisfy safety, traffic-operation, and cost objectives.

The IMRA methodology currently exists as a mathematical algorithm. This algorithm can be executed by following a series of computational steps that have been specified. Although no computer program is currently available to implement the IMRA methodology, such a program could be developed using any high-level language such as Fortran, Basic, or C. One of the steps in the IMRA methodology requires a nonlinear optimization procedure, which can be provided by commercially available nonlinear optimization software.

Another multiobjective resource allocation approach was developed in NCHRP Project 20-29, "Development of a Multimodal Framework for Freight Transportation Investment: Consideration of Rail and Highway Trade-offs" (*34*). This approach is based on establishing rating scales for each goal or objective evaluated and developing formal weights for use in making comparisons across those various scales. The authors refer to this process as a multicriteria cost-benefit analysis (MCCBA).

Assessment of Alternative Resource Allocation Methods

There appears to be three alternative resource allocation methods that are suitable for evaluation of 3R projects but that would require all costs and benefits of 3R projects to be stated in monetary terms. These are

- Incremental benefit-cost analysis,
- Integer programming, and
- Dynamic programming.

The literature indicates that, given the same problem, all of these approaches (if properly formulated) would provide the same or nearly the same solution (i.e., there is generally a unique optimum solution). It appears that the greatest variety of existing software is available for the integer programming approach. In addition, McFarland et al. (*22*) indicate that integer programming is more efficient in use of computer time than dynamic programming and is conceptually simpler than incremental cost-benefit analysis. Therefore, a decision was reached to use integer programming in this research as the optimization technique for allocating resources for safety improvements in conjunction with resurfacing.

Multiobjective resource allocation methods were considered for use in the research, but the authors determined that these methods require too much intervention by the user and require relatively expensive software to implement. Therefore, multiobjective resource allocation methods were not recommended for this application.

CHAPTER **3**

3R POLICIES AND PRACTICES

This chapter presents the results of the review of 3R policies and practices conducted during the research. It presents an overview of the federal 3R program, a discussion of the magnitude of the 3R program, an overview of the recommendations of TRB *Special Report 214* (*12*) concerning the role of safety in the 3R program, a summary of the state highway survey conducted as part of the research, an overview of state highway agency 3R design policies, and a discussion of tort liability issues related to the 3R program.

OVERVIEW OF THE FEDERAL 3R PROGRAM

The federal program for 3R of existing Federal-Aid highways was created by the Federal-Aid Highway Act of 1976. Until that time, Federal-Aid funds could be used only for construction of new highways and for complete reconstruction of existing highways. However, the deterioration of the U.S. highway system, through lack of timely maintenance and the financial burden placed on the states for maintenance of the many miles of new highway projects constructed during the 1950s and 1960s, led Congress to authorize the expenditure of Federal-Aid funds for maintenance for the first time in 1976.

The 3R program is intended not only to extend the service life of highway pavements through resurfacing and restoration projects but also to enhance safety and traffic operations through accompanying geometric design improvements. Since the advent of the 3R program, highway agencies have faced two dilemmas in their programs to maintain the structural integrity and ride quality of highway pavements: determining the appropriate balance of resurfacing and geometric improvements and determining the appropriate balance of large and small projects.

Highway agencies have a responsibility to the traveling public to maintain the pavements of all roads under their jurisdiction in serviceable condition. Furthermore, timely resurfacing is essential to prevent degradation of the pavement structure; if resurfacing is postponed too long, it may become necessary to replace the entire pavement structure down to the subgrade, which involves a large and unnecessary cost to the public. On the other hand, highway agencies also have a responsibility to make geometric improvements to enhance both the safety and traffic-operational efficiency of the roads under their jurisdiction. Clearly, there are economies of scale in making geometric improvements in conjunction with resurfacing and restoration projects. Existing knowledge of the safety and traffic-operational effects of geometric improvements has not been sufficiently organized and evaluated to assist highway agencies in evaluating the trade-offs between these competing goals. The existing knowledge is also insufficient to optimize, on a systemwide basis, the safety and operational benefits of geometric improvements while still meeting obligations to maintain the pavement structure of the roads under the highway agency's jurisdiction. Highway agencies have struggled for many years with the trade-offs between the competing goals described above to square their own perceptions of the interests of the traveling public with conflicting advice and requirements from the federal government, safety advocates, and other sources.

The most widely used highway geometric design criteria are those presented in the AASHTO Green Book (*1*). The geometric design criteria in the current edition of the Green Book and its predecessors are intended to apply to new construction and major reconstruction of highways and streets. Thus, when the 3R program began, there were no established geometric criteria for projects that did not involve new construction or major reconstruction.

In 1977, AASHTO published a *Geometric Design Guide for Resurfacing, Restoration, and Rehabilitation (RRR) of Highways and Streets* (*2*), also known as the Purple Pamphlet. The intent of this guide was to assist highway agencies in identifying geometric features that should, and those that need not, be improved in conjunction with 3R projects. Controversy followed, as safety advocates sued the U.S. DOT to prevent the adoption of the AASHTO *Guide*, or similar reduced geometric criteria, as federal policy.

For several reasons, the focus of the debate has been nonfreeway facilities—highways with two-lane, multilane undivided and multilane divided cross sections and without full access control. First, freeway facilities with full access control typically carry higher traffic volumes that make it easier to justify geometric improvements as cost-effective. Second, pavement damage from heavy vehicles often makes reconstruction (rather than just resurfacing) a preferred option for freeways at an earlier date than for nonfreeways. Third, improvements to interstate freeways have been funded under the federal Resurfacing, Restoration, Rehabilitation, and Reconstruction (4R) program that includes funding for reconstruction projects.

Safety advocates pressed for FHWA to require states to improve all geometric elements that were not in full compliance with geometric design criteria for new construction in each 3R project. Although this would be an optimal policy if available resources were unlimited, it is not at all clear—in the real world of limited budgets—that such a policy would maximize safety benefits alone, much less result in an optimal mix of pavement rehabilitation and safety investments. The focus on project-by-project decision making discourages a systemwide view of the cost and benefits of 3R projects and increases the risk of suboptimization: safety and operational benefits are maximized for particular projects, but not for the highway system as a whole.

Subsequent to the controversy of the late 1970s, most state highway agencies proceeded to manage geometric improvements in conjunction with federal 3R projects by requesting formal design exceptions for projects in which, in the agency's best judgment, it was not necessary to improve geometric elements that did not fully comply with AASHTO policy for new construction. Under this approach, decisions about appropriate geometric policies were made on a case-by-case basis. In recent years, some state agencies have adopted, and obtained federal approval for, formal policies on acceptable geometric design criteria for 3R projects. Some agencies, such as the New York State Department of Transportation, have published a formal 3R geometric design guide as a stand-alone document, whereas other agencies, such as the Illinois Department of Transportation, have included in their geometric design manual both criteria for new construction and criteria for geometric elements that are "allowed to remain in place" in 3R projects. Other state agencies do not have formal 3R policies but continue to use the design exception process for 3R projects.

A fundamental problem in both the design exception approach and the 3R design policy approach has been the lack of research on the safety and operational effects of geometric improvements on which to base decisions concerning design exceptions or the adoption of 3R design policies. In the absence of reliable research, such decisions necessarily rely on engineering judgment.

MAGNITUDE OF THE 3R PROGRAM

Because of the flexibility available to state highway agencies under the current Federal-Aid highway program, the magnitude of the 3R program varies markedly from state to state and is difficult to document. The Federal-Aid Highway Act of 1976, which created the 3R program, required that at least 20 percent of the regular Federal-Aid funds for primary and secondary roadway systems be spent on 3R work. The Surface Transportation Assistance Act (STAA) of 1982 modified this provision so that at least 40 percent of primary, secondary, and urban system funds could be used on a combination of 3R work and reconstruction.

The Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) dispensed with the categorical funding programs by roadway system and provided flexibility for states to spend their allocated Federal-Aid funds on any type of qualifying project, including 3R work. This approach has been continued by the Transportation Equity Act for the 21st Century (TEA-21). For roadways that are part of the National Highway System (NHS) created by ISTEA, 3R work can be performed with a normal matching ratio of 80-percent federal funds and 20-percent state funds. Similarly, under the Surface Transportation Program (STP), 3R work can be done on any roadway, including NHS roadways that are not functionally classified as local or rural minor collectors. The STP program also normally involves an 80/20, federal/state matching ratio. The STP program earmarks specific portions of a state's available funding for safety projects, transportation enhancements with environmental benefits, and for urbanized and nonurbanized areas.

The flexibility provided to state highway agencies by ISTEA and continued by TEA-21 makes it difficult to determine just how much money states are spending on 3R work each year. Except for the STP earmarking of funds described above, there is essentially no required minimum or maximum amount of a state's Federal-Aid funding that must be spent on 3R projects. Furthermore, some 3R work that addresses both pavement rehabilitation needs and safety improvement needs is undoubtedly carried on under the STP hazard elimination program at sites with poor accident histories. Similarly, some 3R work that addresses both pavement rehabilitation needs and existing traffic-operational problems is undoubtedly carried on under the NHS operational improvement program. The flexibility of the current funding provisions makes it of little consequence whether 3R work that also accomplishes another purpose is classified as 3R work, hazard improvement work, or operational improvement work.

Finally, it must be recognized that, whereas substantial 3R work is accomplished with federal/state matching funds within the 3R program, much 3R work is also accomplished with 100-percent state funds outside the 3R program, just as it was before 1976. This makes it apparent that, whereas the Federal-Aid highway program has been the focus of the debate over the role of safety improvements in the 3R program, state highway agencies potentially face a similar dilemma in allocating funds among pavement, safety, and operation improvements in their own projects.

TRB SPECIAL REPORT 214

A major evaluation of the federal 3R program was undertaken during the mid-1980s by a special committee of TRB. The results of this evaluation were published in TRB *Special Report 214*: *Designing Safer Roads: Practices for Resurfacing, Restoration, and Rehabilitation* (*12*), which focused on the role of safety improvements in the 3R program. TRB

Special Report 214 reported the following findings on state practices for 3R projects:

- *3R design practices vary widely from agency to agency*. Safety is an important consideration in the 3R design practices of some highway agencies, whereas others do not put special emphasis on safety.
- *3R projects are initiated primarily to address pavement repair and rehabilitation needs*. Generally, safety is not considered in the programming stage. In many cases, by the time safety is considered, it is too late to accommodate any geometric improvements.
- *Federal-Aid 3R projects frequently widen lanes and shoulders but seldom reconstruct sharp curves or replace bridges with narrow decks*. Because there is a higher concentration of accidents at curves and bridges, improvements at these locations, despite high costs, can sometimes be more cost-effective with respect to safety than routine cross-section improvements.
- *Not enough is known about the safety gains that will occur after the geometry of existing highways is improved or other safety-oriented improvements are made.* The safety effects of geometric improvements are not well understood, and this seriously limits their cost-effective application in resurfacing practices.
- *Engineers who administer state traffic and safety programs seldom participate in the design of 3R projects*. This seriously limits the chances of a cost-effective and safety-conscious design process for 3R projects.

TRB *Special Report 214* recommended several practices for 3R projects under the following five categories:

1. Safety-conscious design process,
2. Design practices for key highway features,
3. Other design procedures and assumptions,
4. Planning and programming 3R projects, and
5. Safety research and training.

Table 3 shows different tasks recommended under these five categories.

TRB *Special Report 214* has had a substantial impact on reshaping the procedures used by state highway agencies in the design of 3R projects. Specific state highway geometric design policies applicable to 3R projects are reviewed in a later section of this report.

TABLE 3 Recommendations for 3R practices (*12*)

General category	Tasks
1. Safety-Conscious Design Process	1. Assessment of Site Conditions Affecting Safety 2. Determination of Project Scope 3. Documentation of the Design Process 4. Review by Traffic and Safety Engineers
2. Design Practices for Key Highway Features	1. Minimum Lane and Shoulder Widths 2. Horizontal Curvature and Superelevation 3. Vertical Curvature and Stopping Sight Distance 4. Bridge Width 5. Side Slopes and Clear Zones 6. Pavement Edge Drop and Shoulder Type 7. Intersections 8. Normal Pavement Crown
3. Other Design Procedures and Assumptions	1. Traffic Volume Estimates for Evaluating Geometric Improvements 2. Speed Estimates for Evaluating Geometric Improvements 3. Design Values for Geometric Improvements 4. Design Exceptions
4. Planning and Programming 3R Projects	1. Screening of Highways Programmed for 3R Projects 2. Assessment of the Systemwide Potential for Improving Safety
5. Safety Research and Training	1. Special Task Force to Assess Highway Safety Needs and Priorities 2. Compendium of Information on Safety Effects of Design Improvements 3. Increased Research on the Relationships Between Safety and Design 4. Safety Training Activities for Design Engineers

STATE HIGHWAY AGENCY SURVEY

A survey of the state highway agencies was conducted to gather more detailed information on practices related to safety improvements and resurfacing. A questionnaire, which is included in Appendix A, was mailed to the appropriate division responsible for the design of 3R projects within each of the 50 state highway agencies. A total of 36 of the 50 state agencies responded (72 percent).

The survey was conducted as part of NCHRP Project 17-9(2), "Safety Impacts of Resurfacing Projects With and Without Additional Safety Improvements." However, the questionnaire was designed to meet the needs of both Project 17-9(2) and the research conducted for this report.

Also, please note that a response to a specific question requiring either a "yes" or "no" answer was counted only when one of these responses was given. Therefore, although 36 agencies responded to the questionnaire, for some questions the total number of responses was less than 36. The percentages for specific responses given in the text are based on the actual total number of responses to that question (e.g., 28 of 35, or 80 percent).

Geometric Design Standards/Guidelines for 3R Projects

Most states (32 of 36, or 89 percent) responded that they have specific geometric design standards and/or guidelines for 3R projects that differ from the design standards or guidelines used for new construction. Many states provided us with a copy of their 3R guidelines. These guidelines are helpful in identifying a particular state's approach to considering safety in resurfacing projects. Chapter 4 addresses the specific state 3R design policies and how they relate to the recommendations of TRB *Special Report 214*.

Only one state responded that its geometric design standards for 3R projects do not differ from the design standards or guidelines used for new construction and that state does use design exception when appropriate for 3R projects.

Resurfacing Project Selection Process

The most common response to this question was that most states use pavement condition data to identify the need for resurfacing. Although many states did not indicate where these data reside, it is likely that most states maintain pavement condition data as part of their pavement management system. Some pavement condition data that are considered by states when selecting roads for resurfacing include roughness, distress, rutting, and skid resistance. Nine states specifically mentioned that they use their pavement management system in identifying and selecting roads for resurfacing. These responses indicated that most states use pavement condition criteria rather than accident experience in identifying and selecting roads for resurfacing.

The process of identifying and selecting roads for resurfacing was found to vary by highway agency district in 7 of 33 responding states (21 percent), by area (urban, suburban, or rural) in 9 of 33 states (27 percent), and by type of highway in 17 of 34 responding states (51 percent).

Safety Improvements Implemented in Conjunction with Resurfacing Projects

Respondents to the survey identified the following types of safety improvements as being made in conjunction with resurfacing projects (the numbers in parentheses represent the number of responses):

- Widen outside shoulders on horizontal curves (5);
- Add shoulders (2);
- Improve superelevation on horizontal curves (3);
- Increase the clear zone/remove fixed objects within the clear zone (7);
- Install signs/delineation/markings/raised markers, and so forth (15);
- Make minor alignment changes (6);
- Do minor widening (5);
- Add guardrail including end treatments, reconstruction, extension, addition, and removal and flattening slopes (1);
- Upgrade existing guardrail system (11);
- Extend culverts (3);
- Remove curbs (1);
- Remove headwalls (1);
- Build up shoulders (1);
- Upgrade earth shoulders to granular surfaced shoulders (2);
- Install or replace rumble strips (3);
- Mark and/or delineate pavement marking (10);
- Remove trees (1);
- Protect rock cuts (1);
- Install traffic-control devices (1);
- Add turn lanes at intersecting roads (5);
- Flatten slopes (5);
- Make minor drainage improvements (5);
- Install bendaway or breakaway sign supports (1);
- Add acceleration/deceleration lanes (1);
- Improve sight distance (7);
- Replace delineation signing (4);
- Upgrade breakaway features (1);
- Adjust guardrails (2);
- Upgrade barrier ends and barrier-end protections (1); and
- Install three-beam guardrail on standard bridge rail (1).

In addition to giving examples of specific improvements, some states explained their practices in selecting safety improvements in conjunction with resurfacing projects. Once identified, a safety deficiency may be corrected as part of the 3R project or may be programmed for correction as a separate project. One state indicated that they do not usually consider safety improvements in resurfacing projects; however, this state indicated that they do consider safety deficiencies for any project on the NHS.

Another state noted that they usually implement safety improvements based on the type of project. For example, for resurfacing projects, no safety improvement is usually made, but for projects involving rehabilitation work, potential improvements include minor widening and minor alignment changes.

A third state indicated that they consider potential roadside safety improvements in resurfacing projects. These safety improvements include clear zones, barrier warrants, barrier design, and drainage features. In addition to improving vertical/horizontal alignment changes and superelevation improvements, a fourth state indicated that they perform the following improvements in resurfacing projects: minor widening; side slope flattening; roadside hazard removal; addition of guardrail flares; extension of tapers; provision of rockfall benches and fallout areas; spalled joint repair; provision of lighting, signing, fencing, striping, markings, and curbs; and sidewalk construction to meet requirements of the Americans with Disabilities Act (ADA).

Process to Determine Need for Additional Safety Improvements for Resurfacing Projects

The survey responses indicated that the process for determining the need for safety improvements varies from state to state. The criteria that were identified as considerations in determining safety needs for resurfacing projects include the following:

- Accident history/high accident locations (22),
- Condition of safety features (6),
- Cost-effectiveness analysis of improvements (4),
- Design criteria (4),
- Engineering judgment (6),
- Local demands/politics (1), and
- Skid testing (1).

As in the responses to the previous questions, some general comments were made by the states. One state noted that its main objective in resurfacing is to extend the service life of the pavement. However, if the safety deficiencies were considered significant, then that project would compete for inclusion as a "spot safety improvement" or as a reconstruction project. Another state responded that unless resurfacing is only a "minimum maintenance overlay" (usually 2 in. or less in depth), the state usually considers potential safety improvements.

Fifteen of 35 states (43 percent) responded that their criteria for considering safety in resurfacing projects do not vary by highway type and/or functional class.

Safety Projects Implemented Only in Response to Accident Experience or a Defined Safety Need

The survey respondents indicated that the following types of safety improvements are not typically made unless accident experience or some other factors indicate a definite need:

- Vertical and horizontal alignment changes (14),
- Minor clear zone improvements or provision of a clear zone (5),
- Addition of median barriers (1),
- Geometric improvements (4),
- Addition of guardrails (6),
- Sight distance improvements (6),
- Slope flattening/regrading ditches (1),
- Superelevation (3),
- Additional signing (1),
- Signalization (1),
- Channelization (1),
- Addition of turn lanes (1),
- Bridge widening (2),
- Extension of large box culverts (1),
- Intersection realignment (1), and
- Upgrading of guardrail on non-NHS roads (1).

Established Procedure for Explicitly Considering Safety for Resurfacing Projects

A majority of the responding states (24 of 36, or 67 percent) indicated that they have an established procedure for explicitly considering safety in resurfacing projects. The procedure typically includes review of a 5-year accident history to identify accident locations and causes, a review of high-accident locations, and identification of appropriate countermeasures. In one state, district safety engineers review and assess project design and recommend approval for design exceptions. Illinois evaluates all projects for wet-weather accidents and then recommends appropriate countermeasures.

Geometric Improvements Implemented to Address Operational Problems

Most of the responding states (28 of 35, or 80 percent) make geometric improvements beyond simply resurfacing to address current or anticipated traffic-operation problems. The types of improvements that are made to address traffic-operational problems include the following:

- Add left-turn lanes at intersections (6),
- Make intersection improvements to increase sight distance (2),
- Add other turn lanes (9),
- Add truck-climbing lanes (1),
- Improve or install traffic-control devices (1),

- Improve shoulders (3),
- Flatten slopes (1),
- Install/improve pavement markings and delineators (1),
- Modify or upgrade traffic signals (1),
- Add deceleration lanes and channelization (3),
- Modify acceleration/deceleration lanes (1),
- Add passing lanes (1),
- Widen lanes (5),
- Install lane delineators such as a mountable curb (1),
- Pave shoulders for use as traffic lanes (where grade width and right-of-way is available) (1),
- Realign some intersections as warranted (1),
- Widen shoulders to accommodate bicycles (1),
- Improve sight distance (1),
- Install rumble strips on shoulders (1), and
- Widen pavement to provide additional capacity or to improve an intersection turning radius where vehicles are running off the pavements (3).

Policies and Procedures for Cost-Effectiveness Analysis of Improvement Alternatives

Only 14 of 35 states (40 percent) responded that they have a formal policy or procedure for conducting cost-effectiveness analyses of alternative safety improvements to formally compare project construction cost and the potential for accident reduction. The policies and procedures that were cited by states for use in cost-effectiveness analysis include the AASHTO *Roadside Design Guide* (1996), the ROADSIDE computer program that accompanies the *Roadside Design Guide*, TRB *Special Report 214*, and agency-specific benefit-cost or cost-effectiveness procedures.

Resource Allocation Tools

Only 11 of 26 states (42 percent) indicated that they have used resource allocation tools for prioritizing potential resurfacing projects. The following resource allocation tools have been used by the states:

- Benefit-cost analysis/incremental benefit-cost analysis (5),
- Dynamic programming (1),
- MicroBENCOST (3),
- Life-cycle analysis (3),
- Linear programming (1),
- AASHTO *Roadside Design Guide* (1),
- State programming instructions (2), and
- State pavement management system (3).

Some states responded that they use nontraditional resource allocation tools. For example, one state prioritizes projects based on subjective weighing of accident severity, traffic volumes, area (urban/rural), and terrain. Another state uses a highway condition database and accident data for development of project scope and for prioritization of projects.

Differences Between Federal- and State-Funded 3R Projects

Respondents in 14 of 32 states (44 percent) indicated that the criteria used for safety improvements in conjunction with resurfacing projects differ in federal 3R projects and state-funded resurfacing projects. The respondents generally indicated that safety improvements were less likely to be included in state-funded projects.

Related State Research

Only 9 of 26 states (35 percent) indicated that they have conducted or sponsored any research on the safety and/or operational effects of resurfacing. The topics of state-sponsored research cited in the survey are skid testing (5) and before-and-after analyses (4).

In particular, the response from New York referred to the evaluation by Hauer, Terry, and Griffith (*11*) of the safety impacts of New York's "fast-track" and R&P projects. Fast-track projects included simple resurfacing and restriping. R&P projects included roadway and roadside safety improvements such as superelevation, shoulder, drainage, and guardrail improvements; slope flattening; removal of fixed objects; and resurfacing. The result of this research showed a negative safety impact at fast-track locations during the first 30 months after resurfacing. This negative impact dissipated after the initial 30-month period. Traffic accident experience remained relatively constant throughout the study period for the R&P projects. These results may indicate that immediately after resurfacing drivers drive faster and less carefully because the pavement surface is smoother. On the other hand, the positive safety effects of any roadway and roadside improvement done in the R&P project may compensate for any short-term decrease in safety.

Computerized Pavement Management System

Nearly all states (34 of 36, or 94 percent) indicated that they have a computerized pavement management system. Twenty-seven of 32 states (84 percent) indicated that their pavement management system contained pavement condition data, and 31 of 34 states (91 percent) indicated that their pavement management system applied criteria to identify the need for resurfacing.

Postresurfacing Evaluation

Only 10 of 34 states (29 percent) indicated that they conduct postproject safety and operational evaluations of resurfacing projects. These 10 states cited the following activities as included in their postproject evaluation:

- Before-and-after accident evaluation (1),

- Postconstruction review as part of the construction engineering activity (5), and
- Surface friction analysis/skid testing (4).

One additional state indicated that in the future they plan to conduct before-and-after accident evaluations for selected resurfacing projects.

STATE HIGHWAY AGENCY 3R DESIGN POLICIES

As stated earlier, the issue of appropriate geometric design policies for 3R projects was quite controversial in the early years of the 3R program. This controversy has largely been resolved through the work that led to TRB *Special Report 214* (*12*). That report made specific recommendations concerning appropriate geometric design criteria for 3R projects. These recommendations are intended to help the designer to determine whether an existing feature that does not meet the geometric criteria of the AASHTO Green Book should be upgraded as part of a 3R project.

TRB *Special Report 214* recommends that specific minimum design criteria for 3R projects that differ from those in the AASHTO Green Book are warranted when the following conditions are met:

- Trade-offs between safety performance and cost can be evaluated quantitatively, and conclusions can be drawn about the safety cost-effectiveness of different design criteria generally applicable regardless of the state or project;
- Specific design criteria for 3R projects would help refocus 3R expenditures on more safety cost-effective geometric improvements; and
- Specific design criteria for 3R projects would simplify parts of the design process and FHWA approval procedures, freeing design resources for the analysis of site improvements that cannot be covered by numerical criteria.

For situations in which these conditions are not met, TRB *Special Report 214* presents other design practices that will help achieve the same safety objectives as minimum criteria.

The following discussion presents the recommendations of TRB *Special Report 214* for each of the following geometric features: lane and shoulder widths, horizontal curvature and superelevation, vertical curvature and stopping sight distance, roadside slopes and clear zones, and intersections. Reference is made, when appropriate, to the 3R design policies of the various state highway agencies that are presented in Appendix B and compared there to the recommendations in TRB *Special Report 214*.

Minimum Lane and Shoulder Widths

Widening lanes and shoulders can provide safety benefits over the length of a roadway. Wider lanes and shoulders increase the opportunity for recovery of errant vehicles and provide increased lateral separation between passing and meeting vehicles. Previous research indicates the following relationships between accidents and the width of lanes and shoulders (*35*):

- Accident rates decrease as lane and shoulder widths increase;
- In terms of accidents eliminated per foot of added width, widening lanes has a bigger payoff than widening shoulders; and
- Roads with stabilized shoulder surfaces have lower accident rates than nearly identical roads with unstabilized earth, turf, or gravel shoulders.

The minimum lane- and shoulder-width design criteria recommended by TRB *Special Report 214* for use on rural two-lane highways are presented in Table 4.

A few states have adopted the same lane- and shoulder-width criteria shown in Table 4 for their own use, and many other states have modeled their criteria on Table 4 with some variations. The specific state design criteria for minimum lane and shoulder widths on 3R projects are presented in Appendix B.

Horizontal Alignment and Superelevation

Research has consistently shown that horizontal curves experience higher accident rates and higher accident severities than tangents (*36*). This probably occurs because horizontal curves place greater demands on the driver and may violate driver expectations.

Although it is clear that a relationship exists between horizontal curves and accident experience, the cost-effectiveness of reconstructing horizontal curves is not well defined (*37*). Therefore, most states do not set minimum 3R standards for reconstruction of horizontal curves.

TRB *Special Report 214* recommends that highway agencies should evaluate the safety benefits and added costs of curve reconstruction when there is a reasonable possibility that reconstruction will be cost-effective. In particular, TRB *Special Report 214* recommends that highway agencies

- Evaluate the reconstruction of horizontal curves when the design speed of the existing curve is more than 15 mph below the running speeds of approaching vehicles and the average daily traffic (ADT) volume is greater than 750 veh/day, and
- Increase the superelevation of horizontal curves whenever the design speed of an existing curve is below the

TABLE 4 Minimum lane and shoulder widths for 3R projects on rural two-lane highways (*12*)

Design year ADT (veh/day)	Running speed (mph)	Less than 10% trucks: Lane width (ft)	Less than 10% trucks: Combined lane and shoulder width (ft)	10% trucks or more: Lane width (ft)	10% trucks or more: Combined lane and shoulder width (ft)
1-750	Under 50	9	11	10	12
	50 and over	10	12	10	12
751-2000	Under 50	10	12	11	13
	50 and over	11	14	12	15
Over 2000	All	11	17	12	18

running speeds of approaching vehicles and the existing superelevation is below the allowable maximum specified by AASHTO's new construction policies.

The following states use the 3R guidelines from TRB *Special Report 214*, as described above, for horizontal curvature and superelevation: Arkansas, Kansas, New Mexico, North Dakota, Ohio, Oregon, Pennsylvania, Vermont, Virginia, Wisconsin, and Wyoming. State 3R design policies for horizontal curvature that differ from TRB *Special Report 214*'s guidelines are presented in Appendix B.

Vertical Alignment

Several studies have been conducted to determine the relationship between vertical curvature and accident experience. Although these studies have generally lacked control of large variances associated with interdependent variables and length of grade, they indicate the following general conclusions (*9*):

- Grade sections have higher accident rates than level sections,
- Steep grades have higher accident rates than mild grades, and
- Downgrades have higher accident rates than upgrades.

The findings of a 1984 study by Olson et al. (*38*), presented in *NCHRP Report 270*, indicate that overall accident frequencies were 52 percent greater at sites with sight distance restrictions than at similar sites without sight restrictions. However, a recent evaluation by Fambro et al. (*39*) in *NCHRP Report 400* found that relatively few of the accidents that occur on crest vertical curves involve small objects like the 6-in. object that is currently used in stopping sight distance design. Thus, the greatest accident potential related to vertical alignment seems likely where a crest vertical curve limits a driver's view of an intersection or a horizontal curve where other vehicles may be present.

Although there may be some relationship between vertical curvature and accident experience, the incremental safety benefits of flattening crest vertical curves have not been well determined and appear to be quite small. Therefore, 3R design policies do not generally set quantitative requirements for vertical curvature and stopping sight distance.

TRB *Special Report 214* (*12*) recommends that reconstruction of crest vertical curves may be cost-effective for sites with ADT greater than 1,500 veh/day, depending on site conditions. It is recommended that highway agencies should evaluate the need for reconstruction of hillcrests when

- The hillcrest hides from view major hazards such as intersections, sharp horizontal curves, or narrow bridges;
- The ADT is greater than 1,500 veh/day; and
- The design speed of the hillcrest (based on the minimum stopping sight distance provided) is more than 20 mph below the running speeds of vehicles on the crest.

The following states use 3R policies for vertical alignment that are essentially the same as those presented in TRB *Special Report 214* for vertical curvature and stopping sight distance: Arkansas, California, Idaho, Indiana, Maine, Nebraska, New Mexico, North Carolina, North Dakota, Ohio, Oregon, Pennsylvania, South Carolina, Vermont, Virginia, Wisconsin, and Wyoming. State highway agency 3R policies for vertical curvature and stopping sight distance that differ from the recommendations of TRB *Special Report 214* are presented in Appendix B.

Roadside Slopes and Clear Zones

Previous studies have found meaningful relationships between accident rates and roadside conditions (*12*).

TRB *Special Report 214* has recommended that state highway agencies should develop consistent procedures for evaluating and improving roadside features. These improvements should have the following objectives:

- Flatten sideslopes of 3:1 or steeper at locations where run-off-road accidents are likely to occur (e.g., on the outside of sharp horizontal curves);
- Retain current slope widths (without steepening sideslopes) when widening lanes and shoulders unless warranted by special circumstances; and
- Remove, relocate, or shield isolated roadside obstacles.

Only one state, Oregon, has adopted these policies without variations. A summary of other state highway agency 3R policies for improving roadside slopes and clear zones is presented in Appendix B.

Intersections

Intersections, which constitute a very small portion of rural and urban roadway systems, are implicated in many motor vehicle accidents (*12*). Furthermore, the percentage of total motor vehicle accidents classified as related to intersections has risen substantially in the past 20 years.

There are no quantitative 3R design criteria for intersections. However, TRB *Special Report 214* and the design policies of several states provide general guidelines for improving intersections in 3R projects. In particular, TRB *Special Report 214* recommends that state highway agencies should develop consistent procedures and checklists for evaluating intersection improvements on 3R projects. A summary of current state policies concerning design features of intersections within 3R projects is presented in Appendix B.

TORT LIABILITY CONCERNS

Tort liability is an increasing concern of highway agencies today. In connection with 3R projects, highway agencies must consider the extent to which they have a duty in the course of 3R improvements to upgrade safety-related elements currently below recommended criteria.

Highway agency liability for tort claims related to 3R projects depends on the statutory and common law of the state. It appears, based on the limited research for this project, that there is considerable variation among states, and even among different judicial levels within a state, in the analysis of highway agency liability for upgrading highways to current engineering criteria. Four principal judicial variants were found:

1. Some courts hold that decisions on highway improvements are planning-level decisions protected by the discretionary function exception and thus are not subject to judicial review on negligence allegations.
2. Other courts find statutory immunity for highway design decisions that eliminates, in the court's opinion, any duty to upgrade original designs on existing highways.
3. Other jurisdictions rule that design immunity is not perpetual when changed circumstances have created a dangerous condition, as may be evidenced by criteria such as accident history. In such situations, the state highway agency has a duty to carefully consider alternatives and to take reasonable action to protect highway users from injury associated with the risks of the condition. In these jurisdictions, however, safety elements below current criteria are not considered dangerous conditions in and of themselves.
4. Some courts have held that highway agency decisions on updating highway elements are not of the nature protected by the discretionary function exception and thus are subject to judicial examination for negligence. In these instances, it will be important for the state highway agency to show that it has acted reasonably by being aware of sites in need of treatment, by having a program of corrective action for these sites, and by correcting sites on the basis of a reasonable priority scheme as funds become available.

The investigation of tort liability was necessarily limited in scope. Elements of this investigation included (1) a review of published literature related to tort liability concerns of highway agencies, (2) a review of case law concerning tort claims that were specifically related to 3R projects and to related cases, (3) discussions with state attorneys or risk managers in a half-dozen states, and (4) a legal analysis involving reasoning by analogy from cases involving the upgrading of highway elements to specific concerns related to 3R criteria.

No state of which the authors of this report are aware maintains records concerning the frequency of tort actions that specifically involve 3R projects. A review of tort liability experience in TRB *Special Report 214* (*12*) found that in four states that compile summary information—Florida, Louisiana, New York, and Pennsylvania—the geometric features addressed by 3R policies are cited only infrequently in tort claims. However, in California, state officials indicate that geometric features are more frequently cited in tort claims than the tort liability experience in the other states suggests. Specifically, geometric features were involved in 8.0 percent of the tort claims filed in New York and 7.1 percent of the tort claims filed in Florida. Geometric features were involved in 8.5 percent of tort settlements or judgments in Pennsylvania and 1.2 percent of settlements or judgments in Louisiana.

TRB *Special Report 214* concluded that use of geometric criteria less stringent than new construction criteria for 3R projects is unlikely to be the basis for a tort claim because most states have some type of design immunity that may cover the use of 3R design criteria as long as reasonable procedures are followed. In general, state decision making concerning 3R projects seems to be the type of policy-like issue that would be protected by the discretionary function exception; however, the application of this exception can vary widely among jurisdictions.

CHAPTER **4**

EFFECTS OF RESURFACING ON VEHICLE SPEEDS AND SAFETY

This chapter presents the results of research on the effects of resurfacing on vehicle speeds and on safety.

EFFECT OF RESURFACING ON VEHICLE SPEEDS

The literature review presented in Chapter 2 found no definitive information concerning the effect of resurfacing on vehicle speeds. Therefore, a data collection and analysis effort was undertaken to address this issue as part of the research for this report.

Speed data were collected by five participating state highway agencies before and after resurfacing of 39 sites on rural two-lane highways. The states that participated in this evaluation were Maryland, Minnesota, New Mexico, New York, and West Virginia.

At each of the 39 sites, spot speed data were collected at a level, tangent location, well removed from intersections and driveways, within 2 months before resurfacing. Comparable spot speed data were collected at the same location within 2 to 4 months after resurfacing.

Comparisons of the speed study results for individual sites found that the differences in mean speed from before to after resurfacing ranged from an increase of 7 mph to a decrease of 4 mph, with an average of 1 mph increase. The differences in 85th-percentile speed ranged from an increase of 6 mph to a decrease of 4 mph, also with an average difference of 1 mph. Both the observed difference in mean speed and the observed difference in 85th-percentile speed were found by a weighted *t*-test procedure to be statistically significant at the 5-percent significance level (i.e., 95-percent confidence level). The analysis of these data is presented in more detail in Appendix C.

The results indicate that, on average, there is a small but statistically significant increase of approximately 1 mph in both mean speed and 85th-percentile speed from before to after resurfacing. However, this effect can vary substantially from site to site. It is not unusual for speeds to increase by up to 7 mph after resurfacing at some sites and for speeds to decrease by up to 4 mph at other sites. Despite this wide variation, the analysis results indicate that, on average, a small increase in vehicle speeds of approximately 1 mph is likely during the period from 2 to 4 months after resurfacing. No data are available to indicate how long after resurfacing such increases in vehicle speeds are likely to persist.

EFFECT OF RESURFACING ON SAFETY

As noted in Chapter 2, an evaluation of the effect of resurfacing on safety was conducted previously by Hauer, Terry, and Griffith (*11*). The study found a short-term decrease in safety following resurfacing. A larger evaluation of this issue was conducted in NCHRP Project 17-9(2) simultaneously with the research reported here. The evaluation considered data from five states and looked explicitly at projects with and without geometric improvements. However, the results of this evaluation were inconclusive because the effect of resurfacing on safety appeared to be positive in some states and negative in others.

Because the results of the analysis in NCHRP Project 17-9 (*2*) were inconclusive, a decision was reached to use the Hauer, Terry, and Griffith (*11*) results to represent the effects of resurfacing on safety in the resource allocation process developed in this study. This study concluded that, when resurfacing was done with no additional safety improvements, nonintersection accidents increased by 21 percent over the first 30 months after resurfacing, and intersection accidents increased by 35 percent over the first 12 months after resurfacing. Beyond these initial periods after resurfacing, the resurfacing project no longer had any effect on safety.

CHAPTER 5

RESOURCE ALLOCATION PROCESS TO MAXIMIZE THE COST-EFFECTIVENESS OF RESURFACING PROJECTS

This chapter presents the resource allocation process developed in the research for this report. The term "resource allocation process" implies that the process is intended to allocate limited resources among competing projects. It can also be considered an optimization process because it is intended to maximize the net benefits from the investment of the available resources. As noted in Chapter 2, the process is based on integer programming.

This chapter discusses every aspect of the resource allocation process and presents the equations and variables used in the process. The process is one that was developed and tested within the funding available in Phase 2 and Phase 3 of the research project, taking advantage of results available from other research that was under way simultaneously. The resource allocation process was implemented in computer software called the Resurfacing Safety Resource Allocation Program (RSRAP), which is described briefly in Chapter 6 and in more detail in Part 2 of this report, the Resurfacing Safety Resource Allocation Program (RSRAP) User's Guide. The RSRAP software is provided on CD-ROM with this report.

OBJECTIVES OF THE RESOURCE ALLOCATION PROCESS

The objective of the resource allocation process is to allow highway agencies to maximize the cost-effectiveness of the funds spent on 3R projects by improving safety on nonfreeway facilities while maintaining the structural integrity and ride quality of highway pavements. In order to do this, the process considers the following:

- A specific set of highway sections that are in need of resurfacing either at the present time or within the relatively near future;
- A specific set of improvement alternatives for each candidate site, including doing nothing, resurfacing only, and various combinations of safety improvements for the site; and
- A maximum limit on the funds available for improvements to the set of highway locations.

The result of the process is a recommended improvement alternative for each highway section that results in the maximum net safety benefit while not exceeding the available budget. The process addresses the identification of the highest priority improvements, those that should be made during the next construction season.

The process was structured so that it can be used by highway agencies in two different ways. These are the following:

- **Option 1—Optimize Safety Improvements**. The objective of this option is to select the safety or operational improvements that should be implemented at a given set of locations that have already been scheduled for resurfacing during a specific year. This option would be appropriate for an agency that budgets funds for safety improvements separately from resurfacing funds and wants to maximize the net benefits from those safety improvements.
- **Option 2—Optimize Both Resurfacing and Safety Improvements**. The objective of this option is to select both the projects that should be resurfaced and the safety improvements that should be implemented from among a given set of locations for which a decision has not yet been made about resurfacing during a specific year. This option would be appropriate for a highway agency that wants to maximize the net benefits from the combined resurfacing and safety improvement program.

Users also have the option to select whether the resource allocation process should include a safety penalty for resurfacing a road without accompanying geometric improvements.

Similarly, users have the option to make selections based on improvement costs and safety benefits alone or to consider the traffic-operational effects of resurfacing as well. These two types of analysis are identified as the following:

- Consider safety benefits only (do not consider the travel time reduction associated with resurfacing) and
- Consider safety and speed benefits (includes the travel time reductions associated with resurfacing).

If the user elects to consider safety and speed benefits, then the penalty for resurfacing without accompanying safety improvements should also be included. This is recommended as the speed benefits and safety penalty are based on similar research results.

The resource allocation process has been developed to be applicable to any improvement program that involves resurfacing and safety improvements. The process is not tied in any specific way to the federal 3R program. Thus, it is applicable to sites being considered for the federal 3R program, for sites being considered for state programs conducted with 100-percent state funds, or for a mixture of sites considered for both types of programs.

The remainder of this chapter presents the components of the resource allocation process, including some default assumptions used in the RSRAP software. The RSRAP software is described more fully in Chapter 6.

COMPONENTS OF THE RESOURCE ALLOCATION PROCESS

There are 10 major components of the conceptual resource allocation process. These components are as follows:

- Identify the sites to be considered,
- Identify the improvement alternatives (and combinations of alternatives) to be considered for each site,
- Convert future costs and benefits to present values,
- Estimate the construction cost of each improvement alternative,
- Estimate the safety benefits for each improvement alternative,
- Estimate the penalty for not resurfacing,
- Estimate the safety penalty for each improvement alternative that involves resurfacing without other geometric improvements,
- Estimate the traffic-operational benefits for each improvement alternative,
- Determine the net benefits for each improvement alternative, and
- Select the most suitable improvement alternative for each site within the available budget by applying optimization logic.

Each of these components is discussed below.

Identify Sites to Be Considered

The resource allocation process is intended for application to a specific identified set of highway sections. These typically would be sites that have been selected for resurfacing as part of a highway agency's resurfacing program for a specific year, or a larger set of sites, each expected to be in need of resurfacing within a period of several years. The sites could represent all suitable resurfacing candidates statewide, all suitable candidates within a particular highway district or geographical area, all suitable candidates on a particular roadway system, or all suitable candidate sites eligible for a particular funding source, or some combination of these. The process is based on two assumptions:

1. The sites considered represent all sites eligible for improvement with funds from a particular budget, and
2. The budget being considered is the only source of funding for the improvements being considered.

If these assumptions are not met, then the set of sites, the range of improvement alternatives, and/or the size of the budget considered might need to be expanded until the assumptions are met.

The following data will be needed, at a minimum, to apply the resource allocation process for each highway section under consideration:

- County,
- Route number,
- Site description (text description of project limits or mileposts),
- Area type (urban/rural),
- Length (mi),
- Number of lanes (count through travel lanes only),
- Presence of median (divided/undivided),
- ADT (veh/day),
- Number of nonintersection-related accidents per year,
- Number of intersection-related accidents per year,
- Estimated average travel speed (mph),
- Existing lane width (ft),
- Existing shoulder width (ft),
- Existing shoulder type (paved/gravel/turf/composite), and
- Estimated time remaining before mandatory resurfacing (yr).

Additional data inputs are required if the candidate improvements for a site include horizontal curves, roadside features, intersections, or other user-defined improvement alternatives.

Most of the input data listed above should be readily available to highway agencies. To keep the process as simple as possible, it is best if each highway section considered is relatively homogeneous with respect to area type, annual average daily traffic (AADT), and cross-section geometrics. Minor variations within a section in cross section, for example, may be permitted; however, where distinct subsections with different cross sections are present, it will usually be desirable to divide these into separate sites. Site boundaries should also be based on pavement type and condition considerations, which might warrant different resurfacing treatments. The process addresses only nonfreeway facilities.

Expected accident experience could be based on predictive models such as those developed by Zegeer et al. (*15*) or Vogt and Bared (*40*). However, users are strongly encouraged to supply safety estimates based on actual accident histories for the sites in question. Default values from predictive models necessarily represent average conditions. However, the site-to-site variations in observed accident frequency (even among sites that are nominally similar) may have important implications for the cost-effectiveness of particular safety improvements, and, therefore, accident data for the specific sites in question are vital to the objectives of the optimization process. For this reason, the program does not estimate the safety performance of candidate sites and requests the user to provide this information as input.

A new approach to combining expected and observed accident frequencies, known as the Empirical Bayes (EB) technique, has been presented by Hauer (*41*). The EB technique has not been implemented in the resource allocation process, but could be added to it in the future. This would require the user to have predictive models such as those developed by Zegeer et al. (*15*) or Vogt and Bared (*40*) and a calibration process such as the one presented by Harwood et al. (*7*).

Identify Improvement Alternatives to Be Considered

The next step in the process is to define the set of improvement alternatives to be considered for each site. The appropriate candidate improvements will vary from site to site depending on the existing site conditions. The objective of this step in the process is to include all alternatives that might potentially be the most appropriate improvement for the site, that is, to be as inclusive as possible while remaining within the scope of projects eligible for the particular funding source being considered. Improvement alternatives selected at this stage that ultimately prove not cost-effective or less cost-effective than some other alternative will be eliminated at a later stage in the process.

The process is capable of considering the following types of improvements:

- Pavement resurfacing,
- Lane widening,
- Shoulder widening,
- Shoulder paving,
- Horizontal curve improvements,
- Roadside improvements,
- Intersection turn lane improvements, and
- Other user-defined alternatives.

The resource allocation process is capable of considering the safety effects of these individual improvement types, as well as the best available estimate of their effects in combination. The software developed to implement the process includes default methods for estimating the effects of each of the improvement types listed above, with the exception of user-defined alternatives. However, no default method can provide effectiveness estimates that are appropriate to all potential sites. Therefore, users of the process will be encouraged to replace the default effectiveness estimates for the improvements under consideration with better site-specific estimates whenever such estimates are available.

The following improvement alternatives will be considered by default for each site evaluated:

- Do nothing.
- Resurface pavement.
- Resurface pavement and widen lanes for all sites with lanes less than 12 ft in width. (Widening of lanes is considered in increments of 1 ft; therefore, for a site with 9-ft lanes, widening by 1, 2, and 3 ft will be considered).
- Resurface pavement and widen shoulders for all sites with shoulders less than 8 ft in width. (Widening of shoulders is considered in increments of 2 ft; therefore, for a site with 2-ft shoulders, widening by 2, 4, and 6 ft will be considered).
- Resurface pavement and pave shoulder (if shoulder is currently unpaved).
- Resurface pavement with all feasible combinations of lane widening, shoulder widening, and shoulder paving.

Other improvement types and combinations of improvement types may be added at each site based on user assessment of appropriate improvement needs for that site (e.g., horizontal curve, roadside, or intersection improvements). This will require user analysis of improvement needs outside the scope of the resource allocation process.

Convert Future Costs and Benefits to Present Values

All costs and benefits in the optimization process are converted to their present values for comparison. The use of the net present value method has been accepted for many years in highway economic analyses, first in the AASHTO *Manual on User Benefit Analyses for Highway and Bus Transit Improvement* (*27*) and later in the MicroBENCOST program (*42*).

One-time costs or benefits in a specific future year are reduced to their present values using the single-amount present worth factor:

$$(P/F,\, i,\, n) = \frac{1}{(1+i)^n} \tag{11}$$

where

- $(P/F, i, n)$ = single-amount present worth factor to convert an amount in a specific future year to its present value,
- i = minimum attractive rate of return expressed as a decimal fraction (i.e., for a 4-percent minimum attractive rate of return, $i = 0.04$), and
- n = number of years until amount is paid or received.

Future benefits and costs that will recur annually over the service life of the improvement are reduced to their present values by the uniform-series present worth factor:

$$(P/A,\, i,\, n) = \frac{(1+i)^n - 1}{i(1+i)^n} \tag{12}$$

where

$(P/A, i, n)$ = uniform-series present worth factor to convert a series of uniform annual amounts to its present value and
n = number of years that amounts are paid or received.

The discount rate, or minimum attractive rate of return (i), used in computing these factors represents the rate of return that could be earned on alternative investments. Highway expenditures are expected to exceed this minimum attractive rate of return to represent good investments for taxpayers. Federal policy recommends the use of a minimum attractive rate of return of 7 percent per year ($i = 0.07$) in investments of public funds (*43*). However, this 7-percent return includes the effect of inflation. Because the future costs and benefits derived below are expressed in constant dollars (i.e., they do not include any effects of inflation), inflation should be excluded from the minimum attractive rate of return as well. The current inflation level is approximately 3 percent per year, so a minimum attractive rate of return of 4 percent per year ($i = 0.04$) appears to be appropriate for use in the resource allocation process. AASHTO has indicated in the past that they consider 4 percent per year above the inflation rate to represent the real long-term cost of capital (*27*).

The number of years until the amount is paid or received (n) represents the life of the safety improvement, not the service life of the pavement. Although the number of years and discount rate are offered as default values in RSRAP, there may be changes on a global or site-specific basis. However, it is recommended that these values are used globally and not changed on a site-by-site basis.

Estimate Construction Cost of Each Improvement Alternative

The construction cost of each improvement alternative is estimated by the resource allocation process based on the input site condition data and default unit construction cost values. Default methods for computing improvement construction costs are provided in the RSRAP software and presented here for the following improvement types:

- Pavement resurfacing,
- Lane widening,
- Shoulder widening,
- Shoulder paving, and
- Installation of intersection turn lanes.

The default cost estimates are based on average cost data supplied by highway agencies. Users must supply the improvement construction costs for horizontal curve improvements, roadside improvements, and other user-defined alternatives because the costs of these alternatives are generally too site-specific to use a global default value.

Users have the option to replace the default construction cost estimates determined in RSRAP with their own data, either globally, for all sites, or just for specific sites.

Construction costs represent expenditures at the beginning of the analysis period, so no conversion to present value is required.

Specific construction cost equations were developed based on the type of improvement considered. Below is the list of the construction cost equations used in the resource allocation process:

- **Unpaved Shoulder Before and After:**

$$\begin{aligned} CC' = {} & LWcost * L_{site} * 5280 * Nlanes \\ & * (LW2 - LW1) + SWcost * L_{site} * 5280 \\ & * 2 * \{[(LW2 - LW1) * (Nlanes/2)] \\ & + (SW2\text{-}SW1)\} + Rescost * L_{site} * 5280 \\ & * Nlanes * LW2 \end{aligned} \tag{13}$$

- **Paved Shoulder Before and After:**

$$\begin{aligned} CC' = {} & LWcost * L_{site} * 5280 * Nlanes \\ & * (LW2 - LW1) + SWcost * L_{site} * 5280 \\ & * 2 * \{[(LW2 - LW1) * (Nlanes/2)] \\ & + (SW2 - SW1)\} + Rescost * L_{site}*5280 \\ & * Nlanes * LW2 + Srescost * L_{site} * 5280 \\ & * 2 * SW2 \end{aligned} \tag{14}$$

- **Unpaved Shoulder Before and Paved Shoulder After:**

$$\begin{aligned} CC' = {} & LWcost * L_{site} * 5280 * Nlanes \\ & * (LW2 - LW1)(SWcost + Srescost) \\ & * L_{site} * 5280 * 2 * SW2 + Rescost * L_{site} \\ & * 5280 * Nlanes * LW2 \end{aligned} \tag{15}$$

where

CC' = construction cost for lane and shoulder widening and shoulder paving based on shoulder-type conditions before and after improvement ($),
L_{site} = total length of the site under analysis (mi),
$Rescost$ = cost for pavement resurfacing only ($/ft^2),
$LWcost$ = lane-widening cost ($/ft^2),
$SWcost$ = shoulder-widening cost ($/ft^2),
$Srescost$ = shoulder-paving cost ($/ft^2),
$LW1$ = lane width before improvement (ft),
$LW2$ = lane width after improvement (ft),
$SW1$ = shoulder width before improvement (ft),
$SW2$ = shoulder width after improvement (ft), and
$Nlanes$ = number of lanes.

Table 5 presents the default construction cost values used when developing the RSRAP software. The variable, *Reconcost*, in Table 5, represents the total pavement replacement cost ($/ft).

For intersection improvements, RSRAP estimates the construction cost of adding a left- or right-turn lane ($CC_{TurnLane}$). For rural areas, $CC_{TurnLane}$ is $60,000. For urban areas, $CC_{TurnLane}$ is $112,000.

The total estimated construction cost for each improvement alternative combines the construction cost estimates for all specific improvement types that are part of that alternative. When entering the cost for a horizontal curve improvement, the user should develop that cost assuming that no lane widening, shoulder widening, or shoulder paving will be needed. The resource allocation process will supply the additional costs for these widening and paving alternatives as they are considered. For example, if an alternative analyzed includes lane widening and horizontal curve improvements, the following equation is used to calculate the final construction cost:

$$CC = \frac{CC'(L_{site} - L_{IHC})}{L_{site}} + CC_{IHC} + C'' \tag{16}$$

where

CC = construction cost ($),
CC_{IHC} = construction cost for all horizontal curve improvements ($),
CC' = construction cost for lane-widening improvements,
C'' = construction cost because of lane and shoulder widening and shoulder-paving improvements at the horizontal curves (see below),
L_{site} = total length of the site under analysis (mi), and
L_{IHC} = length of all horizontal curves to be improved (mi).

Calculations for determining C'' are shown below.

If $LW2 = LW1$ and $SW2 = SW1$ and $SP2 = SP1$

$$C'' = 0 \tag{17}$$

If $SW2 = 0$

$$C'' = L_{IHC} * (LW2 - LW1) * (LWcost + Rescost) * 5280 * Nlanes \tag{18}$$

If $SP1$ = unpaved and $SP2$ = unpaved

$$C'' = L_{IHC} * (LW2 - LW1) * (LWcost + Rescost) * 5280 * Nlanes + L_{IHC} * LWcost * 5280 * 2 * \{(SW2 - SW1) + [(LW2 - LW1) * Nlanes/2]\} \tag{19}$$

If $SP1$ = paved and $SP2$ = paved

$$C'' = L_{IHC} * (LW2 - LW1) * (LWcost + Rescost) * 5280 * Nlanes + L_{IHC} * (LWcost + Srescost) * 5280 * 2 * \{(SW2 - SW1) + [(LW2 - LW1) * Nlanes/2]\} \tag{20}$$

If $SP1$ = unpaved and $SP2$ = paved

$$C'' = L_{IHC} * (LW2 - LW1) * (LWcost + Rescost) * 5280 * Nlanes + L_{IHC} * (LWcost + Srescost) * 5280 * 2 * SW2 \tag{21}$$

where

$SP1$ = shoulder type before improvement (paved or unpaved) and
$SP2$ = shoulder type after improvement.

Estimate Safety Benefits for Each Improvement Alternative—PSB

An estimate of the safety benefits, designated *PSB*, of each improvement alternative considered for each site was determined in the resource allocation process. Default methods were provided for a set of improvement types that include the following:

- Widen lanes,
- Widen shoulders,
- Pave shoulders,
- Provide left-turn lanes at intersections,
- Provide right-turn lanes at intersections,
- Make minor changes in horizontal alignment to increase curve radii, and
- Improve roadside conditions.

Expected percentage reductions in accidents, also known as accident modification factors (AMFs), are available for the improvement types listed above, for rural, urban, two-lane, and multilane highways. These AMFs are based on the liter-

TABLE 5 Default unit construction cost estimates used in the RSRAP

Area type	Default unit costs ($/ft^2)				
	Rescost	LWcost	SWcost	Srescost	Reconcost
Rural	1.07	3.93	5.32	0.47	12.10
Urban	1.80	3.93	5.32	0.47	12.10

ature discussed in Chapters 2 and 4 and the findings of an expert panel. The user can also create user-defined alternatives that take into account other improvements as long as accident reduction effectiveness estimates for the improvements are known.

The benefits attributable to accidents reduced by a geometric or traffic-control improvement were estimated using a safety benefit equation that takes into account the following variables: expected number of annual accidents for location type *m* at site *j* (N_{jm}), AMF for improvement alternative *k* at location type *m* expressed as decimal fraction (AMF_{mk}), proportion of total accidents to which AMF_{mk} applies expressed as a decimal fraction and based on severity levels (RF_{ms}), and accident reduction cost by severity level (AC_s). These subscripts and variables are described in detail below.

Subscripts

The index variable *m* represents two location types at which accident reduction benefits are estimated separately:

- Nonintersection locations ($m = 1$) and
- intersections ($m = 2$).

The index variable *s* represents two accident severity levels for which accident costs differ:

- fatal and injury accidents ($s = 1$) and
- property-damage-only accidents ($s = 2$).

The index variable *k* represents the improvement alternative considered (e.g., an improvement alternative may be a 1-ft increase in lane width, a 2-ft increase in shoulder width, and paving of the existing unpaved shoulder).

The index variable *j* represents the site at which a particular improvement is being made.

AMFs for Specific Improvement Types

The incremental effects on safety of specific geometric design and traffic control elements are represented by AMFs. The AMF for the nominal or base value of each geometric design traffic control feature has a value of 1.0. Any feature associated with higher accident experience than the nominal or base condition has an AMF with a value greater than 1.0; any feature associated with lower accident experience than the base condition has an AMF with a value less than 1.0.

For any improvement being evaluated, the ratio of the appropriate AMF after the improvement to the appropriate AMF before the improvement represents an AMF for the improvement itself. Thus, an improvement with an AMF of 0.95 would be expected to decrease accident frequency by 5 percent, whereas an improvement with an AMF of 1.05 would be expected to increase accident frequency by 5 percent.

The AMFs used in RSRAP for two-lane highway improvements are those presented by Harwood et al. (*7*). For multilane highways, slightly modified versions of the two-lane highway AMFs for lane widening and horizontal curve improvements were developed as part of this project. The AMFs for lane widening, shoulder widening, and shoulder paving apply only to related accident types (which include single-vehicle, run-off-road accidents; multiple-vehicle, same-direction, sideswipe accidents; and multiple-vehicle, opposite-direction accidents). AMFs for other improvement types apply to total accidents.

A description of the AMF formulas and quantitative values used in the resource allocation process is presented below.

Lane-Widening AMF

The nominal or base value of lane width is 12 ft. Thus, 12-ft lanes are assigned an AMF of 1.00. Figure 1 illustrates the recommended values of the AMF for lane widths from 9 to 12 ft. Table 6 presents the equations used to represent the graphical values presented in Figure 1. The AMF for any lane widths within the range of 9 to 12 ft is interpolated between the lines shown in Figure 1. Lanes less than 9 ft in width are assigned an AMF equal to that for 9-ft lanes. Lanes greater than 12 ft in width are assigned an AMF equal to that for 12 ft. As shown in Figure 1, the AMFs for lanes less than 12 ft in width are constant for all ADTs above 2,000 veh/day, but decrease to a substantially smaller value over the range of traffic volumes between 400 and 2,000 veh/day. The AMFs have constant, but lower, values when ADT is below 400 veh/day. The AMFs in Figure 1 are those derived by Harwood et al. (*7*) based on the work of Zegeer et al. (*15*) and Griffin and Mak (*44*).

The AMFs for lane widening apply to related accidents (single-vehicle, run-off-road accidents; multiple-vehicle, head-on accidents; opposite-direction, sideswipe accidents, and same-direction, sideswipe accidents). The AMFs expressed on this basis must therefore be adjusted to total accidents within the accident prediction algorithm. Equation 22 provides a method to incorporate such a proportion into the accident computation. If an AMF applies to total accidents, then the value of P_{ra} should be set equal to 1.0. However, if the AMF applies only to certain accidents, then the value of P_{ra} should be based on the actual accident history for the site in question or on default data from the literature.

$$AMF_1 = f\,(AMF_{ra} - 1.0)\,P_{ra} + 1.0 \qquad (22)$$

where

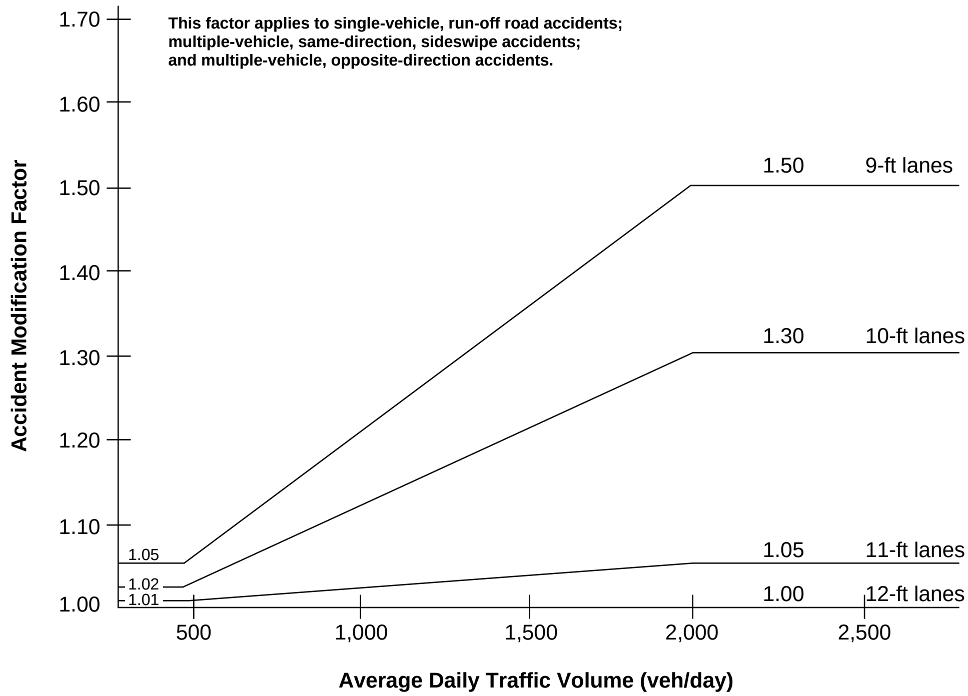


Figure 1. Recommended accident modification factor for lane width.

TABLE 6 Recommended accident modification factors for lane width

ADT	Lane Width			
	9 ft	10 ft	11 ft	12 ft
≤ 400	1.05	1.02	1.01	1.0
400 to 2000	$1.05+2.81\text{x}10^{-4}$ (ADT-400)	$1.02+1.75\text{x}10^{-4}$(ADT-400)	$1.01+2.5\text{x}10^{-5}$ (ADT-400)	1.0
≥ 2000	1.5	1.3	1.05	1.0

AMF_1 = accident modification factor for the effect of lane width on total accidents,
AMF_{ra} = accident modification factor for related accidents,
P_{ra} = proportion of total accidents constituted by related accidents, and
f = factor for roadway type effect as defined in Table 7.

The AMF_{ra} is calculated by dividing the AMF taken from Table 6 for after-improvement conditions by the AMF taken from the same table for existing (or before) conditions. The proportion of related accidents (P_{ra}) is estimated as 0.35 (i.e., 35 percent) based on the default distribution of accident types presented by Harwood et al. (*7*). This default accident type distribution, and therefore the value of P_{ra}, may be changed by the highway agency as part of the calibration process.

Shoulder-Widening and Shoulder-Type AMF Calculation

The nominal or base value of shoulder width and type is a paved 6-ft shoulder, which is assigned an AMF value of 1.00. Figure 2 illustrates the recommended AMF for shoulder widths that differ from 6 ft. Table 8 presents the values illustrated in Figure 2 in the format of equations. These AMFs are

TABLE 7 Values of f based on type of highway

Type of highway	Number of lanes	*f*
Two-lane undivided	≤ 3	1.00
Multilane undivided	≤ 4	0.75
Multilane divided	≤ 4	0.50

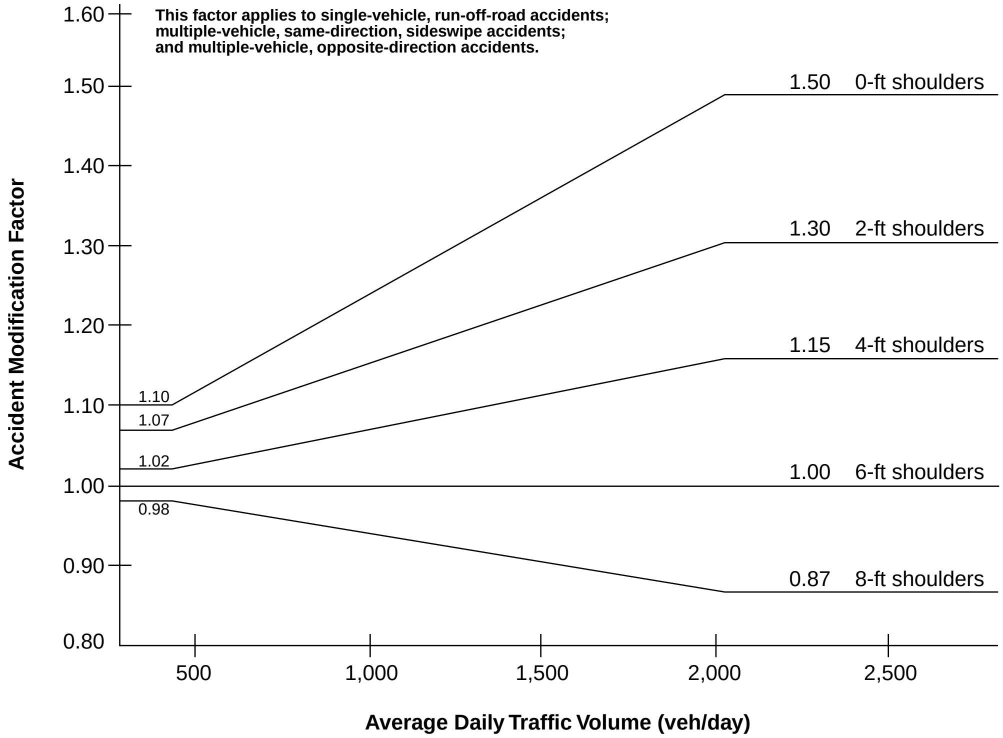


Figure 2. Accident modification factor for shoulder width (7).

TABLE 8 Recommended accident modification factors for shoulder width

ADT	Shoulder width				
	0 ft	2 ft	4 ft	6 ft	8 ft
≤ 400	1.10	1.07	1.02	1.0	0.98
400 to 2000	$1.1+2.5 \times 10^{-4}$ (ADT-400)	$1.07+1.43\text{x}10^{-4}$ (ADT-400)	$1.02+8.125\text{x}10^{-5}$ (ADT-400)	1.0	$0.98-6.875\text{x}10^{-5}$ (ADT-400)
≥ 2000	1.5	1.3	1.15	1.0	0.87

those developed by Harwood et al. (*7*) based on the work of Zegeer et al. (*15*) and Miaou (*45*).

Table 9 presents the AMF values for different shoulder types (gravel, turf, composite, and paved shoulders).

The AMFs for shoulder width and type apply only to related accident types. The AMFs expressed on this basis must therefore be adjusted to total accidents within the accident prediction algorithm. This can be accomplished with the following equation:

$$AMF_2 = (AMF_{mra}\, AMF_{tra} - 1.0)\, P_{ra} + 1.0 \qquad (23)$$

where

AMF_2 = accident modification factor for the effect of shoulder width on total accidents,

AMF_{mra} = accident modification factor for related accidents based on shoulder width (from Figure 2), and

TABLE 9 Recommended accident modification factors for shoulder type

Shoulder type	Shoulder width (ft)				
	0	2	4	6	8
Paved	1.00	1.00	1.00	1.00	1.00
Gravel	1.00	1.01	1.01	1.02	1.02
Composite	1.00	1.02	1.03	1.04	1.06
Turf	1.00	1.03	1.05	1.08	1.11

AMF_{tra} = accident modification factor for related accidents based on shoulder type (from Table 9).

AMF_{mra} and AMF_{tra} are calculated by dividing the AMF after improvement by the AMF corresponding to the existing conditions. The proportion of related accidents (P_{ra}) is estimated as 0.35 (the same proportion used for the lane-widening AMF).

Horizontal Curves

The nominal or base condition for horizontal alignment is a tangent roadway section. An AMF has been developed to represent the manner in which accident experience of curved alignments differs from that of tangents. This AMF applies to total roadway segment accidents, not just the related accident types considered for lane and shoulder widths.

The AMF for a horizontal curve has been determined from the regression model developed by Zegeer et al. (*46*). This model includes the effects on accidents of length of horizontal curve, degree of horizontal curve, and presence or absence of spiral transition curves.

The AMF for horizontal curvature is in the form of an equation and thus might be termed an accident modification function rather than an AMF. The equation for the AMF for horizontal curvature is:

$$AMF_3 = \frac{\left[1.55L_c + \frac{80.2}{R} - 0.012S\right]}{1.55L_c} f_{rt} \qquad (24)$$

where

AMF_3 = accident modification factor for the effect of horizontal curvature on total accidents;
L_c = length of horizontal curve (mi);
R = radius of curvature (ft);
f_{rt} = factor for roadway type effect, as defined in Table 10; and
S = 1 if a spiral transition curve is present, 0 if a spiral transition curve is not present.

In applying the accident modification functions for curves with spiral transitions, the length variable should represent the length of the circular portion of the curve.

The user can consider change in horizontal curvature as an option to be analyzed by the resource allocation program. The process will consider two alternatives: improve all the curves and do not improve the curves. The total cost for horizontal improvement includes the cost of improving all curves considered. If the accident history for the individual horizontal curves to be improved is known, the user can choose to use the known accident history instead of estimating the values.

Roadside Design

For the purposes of the accident prediction algorithm, the quality of roadside design is represented by the roadside hazard rating system developed by Zegeer et al. (*15*). The roadside hazard is ranked on a seven-point categorical scale from 1 (best) to 7 (worst). The seven categories of roadside hazard rating (RHR) are shown below.

- **Rating = 1**
  Wide clear zones greater than or equal to 30 ft from the pavement edgeline.
  Sideslope flatter than 1 : 4.
  Recoverable.
- **Rating = 2**
  Clear zone between 20 and 25 ft from pavement edgeline.
  Sideslope about 1 : 4.
  Recoverable.
- **Rating = 3**
  Clear zone about 10 ft from pavement edgeline.
  Sideslope about 1 : 3 or 1 : 4.
  Rough roadside surface.
  Marginally recoverable.
- **Rating = 4**
  Clear zone between 5 and10 ft from pavement edgeline.
  Sideslope about 1 : 3 or 1 : 4.
  May have guardrail (5 to 6.5 ft from pavement edgeline).
  May have exposed trees, poles, or other objects (about 10 ft from pavement edgeline).
  Marginally forgiving, but increased chance of a reportable roadside collision.
- **Rating = 5**
  Clear zone between 5 and10 ft from pavement edgeline.

TABLE 10 Accident modification factor for horizontal curvature

Curve radius (R) (ft)	Recommended value of f_{rt} for specific roadway type	
	Two-lane highway	Multilane-divided or undivided highway
0 to 1,000	1.0	1.20
1,000 to 1,600	1.0	$0.80 + \frac{R-1000}{600}(0.4)$
Over 1,600	1.0	0.80

Sideslope about 1 : 3.
May have guardrail (0 to 5 ft from pavement edgeline).
May have exposed trees, poles, or other objects (about 10 ft from pavement edgeline).
Virtually nonrecoverable.

- **Rating = 6**
  Clear zone less than or equal to 5 ft.
  Sideslope about 1 : 2.
  No guardrail.
  Exposed rigid obstacles within 0 to 6.5 ft of the pavement edgeline.
  Nonrecoverable.
- **Rating = 7**
  Clear zone less than or equal to 5 ft.
  Sideslope 1 : 2 or steeper.
  Cliff or vertical rock cut.
  No guardrail.
  Nonrecoverable with high likelihood of severe injuries from roadside collision.

The nominal or base value RHR employed in the base model for roadway sections is 3. The AMF is the ratio of the accident experience predicted by the base model using the actual roadway section in question to the accident experience predicted by the base model using the nominal value RHR of 3. The equation for calculating the AMF for roadside improvement is the following:

$$AMF_4 = \frac{\exp(-0.6869 + 0.0668\,\mathrm{RHR})}{\exp(-0.4865)} \quad (25)$$

where

AMF_4 = accident modification factor for the effect of roadside design on total accidents.

The RSRAP software incorporates 14 specific combinations of roadside characteristics. Table 11 lists these combinations, as defined by clear zone width, roadside slope, and type and location of roadside obstacles. The table also shows the RHR that corresponds to each of the 14 categories. Users of the RSRAP software are asked to characterize the safety performance of roadside designs by identifying the percentage of roadway length that falls in each of the 14 roadside design categories shown in Table 11.

At-Grade Intersections

The improvements that the resource allocation process considers for intersection improvements are the addition of left-turn and right-turn lanes. The two types of intersection traffic controls considered are (1) intersections with minor-road stop control (three- and four-leg intersections) and (2) intersections with traffic-signal control (four-leg intersections).

Intersections with minor-road yield control are treated identically to those with minor-road stop-control intersections. Intersections with all-way stop control are not evaluated by RSRAP; all-way stop control is most appropriate for lower-speed roadways with relatively equal traffic volumes on all legs of the intersection.

The nominal or base condition for intersection turn lanes is the absence of the corresponding turn lanes on the major-road approaches. The AMFs for presence of left-turn lanes and right-turn lanes on the major road are presented in Tables 12 and 13, respectively. The AMFs for left-turn lanes and the AMFs for right-turn lanes are equal to 1.0 for intersections that do not have left- and right-turn lanes. For all others, look at Tables 12 and 13. These AMFs apply to total intersection-related accidents and were developed in two FHWA research projects by Harwood et al. (*7*,*20*).

The resource allocation program also uses four base models to calculate the predicted number of total accidents per year on a particular intersection depending on the type of at-grade intersection. The base models for each of these intersection types predict total accident frequency per year for intersection-related accidents within 250 ft of a particular intersection. These equations are only used to adjust the number of accidents for right-turn lanes and left-turn lanes.

TABLE 11 Definition of roadside design categories

Roadside obstacles	Clear zone width (ft)	Roadside slope	Hazard rating
None within clear zone	30 or more	Flatter than 1:4	1
None within clear zone	30 or more	1:4	1.5
None within clear zone	20 to 30	1:4	2
None within clear zone	20 to 30	1:3	2.5
None within clear zone	10 to 20	1:4	2.5
None within clear zone	10 to 20	1:3	3
None within clear zone	10 to 20	1:2 or steeper	3.5
None within clear zone	5 to 10	1:4	4
None within clear zone	5 to 10	1:3	5
None within clear zone	5 to 10	1:2 or steeper	5.5
None within clear zone	0 to 5	N/A	6
Barrier at 5-6.5 ft from edge of traveled way	None	N/A	4
Barrier at 0-5 ft from edge of traveled way	None	N/A	5
Rock cut or cliff with no barrier	None	N/A	7

TABLE 12 Accident modification factors for installation of left-turn lanes on the major-road approaches to intersections on two-lane rural highways (*7, 20*)

Intersection type	Traffic control	Number of major-road approaches on which left-turn lanes are installed	
		One approach	Both approaches
Three-Leg	STOP Sign	0.56	–
	Traffic Signal	0.85	–
Four-Leg	STOP Sign	0.72	0.52
	Traffic Signal	0.82	0.67

TABLE 13 Accident modification factors for installation of right-turn lanes on the major-road approaches to intersections on two-lane rural highways (*7, 20*)

Intersection type	Traffic control	Number of major-road approaches on which right-turn lanes are installed	
		One approach	Both approaches
Three-Leg	STOP Sign	0.86	–
	Traffic Signal	0.96	–
Four-Leg	STOP Sign	0.86	0.74
	Traffic Signal	0.96	0.92

a. Three-Leg Stop-Controlled Intersections

$$N_{jm} = \exp[-10.9 + 0.79 \ln(ADT_1) + 0.49 \ln(ADT_2)] \quad (26)$$

b. Four-Leg Stop-Controlled Intersections

$$N_{jm} = \exp[-9.34 + 0.60 \ln(ADT_1) + 0.61 \ln(ADT_2)] \quad (27)$$

c. Four-Leg Signalized Intersections

$$N_{jm} = \exp[-5.73 + 0.60 \ln(ADT_1) + 0.20 \ln(ADT_2)] \quad (28)$$

d. Three-Leg Signalized Intersections

$$N_{jm} = \{\exp[-10.9 + 0.79 \ln(ADT_1) + 0.49 \ln(ADT_2)]\} * \{\exp[-5.73 + 0.60 \ln(ADT_1) + 0.20 \ln(ADT_2)]\} / \exp[-9.34 + 0.60 \ln(ADT_1) + 0.61 \ln(ADT_2)] \quad (29)$$

where

N_{jm} = expected annual accident frequency for location type m at site j,
ADT_1 = average daily traffic volume (veh/day) on the major road, and
ADT_2 = average daily traffic volume (veh/day) on the minor road.

For a more detailed explanation of the at-grade intersection base models, see Harwood et al. (*7*).

The user can consider addition of turn lanes as an option to be analyzed by the resource allocation program. The process will consider two alternatives: improve all the intersections and do not improve the intersections. If the accident histories for the individual at-grade intersections to be improved are known, the user can choose to use the known accident history instead of estimating the values. In this case, the user enters only the information related to the intersections to be improved. If the accident history needs to be estimated by the process, the user will need to enter the data related to all intersections of a site (the ones that will be improved and the ones that will not be improved).

User-Defined Alternatives

For the user-defined alternatives, the percentage decrease in nonintersection and intersection accidents and the cost of each specific improvement are input values to the resource allocation process that the user will have to calculate based on the local practice.

The resource allocation process calculates the AMF for the user-defined alternatives using the following equations:

$$AMF_{\text{non-int}} = 1 - \left(\frac{\%AR_{\text{non-int}}}{100}\right) \quad (30)$$

$$AMF_{\text{int}} = 1 - \left(\frac{\%AR_{\text{int}}}{100}\right) \quad (31)$$

where

$AMF_{\text{non-int}}$ = accident modification factor for the effect of a user-defined alternative on total nonintersection accidents,
AMF_{int} = accident modification factor for the effect of a user-defined alternative on total intersection accidents,

$\% AR_{\text{non-int}}$ = percentage decrease in nonintersection accidents because of the specific user-defined alternative, and

$\% AR_{\text{int}}$ = percentage decrease in intersection accidents because of the specific user-defined alternative.

When improvement types with separate AMFs are used as part of the same project, the AMFs are combined in multiplicative fashion.

Accident Severity Distribution

The AMFs for the various improvement types discussed above apply equally to accidents of all severity levels. Knowledge of the safety effects of geometric improvements has not yet progressed to the point that it is possible to reliably estimate such effects separately for each accident severity level. The RSRAP software uses default estimates of the accident severity distribution for roadway segments and intersections to estimate the reduction in accident frequency separately for each of two accident severity levels: (1) fatal and injury accidents and (2) property-damage-only accidents.

The fatal and injury severity levels are combined so that the random occurrence of a single fatal accident does not influence the evaluation process.

Table 14 provides the estimates of the accident severity distribution for roadway segments and at-grade intersections. The default accident severity distribution in Table 14 is based on data from the FHWA Highway Safety Information System (HSIS) for Illinois, Michigan, Minnesota, and North Carolina (*7*).

Expected Annual Accident Frequency

The numbers of expected annual accidents for the roadway section, N_{j1}, and for at-grade intersections, N_{j2}, are user-input values. These accidents are then proportionally divided into individual accident severity levels using the accident severity level proportions presented in Table 14.

Determination of Safety Benefits

The present value of the safety benefits for each improvement alternative is quantified as the following:

$$PSB_{jk} = \left[\sum_{m=1}^{2} \sum_{s=1}^{2} N_{jm} (1 - AMF_{mk}) RF_{ms} AC_s \right] (P/A, i, n) \qquad (32)$$

where

PSB_{jk} = present value of safety benefits of improvement alternative k at site j,

N_{jm} = expected annual accident frequency for location type m at site j,

AMF_{mk} = accident modification factor for improvement alternative k at location type m expressed as decimal fraction,

RF_{ms} = proportion of total accidents in severity level s to which AMF_{mk} applies expressed as a decimal fraction,

AC_s = cost savings per accident reduced for accident severity s, and

$(P/A,i,n)$ = uniform-series present worth factor to convert a series of uniform annual amounts to its present value.

Accident Reduction Cost

The safety benefits of specific improvements evaluated in RSRAP are expressed in monetary terms using accident cost estimates published by FHWA. The most recent FHWA estimates, published in 1994 (*43*), and a 2002 update to those estimates, developed in the research, are shown below in Table 15.

These 2002 estimates of accident cost are used as default values in the RSRAP software.

For analysis purposes, the fatal injury accident level (F) and the other injury accident levels have been combined into a single accident cost level. It is generally inappropriate to treat fatal accident costs separately when analyzing specific sites because the occurrence of a fatal accident at any particular site may be simply random. The injury levels of incapacitating injury accident (A), serious injury accident (B), and minor injury accident (C) have been combined because not all potential users of the resource allocation process have accident records systems that classify accident severity in this way. The accident cost estimates used as default values in RSRAP are as follows:

- AC_1—Fatal or injury accident (F/A/B/C)—$103,000/accident.

TABLE 14 Default distribution for accident severity level used in RSRAP (*7*)

Accident severity level	Proportion of total accidents	
	Roadway segments	Intersections
Fatal and injury	0.321	0.397
Property damage only	0.679	0.603
TOTAL	**1.000**	**1.000**

TABLE 15 FHWA accident cost estimates (*43*)

	1994	2002
Fatal accident (F):	$2,600,000	$3,000,000
Incapacitating injury accident (A):	180,000	208,000
Serious injury accident (B):	36,000	42,000
Minor injury accident (C):	19,000	22,000
Property-damage-only accident (PDO):	2,000	2,300

- AC_2—Property-damage-only accident (PDO)—$2,300/ accident .

Users may replace these accident cost estimates with alternative values used by their agencies.

Accident costs in rural areas may be higher than in urban areas because the proportion of fatal and injury accidents is often higher in rural areas. Although the capability to consider separate accident costs for rural and urban areas is not explicitly included in RSRAP, this can be accomplished by replacing the default accident costs on a site-by-site basis.

Estimate Safety Penalty for Not Resurfacing—PNR

Option 1 of the resource allocation process, presented above, does not require any consideration of resurfacing benefits because under the assumptions of Option 1 the decision to resurface the roadway sections in question has already been made. Option 2, however, is intended to allow resurfacing to compete with safety improvements for available funds. This option does require consideration of resurfacing benefits. Resurfacing benefits are considered by adding a penalty, designated *PNR*, to the do-nothing alternative so that there is an additional cost associated with not resurfacing a site.

In 3R programs, one of three approaches must be selected for every site considered: (1) do nothing, (2) resurface only, or (3) resurface plus implement one or more additional safety improvements. Safety improvements have specific quantifiable benefits in terms of reduced accidents, reduced delays, and/or reduced vehicle operating costs. However, the only direct user benefits or costs of resurfacing are short-term operational benefits caused by increased speeds and possible short-term increases in accidents if resurfacing is not accompanied by geometric improvements. If only these costs and benefits were considered, the resurfacing projects selected would generally be those with the greatest potential for accompanying safety improvements. Such an approach gives no consideration to the pavement condition and the criticality of the need for resurfacing. If resurfacing of a roadway section is postponed too long, it may require a thicker (and more expensive) overlay. Postponing resurfacing until failure occurs may require complete replacement of the pavement structure down to the subgrade.

To give the need for resurfacing its proper weight in the resource allocation process, a penalty for not resurfacing (in terms of future pavement overlay or replacement costs) is assigned to the do-nothing alternative. This value varies with the present condition of the roadway section; it is higher where the present condition of the pavement is worse. The penalty for not resurfacing a roadway section for a specific number of years (when it will require complete replacement) can be represented by the present value of future pavement replacement cost:

$$PNR_{jk} = \begin{cases} -a\,RB_j & \text{for do-nothing alternative} \\ 0 & \text{for all other alternatives} \end{cases} \tag{33}$$

where

PNR_{jk} = present value of not resurfacing improvement alternative k at site j (future pavement replacement cost),

RB_j = pavement replacement cost to be incurred for site j (based on estimate for *Reconcost* in Table 5), and

a = coefficient based on number of years until pavement failure (number of years and default a values are given below).

Number of years	**Default *a* values**
1 yr or less	1
2 yr	0.8
3 yr	0.6
4 yr	0.4
5 yr	0.2
6 yr or more	0

The default values of *a* shown above can be changed by the user according to site-specific data.

Estimate Safety Penalty for Resurfacing Without Other Geometric Improvements for Each Improvement Alternative—PRP

The effect of resurfacing on safety has been a matter of controversy for years. Some researchers have maintained that resurfacing of a road increases speeds, which, in turn, may increase accidents. Others have contended that such an effect is unproven.

Research by Hauer, Terry, and Griffith (*11*) has demonstrated that such an effect of resurfacing on safety exists, but has a relatively short duration (30 months for nonintersection accidents and 12 months for intersection accidents). Research in NCHRP Project 17-9(2) found an inconsistent resurfacing effect: resurfacing had a negative effect on safety in some states and a positive effect on safety in others. Because the NCHRP Project 17-9(2) research was inconclusive, the user has been provided an option to consider or not consider: the safety penalty for resurfacing without accompanying geometric improvements, designated *PRP*, based on the Hauer, Terry, and Griffith results.

According to the research by Hauer, Terry, and Griffith (*11*), resurfacing without accompanying geometric improvements may result in a short-term (approximately 12- to 30-month) increase in accident experience. In the resource allocation process, this penalty (see Equation 34) for resurfacing is added to alternatives that include resurfacing and have existing lane and shoulder width less than 11 and 6 ft, respectively, when these geometric elements were not improved. The default value of the resurfacing effect is an increase in nonintersection accidents of 21 percent over the first 30 months after resurfacing and an increase in intersection accidents of 35 percent over the first 12 months after resurfacing. When geometric improvements (which in the RSRAP software include lane and shoulder width larger than 11 and 6 ft, respectively) are made in conjunction with a resurfacing project, the penalty is set equal to zero. This penalty is presented by the function below:

$$PRP_{jk} = \begin{cases} 0 \quad \text{for do-nothing and alternatives with lane width} \geq 11 \text{ ft and shoulder width} \geq 6 \text{ ft} \\ \left[0.21 \sum_{s=1}^{2} N_{j1}AC_s + 0.35 \sum_{s=1}^{2} N_{j2}AC_s\right](P/F,i,1) + \left(0.21 \sum_{s=1}^{2} AC_s N_{j1})(P/F,i,2\right) + \left(0.105 \sum_{s=1}^{2} AC_s N_{j1}\right)(P/F,i,3) \end{cases} \quad (34)$$

where

PRP_{jk} = present value of short-term safety penalty for resurfacing without accompanying safety improvements for improvement alternative *k* at site *j*,
N_{jm} = expected annual accident frequency for location type *m* at site *j*, and
AC_s = cost savings per accident reduced for accident severity level *s*.

Estimate Traffic-Operational Benefits for Each Improvement Alternative—PTOB

The traffic operation benefits of resurfacing, designated *PTOB*, may also be considered. Research during this project has demonstrated that there is a small speed increase of approximately 1 mph that accompanies resurfacing. This represents an average value of speed changes for approximately 40 sites that were resurfaced. The effect of resurfacing on average values of speed change ranged from a 4-mph decrease in speed to a 7-mph increase in speed. The average 1-mph increase in speed represents a traffic-operational benefit that may partially offset the increase in accident frequency caused by resurfacing discussed above. By default, this effect of resurfacing on traffic operations is included in the resource allocation process analysis, but the consideration of this traffic-operational benefit may be disabled by the user.

The present value of travel time and delay benefits for each improvement alternative is quantified as the following:

$$\begin{aligned} PTOB_{jk} &= \left(\frac{L}{Speed} - \frac{L}{(Speed+1)}\right) ADT365TC(P/F,i,1) \\ &+ \left(\frac{L}{Speed} - \frac{L}{(Speed+1)}\right) ADT365TC(P/F,i,2) \\ &+ \frac{1}{2}\left(\frac{L}{Speed} - \frac{L}{(Speed+1)}\right) ADT365TC(P/F,i,3) \end{aligned} \quad (35)$$

where

$PTOB_{jk}$ = present value of travel time reduction benefits for improvement alternative *k* at site *j*,
L = project length (mi),
$Speed$ = speed (mph) (default values = 60 mph for rural roads, 40 mph for urban roads),
ADT = average daily traffic (vehicles/day), and
TC = cost of time saved for driver ($/hr) (default value = $10/hr).

The traffic-operational benefit attributable to increased speed is considered to last for 30 months after resurfacing. The benefit's present value is calculated taking into account the site length, speed of travel, ADT, and monetary value of time to the driver (the default value in the RSRAP software is $10/hr).

Determine Net Benefits for Each Alternative

The next step in the resource allocation process is to determine the net benefits for each improvement alternative at each site. The formulation of the net benefits depends on which analysis options have been selected by the user.

The net benefit equations to be used for each option selected are presented below:

Option 1A—Safety benefits considering safety improvements only

$$NB_{jk} = PSB_{jk} + PRP_{jk} - CC_{jk} \tag{36}$$

Option 2A—Safety benefits considering both resurfacing and safety improvements

$$NB_{jk} = PSB_{jk} + PNR_{jk} + PRP_{jk} - CC_{jk} \tag{37}$$

Option 1B—Safety and speed benefits considering safety improvements only

$$NB_{jk} = PSB_{jk} + PTOB_{jk} + PRP_{jk} - CC_{jk} \tag{38}$$

Option 2B—Safety and speed benefits considering both resurfacing and safety improvements

$$NB_{jk} = PSB_{jk} + PTOB_{jk} + PNR_{jk} + PRP_{jk} - CC_{jk} \tag{39}$$

where

NB_{jk} = net benefit for improvement alternative *k* at site *j*,
PSB_{jk} = present value of safety benefits of improvement alternative *k* at site *j* (using the AMFs),
$PTOB_{jk}$ = present value of travel time reduction benefits for improvement alternative *k* at site *j*,
PNR_{jk} = present value of penalty for not resurfacing improvement alternative *k* at site *j* (only nonzero for the do-nothing alternative),
PRP_{jk} = present value of short-term safety penalty for resurfacing without accompanying geometric improvements for improvement alternative *k* at site *j*, and
CC_{jk} = construction cost for improvement alternative *k* at site *j*.

If the user has specified that the safety penalty for resurfacing without accompanying safety improvements should be considered, then PRP_{jk} in Equations 36 through 39 is set equal to zero in all cases.

It should be noted that in all formulations of the equation for net benefits each term has already been converted to a present value except the construction cost term, which is, by nature, already a present value.

Select the Most Suitable Improvement Alternative for Each Site Within the Available Budget

An integer programming approach is used to select the most suitable improvement alternative for each site within the available budget. The integer program to provide the optimum mix of improvement alternatives is as follows:

$$\text{Maximize } TB = \sum_{j=1}^{y}\sum_{k=1}^{z} NB_{jk} X_{jk} \tag{40}$$

subject to the following constraints:

$$\sum_{k=1}^{z} X_{1k} = 1 \tag{41}$$

$$\sum_{k=1}^{z} X_{2k} = 1 \tag{42}$$

$$\vdots$$

$$\sum_{k=1}^{z} X_{yk} = 1 \tag{43}$$

$$\sum_{j=1}^{y}\sum_{k=1}^{z} CC_{jk} X_{jk} \le B \tag{44}$$

where

TB = total benefits from all selected improvements,
y = total number of sites,
z = total number of improvement alternatives for a given site,
X_{jk} = an indicator value whose value is 1 if alternative improvement *k* at site *j* is selected as part of the optimum allocation of funds and whose value is 0 if alternative improvement *k* at site *j* is not selected as part of the optimum allocation of funds (for each site exactly one alternative should be selected), and
B = improvement budget or maximum funding available for improvement of the sites under consideration.

Equation 40 is the objective function of the integer program, which represents the total benefits to be maximized. The values of NB_{jk} for each improvement alternative at each site is determined with Equations 36, 37, 38, or 39, depending on the user's objective in analyzing the resource allocation problem.

The constraints on the optimal solution are represented by the equalities and inequalities presented below the objective function. They require that one and only one improvement alternative can be selected for each site. The last inequality constrains the total expenditure on improvements to be less than or equal to the available budget.

The optimal solution to the integer program is the group of improvement alternatives that provides the maximum total benefit given the constraints in Equations 41 through 44. This optimum solution consists of the improvement alternative for each site for which the value of X_{jk} in the integer program is equal to 1. The total net benefits for this group of alternatives can be determined with Equation 40, and the total expenditures on improvements required to achieve those benefits can be determined with the equation used for calculating the cost constraint (expressed as an equality rather than an inequality).

The optimization by integer programming is performed using the Solver program, which is included as a standard feature of the Microsoft Excel spreadsheet package. The version of the Solver program supplied with Excel is limited in the size of problems it can solve, but larger versions of the Solver program that also work with Excel are available commercially.

CHAPTER 6

IMPLEMENTATION OF THE RESOURCE ALLOCATION PROCESS

The resource allocation process has been implemented through a software application developed as part of this research and provided on CD-ROM with this report. This software is called the Resurfacing Safety Resource Allocation Program or RSRAP. This software has been developed, tested, and demonstrated as part of the research. Part 2 of this report is a user guide that explains the process to potential users.

This chapter begins with an overview of the RSRAP software and the RSRAP User Guide. The next section summarizes the demonstration and testing process. Application examples of the resource allocation process using the RSRAP software are then presented. The chapter concludes with an assessment of the benefits of the resource allocation process.

RSRAP SOFTWARE AND USER GUIDE

RSRAP Software

RSRAP, the software developed to implement the resource allocation process (described in Chapter 5), consists of a Microsoft Access database application that utilizes Microsoft Excel's Solver add-in for execution of the optimization process. Access and Excel were chosen for this application because most highway agencies already have these programs. Furthermore, the RSRAP operation and environment resembles many Windows-based applications. It has on-screen graphics, such as dialog boxes, pull-down menus, and other similar utilities that make the application user-friendly. Although this chapter highlights some of the capabilities of RSRAP, a more detailed explanation can be found in Part 2 of this report, the RSRAP User Guide.

RSRAP includes the capability to input site-specific geometric data, select appropriate improvement alternatives for individual sites, specify user-defined alternatives, check input data quality and consistency, generate data input reports, perform cost and benefit computations for specific alternative improvements (and combinations of alternatives), and select the optimal set of improvement alternatives. Two primary screens were developed for managing the majority of these functions: a Site Data Input screen and an Optimization Results screen.

The Site Data Input screen, shown in Figure 3, not only accepts input for site-specific geometrics but also has several subscreens that allow the user to select improvement alternatives, enter data for additional user-specified improvement alternatives, and enter data for site-specific costs and safety estimates. The Alternatives tab/subscreen allows for the selection of improvement alternatives for each site as well as options and entry for user-defined alternatives. If the user elects to consider roadside, horizontal curve, or intersection turn-lane improvements, the corresponding tabs may be accessed to enter additional site geometric data concerning these features. The final two tabs on this screen represent subscreens containing site-specific default construction costs, accident costs, and safety-effectiveness estimates that may be changed to more appropriately reflect the characteristics of a specific site.

An additional feature on the Site Input Data screen is a list box of sites through which data for a specific site can be provided by clicking on the name of that site. There are also several command buttons that allow for the addition/deletion of sites as well as viewing and printing detailed or summary data input reports. Similarly, the menu bar, appearing throughout the program and at the top of the screen in Figure 3, provides a way to import or export current and previously entered data. Finally, some edit checks for data quality are included for these screens to ensure proper execution of the program as well as proper calculation of costs and benefits.

Once data entry for selected sites is complete and the user starts the optimization process, RSRAP prompts the user for a few more inputs and options and then begins the calculation of improvement alternative costs and benefits, the first step in providing the final solution. After these calculations are performed for each improvement alternative, data for all cost-effective alternatives for each site are transferred from Access to Excel in a manner that is transparent to the user. The optimization process is performed in Excel using an add-in program called Solver. Solver optimizes the entire improvement program by selecting the improvement alternatives for each site to collectively provide the maximum benefit. Solver performs this optimization within two sets of constraints. First, one, and only one, improvement alternative may be selected for each site, and second, the total construction cost must be less than or equal to the user-specified budget. Solver arrives at the set of optimized improvements by utilizing integer programming in a process called the Branch and Bound method. The Solver program that is supplied with Excel is limited in the number of alternatives that it can consider in the optimization process (200 alternatives). This constraint applies to

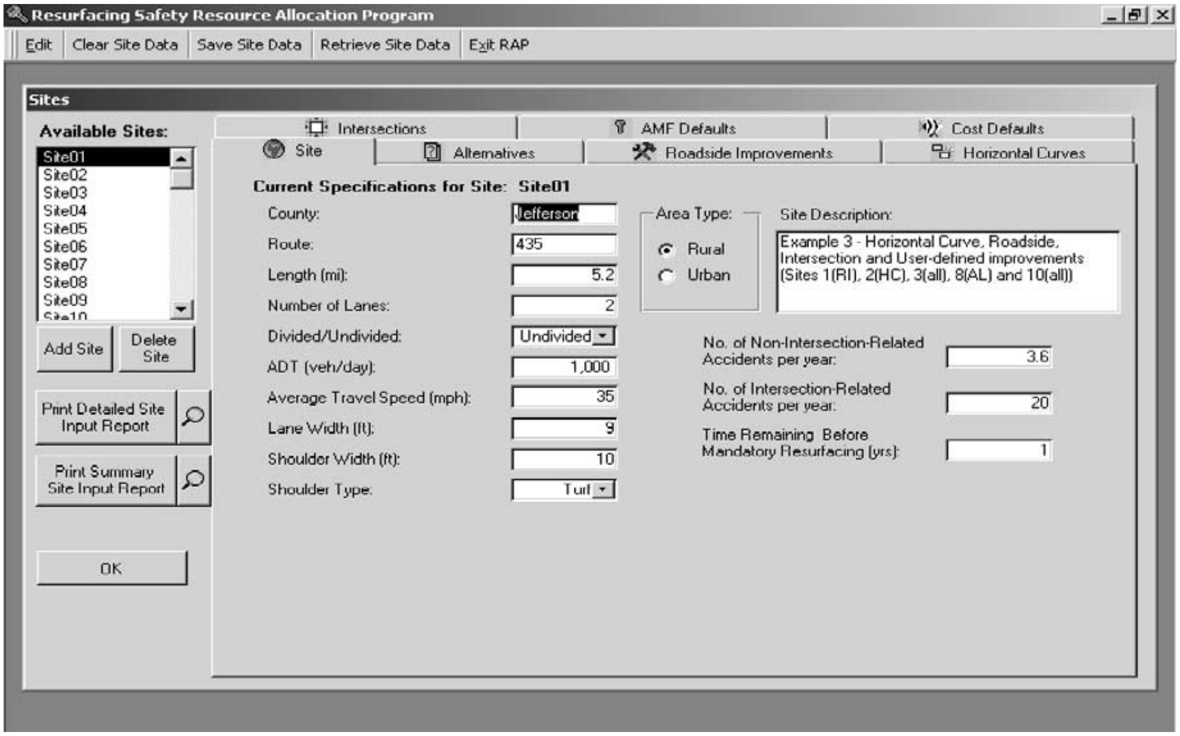


Figure 3. Example of RSRAP Site Input Data screen.

the number of cost-effective alternatives (or combinations of alternatives) for all sites combined, including the do-nothing alternative. Most practical problems for up to 30 or 40 sites can be handled by the default version of Solver. Should more sites or alternatives need to be considered, larger versions of Solver are available commercially.

Once the optimization process is completed, the optimized set of improvements is transferred back to Access for review by the user. The user is notified when the calculations and optimization are complete and is allowed to view the Optimization Results screen, which is shown in Figure 4.

The Results screen and its associated reports present all of the information needed to document for the user which improvement alternatives constitute the optimal improvement program for the sites considered. In the example Results screen shown in Figure 4, the title identifies the analysis options that were selected by the user. The user-specified improvement budget that was used as a constraint in the optimization process is also shown at the top right corner of the screen. Each site selected in the optimization process is shown along with the resurfacing costs, safety improvement costs, and total costs. Similarly, the benefits for each selected alternative are divided into safety and traffic-operational benefits. The expected percentage reduction in total accidents for each site, including both intersection and nonintersection accidents, is also shown. This screen provides command buttons to view or print a summary report or a more detailed report. It also gives the user the option to switch to a more detailed site-by-site result screen.

RSRAP User Guide

Instructions for use of the RSRAP software are provided in the User Guide that is the second part of this report. The User Guide provides an overview of the program objectives and the resource allocation process and step-by-step instructions for operation of the software.

The software application portion of the User Guide begins by providing a quick review of the basic user interface provided by Microsoft Access. That discussion briefly explains the common features of Access applications, including how to open the RSRAP program, how to move between screens, how to enter and edit data, and how to apply the controls used in Access to select specific data records. Navigation of RSRAP itself is documented in the User Guide by a 10-step procedure outlined below:

- Step 1—Start Microsoft Access.
- Step 2—Start RSRAP.
- Step 3—Choose data entry options (proceed to Step 4 or 5).
- Step 4—Change global default values used to determine improvement benefits and costs (optional).
- Step 5—Enter site data:
  Add site to database;
  Enter basic site data;
  Identify improvement alternatives to be considered;
  Enter additional data, when needed, about the improvement alternatives to be considered; and

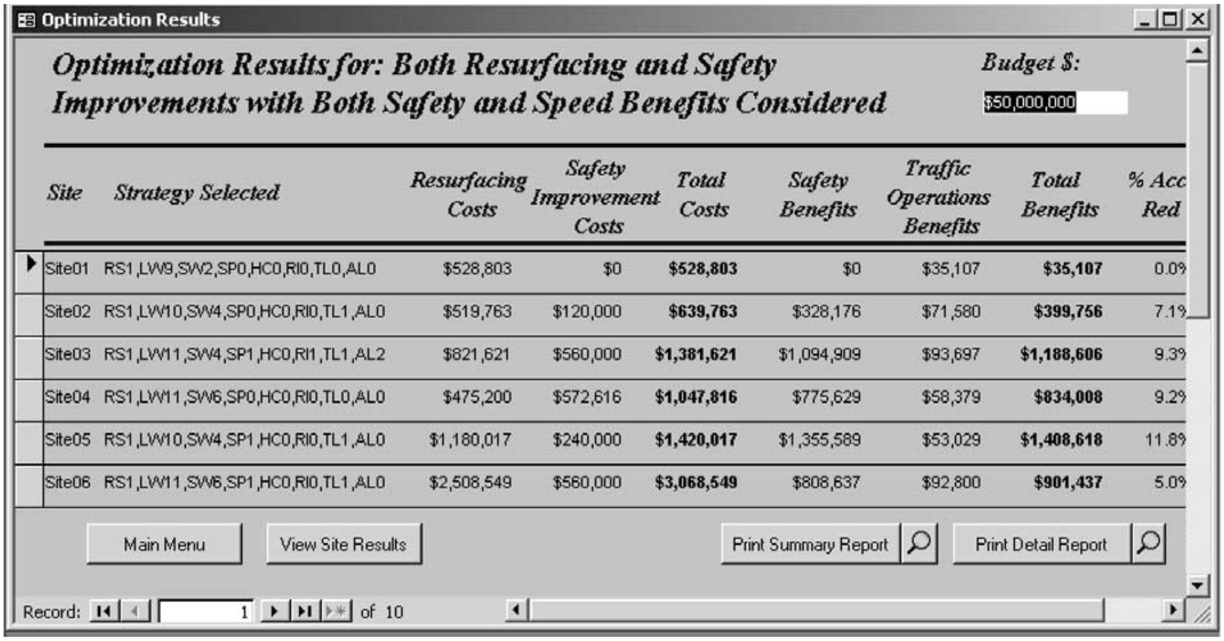


Figure 4. Example of RSRAP Optimization Results screen.

Change site-specific default values (optional).

- Step 6—Choose optimization and analysis options.
- Step 7—Review summary form prior to optimization.
- Step 8—Edit data as needed prior to optimization (optional).
- Step 9—Enter improvement budget and start RSRAP optimization process.
- Step 10—Review optimization results.

For each step of this process, the User Guide provides a detailed explanation complete with screen prints, scenarios, examples, and definitions of input and output. Additionally, it provides suggestions on how the decision maker might use the information.

The User Guide also provides information concerning system requirements, installation, and instructions for upgrading the Solver program (if needed to address larger problems).

DEMONSTRATION AND TESTING OF THE RSRAP SOFTWARE

Testing of the RSRAP Software

The resource allocation process is applicable to a variety of analysis scopes and options. To ensure the accuracy of the program and its calculations, RSRAP was systematically tested. A test plan was developed and executed, and an Excel spreadsheet was developed to verify RSRAP's cost and benefit calculations.

The test plan was designed to itemize all possible paths and options a user could encounter during execution of the program. Specifically, it tested the functionality of command buttons, message boxes, menu items, check boxes, option buttons, and valid input values. It consisted of a test case description, input values, expected output, and observed output. The test plan was utilized throughout the development of the RSRAP allocation process.

The Excel spreadsheet was used to verify the cost and benefit calculations in RSRAP. The Excel spreadsheet calculates all AMFs, benefits, costs, and net benefits for a specific improvement at a given site as specified in the resource allocation process presented in Chapter 5 of this report. It was verified that RSRAP provides results identical to the Excel spreadsheet for a wide variety of cases.

The many iterations of RSRAP performed as part of the testing process not only aided in better program operation but also helped in refining the resource allocation process. For example, some analysis options found to be redundant were eliminated. Additionally, the testing process allowed the authors to assess the benefits of the resource allocation process compared with other approaches.

State Highway Agency Demonstrations

The resource allocation process and the RSRAP software were demonstrated in cooperation with three participating state highway agencies. The demonstration allowed the participating state highway agencies to learn how the process works, to apply the process to actual sites under their jurisdiction, and to provide comments to the research team on potential improvements to the process.

The three state highway agencies that agreed to participate in the demonstration were the California Department of Transportation, the Minnesota Department of Transportation, and the Missouri Department of Transportation. In each demonstration, the research team

- Presented a brief training course on the resource allocation process and software,
- Responded to questions by highway agency staff concerning the resource allocation process and software,
- Provided assistance to the highway agency staff in learning to enter data for sites under their agency's jurisdiction, and
- Provided assistance to the highway agency staff in installing the RSRAP software on their computers.

The highway agency staff then used the software themselves over a period of several months and provided comments to the research team on clarifying the resource allocation process and improving the software.

In addition to the three state highway demonstration efforts, the capabilities of the resource allocation process and software were also presented to FHWA.

APPLICATION EXAMPLE OF THE RESOURCE ALLOCATION PROCESS

This section presents a numerical example of the application of the resource allocation process as described in components presented in Chapter 5. This application example was designed and executed using the RSRAP software presented earlier in this chapter. This example illustrates how a resource allocation process based on maximizing the net benefits of projects within a budget level can assist a highway agency in selecting appropriate design alternatives for safety improvements in conjunction with resurfacing projects. This example uses the most complete of the four analysis options for determining the net benefits, as illustrated in Equations 36 through 39. This most complete option, referred to as Option 2B and illustrated by Equation 39, considers resurfacing and safety improvements and safety and speed benefits.

Sites Considered

The application example considers 10 sites that have been identified as in potential need of resurfacing, that is, a 1- to 2-in. overlay to the current pavement structure. These sites are hypothetical and were devised for illustrative purposes; however, they represent the types of sites that might be considered in the annual resurfacing program of a state highway agency district office. The 10 sites in the example include three sites on rural, two-lane highways; one site on a rural, multilane, undivided highway; two sites on rural, multilane, divided highways; one site on an urban/suburban, two-lane arterial; two sites on urban/suburban, multilane, undivided arterials; and one site on an urban/suburban, multilane, divided arterial. The lengths of the sites vary from 2.3 to 5.7 mi, and the ADT volumes vary from 1,000 to 15,000 veh/day.

Table 16 summarizes the characteristics of the sites, including the area type (rural/urban), roadway type (divided/undivided), length, ADT, number of lanes, lane width, shoulder width, shoulder type, and annual average frequencies of non-intersection- and intersection-related accidents for each site.

The site characteristics vary over a broad range of conditions. For example, one site has an extremely restricted cross section (9-ft lanes with 2-ft shoulders), whereas another has a nearly ideal cross section (12-ft lanes with 8-ft shoulders). The cross sections of the rest of the sites are between these values.

Safety Performance of Candidate Sites

The existing safety performance of the candidate sites entered in RSRAP, expressed as accident frequency per year,

TABLE 16 Characteristics of sites used in the example problem

Site No.	Area type	Roadway type	No. of lanes	ADT (veh/day)	Avg. Speed (mi/h)	Length (mi)	Lane width (ft)	Shoulder width (ft)	Shoulder type	Average annual accident frequency	
										Non-intersection	Intersection-related
1	Rural	Undivided	2	1,000	35	5.2	9	2	Turf	5	3
2	Rural	Undivided	2	3,000	40	4.6	10	4	Composite	4	4
3	Rural	Undivided	2	4,000	45	5.7	11	4	Paved	11	11
4	Urban	Divided	2	7,000	50	2.5	10	4	Paved	15	3
5	Rural	Undivided	4	4,000	55	4.8	10	4	Gravel	10	10
6	Urban	Undivided	4	6,000	55	5.6	11	6	Paved	14	14
7	Rural	Divided	4	5,000	50	5.6	11	4	Paved	13	13
8	Rural	Divided	4	10,000	50	4.5	12	8	Paved	15	15
9	Urban	Undivided	4	10,000	60	3.5	10	2	Paved	12	12
10	Urban	Divided	6	15,000	60	2.3	11	4	Paved	14	14

is also shown in Table 16. These values are used primarily in the calculation of safety benefits for the various improvement alternatives. High expected annual accident frequency makes it more likely that safety improvements will be chosen for that site; low expected annual accident frequency makes it less likely that safety improvements will be cost-effective.

Improvement Alternatives for Candidate Sites

The application example includes a variety of improvement types for the 10 sites. Appendix D presents the summary and detailed input reports for these sites, which document the site characteristics and the improvement alternatives considered by RSRAP for each site. In this example, the following improvements were considered for each of the sites:

- Resurfacing,
- Lane widening,
- Shoulder widening,
- Shoulder type, and
- Installation of turn lanes (left and/or right) at intersections.

A combination of the other three improvement types was considered for some of the sites for illustrative purposes. These other three possible improvements are

- Roadside improvements—three sites,
- Horizontal curve improvements—three sites, and
- User-defined improvements—three sites.

For the application example, it was assumed that each site was currently in need of a 1- to 2-in. overlay. It was also assumed that the pavement for each site was 5 years from failure; that is, the entire pavement structure down to the subgrade would fail and would need to be reconstructed if the site was not resurfaced within 5 years.

RSRAP considers lane widening in 1-ft increments up to a maximum lane width of 12 ft. In other words, if the site had an existing lane width of 9 ft, widening by 1, 2, and 3 ft would be considered. However, if the site had an existing lane width of 11 ft, then lane widening by 1 ft only would be considered. Lane widening is not considered for sites with existing 12-ft lanes, but when calculating the resurfacing cost, the program will consider the existing lane width even if the lane width is greater than 12 ft.

RSRAP considers shoulder widening in 2-ft increments up to a maximum shoulder width of 8 ft. In other words, if a site had an existing shoulder width of 2 ft, then widening of the shoulders by 2, 4, and 6 ft would be considered. However, if the site had an existing shoulder width of 6 ft, then shoulder widening by 2 ft only would be considered. Shoulder widening was not considered for sites with existing 8-ft shoulders.

In this example, the number of intersections considered varied from three to nine intersections per site. Appendix D presents the detailed intersection, horizontal curve, and roadside design information considered for each site.

User-defined alternatives were included for three sites. RSRAP considers each user-defined alternative as a separate alternative that can be considered independently, or in combination with, the other alternatives. Although the example does not specify the particular user-defined improvement types, addition of shoulder rumble strips to shoulders and median enhancements are typical of the types of improvements that might be considered.

In all cases, the do-nothing alternative (not resurfacing and leaving existing geometrics in place) was also considered.

Using the logic described above, the alternatives considered for each improvement can be determined, and the total number of alternative improvements per site can be calculated. For example, at Site 1, which has existing 9-ft lanes, four lane-widening alternatives were considered: maintaining the 9-ft lanes, widening the lanes to 10 ft, widening the lanes to 11 ft, and widening the lanes to 12 ft. Similarly, four shoulder-widening alternatives were considered: maintaining the 2-ft shoulders, widening the shoulders to 4 ft, widening the shoulders to 6 ft, and widening the shoulders to 8 ft. Two shoulder-paving alternatives were considered: leaving turf shoulder as is or paving it. Two turn-lane options were considered: not installing turn lanes or installing both two left-turn lanes and two right-turn lanes at three selected major intersections on the site (for details, see Appendix D). When all possible combinations of the four lane-widening alternatives, four shoulder-widening alternatives, two shoulder-paving alternatives, and two left-turn-lane alternatives are considered, there are a total of 64 ($4 \times 4 \times 2 \times 2 = 64$) feasible geometric design improvement alternatives. Each of the 64 alternatives involves resurfacing the pavement. In addition, one more alternative was considered: the do-nothing alternative in which the pavement is not resurfaced and no geometric improvements are made. Therefore a total of 65 alternatives were considered for Site 1.

Table 17 summarizes the number of improvement alternatives considered for each of the 10 sites. The number of improvement alternatives per site ranges from 9 to 193 depending on the existing geometrics of the site. For the 10 sites as a whole, a total of 672 improvement alternatives were considered.

The net benefits of each of the 672 improvement alternatives were computed using Equation 39. To find the optimum set of improvement alternatives that maximizes the total benefits of the projects selected at the 10 sites, it might initially appear that all combinations of improvement alternatives at each site would need to be considered. The number of such combinations is very large; there are over 6.4 quadrillion combinations ($65 \times 73 \times 193 \times 73 \times 19 \times 9 \times 13 \times 9 \times 25 \times 193$). However, in actual practice, only those improvement alternatives for which the safety benefits are cost-effective need to be considered. Thus, the only alternatives that need to be retained in the optimization are those for which the safety benefits

TABLE 17 Number of improvement alternatives considered for sites in the example problem

Site number	Number of safety improvement alternatives							Total number of alternatives[a]	Alternatives considered by RSRAP[b]
	Lane width	Shoulder width	Shoulder type	Turn lanes	HC	RI	UD		
1	4	4	2	2	1	1	1	65	2
2	3	3	2	2	2	1	1	73	3
3	2	3	1	2	2	2	4	193	5
4	3	3	2	2	1	2	1	73	4
5	3	3	1	2	1	1	1	19	3
6	2	2	1	2	1	1	1	9	3
7	2	3	1	2	1	1	1	13	3
8	1	1	1	2	1	1	4	9	4
9	3	4	1	2	1	1	1	25	3
10	2	3	1	2	2	2	4	193	6
								672	30

[a] Includes the do-nothing alternative in addition to those shown in the table.
[b] Cost-effective alternatives that were not dominated by others.

Note: HC = horizontal curve improvement
RI = roadside improvement
UD = user-defined improvement

exceed the safety improvement costs; other improvements could not, by definition, be part of an optimal improvement program. In addition, any alternative that is dominated by another alternative can also be eliminated from consideration; an alternative is dominated by another alternative if its costs are higher and its benefits lower than the other alternative. The do-nothing alternative is retained for consideration by the optimization process in all cases.

Table 17 shows that, in this example, there were 36 improvement alternatives with net safety benefits greater than zero that were not dominated by other improvement alternatives. The resource allocation process for this example, therefore, evaluated 233,280 possible combinations ($2 \times 3 \times 5 \times 4 \times 3 \times 3 \times 3 \times 4 \times 3 \times 6$) of these alternatives. Although this is still a large number of combinations, it is only a very small fraction (4×10^{-9} percent) of the 6.4 quadrillion total combinations. The linear programming algorithm works efficiently and does not need to evaluate each of the 233,280 combinations separately to find the optimal solution.

Improvement Costs

Estimates of the costs for resurfacing, pavement replacement, lane and shoulder widening, shoulder paving, and adding turn lanes for this example were based on the construction cost estimates presented in Chapter 5. The costs for a 1- to 2-in. overlay vary from \$1.07 to \$1.80/ft^2 based on area type (urban/rural). The costs for pavement replacement were considered to be \$12.10/ft^2 for both area types. The widening costs were based on a paving cost per unit area for the widened roadway, plus an earthwork cost for regrading the roadside slopes. The earthwork cost was based on the assumption that the existing roadside slopes (assumed to be 4 : 1) would be maintained, so that the toe of the slope would be moved further from the roadway.

The costs for installation of left-turn and right-turn lanes were assumed to be \$60,000 for rural areas and \$112,000 for urban areas.

The construction costs for horizontal curve improvements, roadside improvements, and user-defined alternatives are user-input values. The construction costs assumed in this example are presented in the detailed input report (see Appendix D).

Improvement Benefits

The improvement benefits were computed using the approach presented in Chapter 5. Specifically, the safety benefits of geometric improvement alternatives were computed in accordance with Equation 32. The safety effectiveness of lane and shoulder widening is based on the AMFs presented in Figures 1 and 2. The safety effectiveness of shoulder paving, improving horizontal curves, adding right- and left-turn lanes at intersections, and roadside design follows the procedures presented in Chapter 5 in the section entitled “Estimate Safety

Benefits for Each Improvement Alternative." The safety effectiveness of user-defined alternatives is specified by the user.

The penalty for not resurfacing, based on Equation 33, was considered for each do-nothing alternative. For resurfacing without accompanying geometric improvements, a safety penalty based on the results of Hauer, Terry, and Griffith (*11*) was assumed. This penalty was computed with Equation 34. The traffic-operational effects of the improvements (reduction in delay) were considered in this example and were calculated using Equation 35.

Net Benefit Calculation

The optimal set of improvements for this example was calculated considering safety and speed benefits for both resurfacing and safety improvements, taking into account the safety penalty for resurfacing without accompanying safety improvements. This corresponds to Option 2B in the net benefit calculation represented by Equation 39.

Selection of an Optimal Set of Improvement Alternatives Under Different Budget Constraints

Integer programming was used to select the optimal set of improvement alternatives that maximizes net benefits within the available budget for the 10 sites. The optimum mix is calculated in the resource allocation process using Equations 40 through 44. The example problem for the 10 sites was evaluated to determine the optimum mix of improvement alternatives at two different budget levels: $50,000,000 and $10,000,000.

First Budget Level: $ 50,000,000

The first budget level considered, $50,000,000, is sufficiently high that all of the improvements could be made. For $42,011,294, the highway agency could resurface each of the 10 sites and make all of the safety improvements selected for consideration. This is, in effect, a "do-everything" budget.

In fact, the maximum amount that RSRAP will allocate to improvements is the total cost to resurface all sites plus the total cost to make all cost-effective improvements. In this example, the maximum funding needed for these improvements is $16,271,247, which includes resurfacing costs of $11,789,849 and safety improvement costs of $4,481,397.

Table 18 shows that the optimal improvement program includes a mix of improvement types. The mix of projects shown in Table 18 has a total cost equal to the maximum funding level described above ($16,271,247). Expenditures on safety improvements beyond this level would not be justified because the improvements would not be cost-effective. In other words, as long as safety improvements are implemented only when their net benefit exceeds zero, any budget greater than or equal to $16,271,247 would provide the same result from the optimization process as that shown in Table 18.

The resurfacing costs presented in Table 18 represent the costs applicable to resurfacing the existing roadway with no geometric improvements. The resurfacing costs related to lane widening and shoulder widening are included in the safety improvement costs. The net safety benefit is calculated by subtracting the construction costs related to the safety improvements from the total benefits. For the optimum mix of improvement alternatives shown in Table 18, the net safety benefit is $6,159,517 ($10,640,914 – $4,481,397 = $6,159,517). The summary and detailed RSRAP output reports presented in Appendix D show the cost and benefit components used to create Table 18.

Evaluation of the optimal improvement set with an extremely large budget, larger than would be required for all conceivable improvements at the sites considered, is a useful first step in applying the resource allocation process. Even if the budget chosen is much larger than the available funding, the evaluation of a very large budget is an important first step for the analyst because it will identify the maximum funding level and the entire set of cost-effective improvements.

Second Budget Level: $ 10,000,000

The next step in applying the resource allocation process is to apply the RSRAP software to a more realistic funding level, equivalent to the budget actually available for resurfacing and safety improvements. Thus, the second budget level chosen for this example is lower than the maximum funding level ($16,271,247) for the optimum mix presented in the previous example. In this case, the budget selected was $10,000,000. With a lower budget, the optimum mix of projects will either defer resurfacing of some sites, or forego some safety improvements (even though they are cost-effective), or both. The results in Table 19 show that the optimal solution for a $10,000,000 budget defers both resurfacing and all safety improvements (i.e., selects the do-nothing alternative) at Sites 4, 6, and 9 and excludes user-defined alternative Number 2 at Site 8, so that the resurfacing and other safety improvements could be implemented in the other sites. The table shows that the total expenditure of $9,953,579, including $7,440,798 for resurfacing and $2,512,781 for safety improvement construction costs, would provide benefits of $7,187,814. Thus, the net safety benefit would be $4,675,033.

Other budget levels below $16,271,247 would yield different optimal mixes of projects. Therefore, it is important for the highway agency to perform the analysis for the budget level they will actually expect to have available.

BENEFITS OF THE RESOURCE ALLOCATION PROCESS

The resource allocation model developed in this research and the RSRAP software that implements the process are

TABLE 18 Optimal solution to the example problem with an improvement budget of $50,000,000

Site number	Selected improvement alternative	Resurfacing cost[a] ($)	Safety improvement cost ($)	Safety benefits ($)	Traffic-operational benefits ($)	Total benefits from safety improvements ($)	Percent accident reduction
1	Resurface only	528,803	0	0	35,107	35,107	0.0
2	Resurface Implement turn lane improvements	519,763	120,000	328,176	71,580	399,756	7.1
3	Resurface Implement turn lane improvements Implement roadside improvements Implement user-defined alternative No. 2	821,621	560,000	1,094,909	93,697	1,188,606	9.3
4	Resurface Widen lanes from 10 to 11 ft Widen shoulders from 4 to 6 ft	475,200	572,616	775,629	58,379	834,008	9.2
5	Resurface Implement turn lane improvements	1,180,017	240,000	1,355,589	53,029	1,408,618	11.8
6	Resurface Implement turn lane improvements	2,508,549	560,000	808,637	92,800	901,437	5.0
7	Resurface Implement turn lane improvements	1,503,237	360,000	947,234	93,407	1,040,641	6.3
8	Resurface Implement turn lane improvements Implement user-defined improvement No. 2	1,398,989	680,000	1,119,938	150,118	1,270,056	6.5
9	Resurface Implement turn lane improvements	1,365,302	336,000	1,071,895	81,348	1,153,243	7.8
10	Resurface Widen shoulders from 4 to 6 ft Implement horizontal curve improvements Implement turn lane improvements	1,488,369	1,052,781	2,329,256	80,186	2,409,442	15.7
	TOTAL	11,789,849	4,481,397	9,831,263	809,651	10,640,914	

[a] Cost for resurfacing of the existing cross section before any safety improvements are made.

TABLE 19 Optimal solution to the example problem with an improvement budget of $10,000,000

Site number	Selected improvement alternative	Resurfacing cost[a] ($)	Safety improvement cost ($)	Safety benefits ($)	Traffic-operational benefits ($)	Total benefits from safety improvements ($)	Percent accident reduction
1	Resurface only	528,803	0	0	35,107	35,107	0.0
2	Resurface Implement turn lane improvements	519,763	120,000	328,176	71,580	399,756	7.1
3	Resurface Implement turn lane improvements Implement roadside improvements Implement user-defined alternative No. 2	821,621	560,000	1,094,909	93,697	1,188,606	9.3
4	Do nothing	0	0	0	0	0	0
5	Resurface Implement turn lane improvements	1,180,017	240,000	1,355,589	53,029	1,408,618	11.8
6	Do nothing	0	0	0	0	0	0.0
7	Resurface Implement turn lane improvements	1,503,237	360,000	947,234	93,407	1,040,641	6.3
8	Resurface Implement turn lane improvements	1,398,989	180,000	555,526	150,118	705,644	3.2
9	Do nothing	0	0	0	0	0	0
10	Resurface Widen shoulder from 4 to 6 ft Implement horizontal curve improvements Implement turn lane improvements	1,488,369	1,052,781	2,329,256	80,186	2,409,442	15.7
	TOTAL	7,440,798	2,512,781	6,610,690	577,124	7,187,814	

[a] Cost for resurfacing of the existing cross section before any safety improvements are made.

intended to determine the optimal mix of improvement alternatives for a given set of sites within a specified budget level. In the application example presented above, the optimum solution is characterized by the mix of resurfacing-only projects and projects with various types of safety improvements. The purpose of this section is to assess the benefits of using the resource allocation process to determine safety improvement strategies in comparison with strategies that highway agencies might use in the absence of the resource allocation process. Two alternative strategies are

- Resurface all sites with no accompanying safety improvements and
- Resurface all sites, bring each site up to full AASHTO geometric standards, and make all safety improvements suggested by highway agencies.

The following numerical example demonstrates that each of these "fixed" strategies are suboptimal.

Table 20 compares the safety improvement costs and total safety benefits for the optimum mixes for different budget levels determined in the previous example with the two fixed strategies. The optimal mix with a $50,000,000 budget has a net safety benefit of $6,159,517. The optimal mix with a $10,000,000 budget has a net safety benefit of $4,675,033.

Resurfacing all sites with no accompanying safety improvements would cost $11,789,849 and would have a net

TABLE 20 Cost-benefit evaluation of the resource allocation process

Sites	Resurface only		Optimal mix with $50,000,000 budget		Optimal mix with $10,000,000 budget		All improvements	
	Safety improvement costs ($)	Total benefits ($)[a]	Safety improvement costs ($)	Total benefits ($)[a]	Safety improvement costs ($)	Total benefits ($)[a]	Safety improvement costs ($)	Total benefits ($)[a]
01	0	35,107	0	35,107	0	35,107	3,607,204	553,060
02	0	71,580	120,000	399,756	120,000	399,756	3,379,298	724,853
03	0	93,697	560,000	1,188,606	560,000	1,188,606	3,065,053	2,121,861
04	0	58,379	572,616	834,008	0	0	2,597,392	1,754,072
05	0	53,029	240,000	1,408,618	240,000	1,408,618	3,506,335	2,070,377
06	0	92,800	560,000	901,437	0	0	2,551,701	1,279,785
07	0	93,407	360,000	1,040,641	360,000	1,040,641	2,950,157	1,608,573
08	0	150,118	680,000	1,270,056	180,000	705,644	1,880,000	1,975,898
09	0	81,348	336,000	1,153,243	0	0	3,253,623	2,109,422
10	0	80,186	1,052,781	2,409,442	1,052,781	2,409,422	3,430,681	3,777,781
Total	**0**	**809,651**	**4,481,397**	**10,640,914**	**2,512,781**	**7,187,814**	**30,221,444**	**17,975,682**
Net Benefits[a]	***809,651***		***6,159,517***		***4,675,033***		***–12,245,762***	

[a] Includes only benefits from safety improvements and speed increases due to resurfacing.

TABLE 21 Summary of cost and benefit components for the application examples

Application example	Resurfacing cost ($)	Safety improvement costs ($)	Safety benefits PSB ($)	Traffic-operations benefits PTOB ($)	Penalty for resurfacing without accompanying safety improvements PRP ($)	Penalty for not resurfacing PNR ($)	Net safety benefits ($)[a]
Optimal mix for $50,000,000 budget	11,789,849	4,481,397	9,831,263	809,651	1,563,278	0	6,159,517
Optimal mix for $11,789,849 budget	8,806,100	2,848,781	7,682,585	658,472	1,563,278	3,787,281	5,492,276
Optimal mix for $10,000,000 budget	7,440,798	2,512,781	6,610,690	577,124	1,223,009	5,576,145	4,675,033
Resurface only	11,789,849	0	0	809,651	2,337,394	0	809,651
All improvements	11,789,849	30,221,444	17,166,032	809,651	0	0	–12,245,762

[a] Includes only benefits from safety improvements and speed increases due to resurfacing.

benefit of $809,651, attributable entirely to short-term speed increases associated with resurfacing. Thus, the benefit from resurfacing without any other improvements is less than from either of the accompanying strategies. By contrast, if the $11,789,849 cost of resurfacing all 10 sites were spent optimally, the net benefits would be $5,492,276; seven sites would be resurfaced with accompanying safety improvements, and one site would be resurfaced only. This indicates that use of the resource allocation process will provide greater benefits for a given expenditure level than resurfacing sites without accompanying geometric improvements.

Resurfacing all sites and making all of the safety improvements considered would cost $42,011,294 and would have a negative net benefit, –$12,245,762. The net benefit is negative because a number of safety improvements that have higher costs than benefits are included. This result illustrates that a strategy that involves making safety improvements that are not cost-effective results in benefits that are smaller than those that would be obtained using an optimal strategy from the resource allocation process.

Finally, Table 21 summarizes all cost and benefit components for the various strategies, not just those shown in Table 20. Table 21 includes the total safety improvement cost, safety benefit components (safety benefits, traffic-operational benefits, penalty for resurfacing without safety improvements, and penalty for not resurfacing), and net safety benefits (not including penalty for resurfacing without safety improvements and penalty for not resurfacing) for the three budget levels in the examples presented above and for the two fixed strategies. It is evident, once again, that the solutions reached using the resource allocation process for the $50,000,000 and $10,000,000 budgets are superior to the fixed strategies. They present considerably higher net safety benefits than the fixed strategies. The resource allocation process is the best available method to maximize the benefits of safety improvements in conjunction with pavement resurfacing.

CHAPTER **7**

CONCLUSIONS AND RECOMMENDATIONS

The research conducted for this project concluded the following:

1. Resource allocation methods provide an effective method for highway agencies to decide when safety improvements should be made in conjunction with pavement resurfacing projects.
2. For a given set of sites, resource allocation methods provide an optimal mix of resurfacing with accompanying safety improvements and resurfacing without accompanying safety improvements that provides greater benefits than any fixed strategy. Fixed strategies such as resurfacing all sites with no accompanying safety improvements or bringing all resurfaced sites up to full AASHTO geometric criteria are suboptimal and provide less total benefit than the optimal strategy determined from a formal resource allocation process.
3. Resource allocation methods for safety improvements in conjunction with resurfacing projects can be implemented through a mathematical optimization approach known as integer programming. Software known as the Resurfacing Safety Resource Allocation Program, or RSRAP, to implement the optimization process has been developed for use by highway agencies.
4. Pavement resurfacing on rural two-lane highways results in a small, but statistically significant increase in vehicle speeds. On average, mean and 85th-percentile vehicle speeds during the period from 2 to 4 months after resurfacing are approximately 1 mph higher than speeds at the same location before resurfacing. This effect, however, varies substantially from site to site and has been observed to range from a decrease in speeds of 4 mph to an increase in speeds of 7 mph. The duration of the period during which speeds are increased following resurfacing is uncertain, but is unlikely to exceed 30 months.
5. Resurfacing without accompanying geometric improvements may cause a small, short-term increase in accidents resulting from increased speeds, but the evidence for this effect is uncertain. One previous study found an increase in accidents following resurfacing that lasts for 12 to 30 months. Another study found inconsistent results, observing an increase in accidents following resurfacing in some states but a decrease in accidents following resurfacing in others. Given this conflicting information, a short-duration increase in accidents following resurfacing has been incorporated in the resource allocation software, but the user can elect whether or not to include this effect. The increase in accidents following resurfacing is assumed to occur only at sites with existing lane widths less than 11 ft and existing shoulder widths less than 6 ft.

The following recommendations are based on the research presented:

1. The RSRAP software developed during this research should be implemented by highway agencies to decide when safety improvements should be made in conjunction with improvement projects. To accomplish this, the software should be maintained, and technical assistance should be made available to highway agencies.
2. Further research should be undertaken to improve the AMFs used to represent the safety effectiveness of improvement projects.
3. Further research should be undertaken to resolve the effect on safety of resurfacing without accompanying geometric improvements. It is disappointing that a recent major effort to investigate this effect had inconclusive results. Alternative research approaches to investigating this issue should be formulated and implemented.
4. The optimization procedures implemented in the RSRAP software are suitable to be adapted to other applications for resource allocation in safety management. For example, integer programming could be used to optimize a general program of safety improvements not related to resurfacing projects.

PART 2:
RESURFACING SAFETY RESOURCE ALLOCATION PROGRAM (RSRAP) USER GUIDE

CONTENTS

SECTION 1

INTRODUCTION

This user guide provides references for users on basic principles and operations of the Resurfacing Safety Resource Allocation Program—RSRAP—provided on CD-ROM with this report.

The sections included in this guide are the following:

- **Section 2—Background**. This section presents an overview of the dilemma related to resurfacing, restoration, and rehabilitation projects (3R) and the main objective and scope of this research.
- **Section 3—The Resource Allocation Process**. This section presents a review of the resource allocation process, which is described in detail in Chapter 5 of the first part of this report.
- **Section 4—Installation of and Updates to the RSRAP Software**. This section outlines system requirements and how to install RSRAP on a computer system. It also gives instructions for upgrading Excel's Solver add-in.
- **Section 5—Access 97 Basics**. This section presents a quick review of the main commands used to control the RSRAP software within the Microsoft Access environment.
- **Section 6—Running RSRAP**. This section presents a stepwise procedure for using the RSRAP software.
- **Section 7—Input Data Procedures**. This section presents data input screens and default data screens used in entering input data for RSRAP.
- **Section 8—Optimization Process—Step 8**. This section presents the procedures used to initiate the resource allocation optimization process.
- **Section 9—Output Reports—Step 9**. This section presents the report types generated by RSRAP and procedures for generating reports.

SECTION **2**

BACKGROUND

Highway agencies face a dilemma in determining the appropriate balance of resurfacing and geometric improvements, as well as the appropriate mix of large and small projects, in their programs to maintain the structural integrity and ride quality of highway pavements. Highway agencies have a responsibility to the traveling public to maintain the pavements of all roads under their jurisdiction in a serviceable condition. Furthermore, timely resurfacing is essential to prevent degradation of the pavement structure; if resurfacing is postponed too long, it may become necessary to replace the entire pavement structure down to the subgrade, which involves a large and unnecessary cost to the public. On the other hand, highway agencies also have a responsibility to make geometric improvements to enhance both the safety and traffic-operational efficiency of the roads under their jurisdiction. Clearly, there are economies of scale in making geometric improvements in conjunction with resurfacing and restoration projects rather than as separate projects.

In the past, existing knowledge of the safety and traffic-operational effects of geometric improvements has not been sufficiently organized and evaluated to assist highway agencies in assessing the trade-offs between these competing goals. Further, it has been difficult for highway agencies to optimize, on a systemwide basis, the safety and operational benefits of geometric improvements while still meeting their obligations to maintain the pavement structure of the roads under their jurisdiction. The RSRAP software has been developed to implement a process for allocating resources to maximize the effectiveness of 3R projects in improving safety and traffic operations improvements on nonfreeway facilities. The RSRAP software was developed from research done for NCHRP Project 3-56, which is documented in the first part of this report

The types of geometric improvements that are considered within the scope of the RSRAP software are those that have the potential to enhance safety, that can be accomplished in conjunction with resurfacing projects, and that do not require complete reconstruction or replacement of the pavement structure except at spot locations. The improvement types considered include lane widening, shoulder widening, shoulder paving, horizontal curve improvements, roadside improvements, and installation of intersection turn lanes.

SECTION **3**

THE RESOURCE ALLOCATION PROCESS

OBJECTIVES OF THE RESOURCE ALLOCATION PROCESS

The objective of the resource allocation process, as implemented in the RSRAP software, is to allow highway agencies to maximize the cost-effectiveness of the funds spent on 3R projects. In order to do this, the process considers

- A specific set of highway sections that are in need of resurfacing either at the present time or within the relatively near future;
- A specific set of improvement alternatives for each candidate site including doing nothing, resurfacing only, and various combinations of safety improvements for the site; and
- A maximum limit on the funds available for improvements to the set of highway locations.

The result of the process is a recommended improvement alternative for each site that results in the maximum net benefit to highway users while not exceeding the available budget. The process addresses the identification of the highest priority improvements, those that should be made during the next construction season.

The process was structured so that it can be used by highway agencies in two different ways. These are the following:

Option 1—Optimize Safety Improvements—The objective of this option is to select the safety or operational improvements that should be implemented at a given set of locations that have already been scheduled for resurfacing during a specific year. This option would be appropriate for an agency that budgets funds for safety improvements separately from resurfacing funds and wants to maximize the net benefits from those safety improvements.

Option 2—Optimize Both Resurfacing and Safety Improvements—The objective of this option is to select both the projects that should be resurfaced and the safety improvements that should be implemented from among a given set of locations for which a decision has not yet been made about resurfacing during a specific year. This option would be appropriate for a highway agency that wants to maximize the net benefits from the combined resurfacing and safety improvement program.

Users also have the option to select whether the resource allocation process should include a safety penalty for resurfacing a road without accompanying geometric improvements. This safety penalty is discussed further later in this section.

Similarly, users have the option to make selections based on improvement costs and safety benefits alone or to consider the traffic-operational effects of resurfacing, as well. These two types of analysis are identified as the following:

- Consider safety benefits only (do not consider the travel time reduction associated with resurfacing) and
- Consider safety and speed benefits (includes the travel time reductions associated with resurfacing).

If the user elects to consider safety and speed benefits, then the penalty for resurfacing without accompanying safety improvements should also be included. This is recommended as the speed benefits and safety penalty are based on similar research results.

The resource allocation process has been developed to be applicable to any improvement program that involves resurfacing and safety improvements. The process is not tied in any specific way to the federal 3R program. Thus, it is applicable to sites being considered for the federal 3R program, for sites being considered for state programs conducted with 100-percent state funds, or for a mixture of sites considered for both types of programs.

COMPONENTS OF THE RESOURCE ALLOCATION PROCESS

There are 10 major components of the conceptual resource allocation process. These components are as follows:

- Identify sites to be considered,
- Identify improvement alternatives (and combinations of alternatives) to be considered for each site,
- Convert future costs and benefits to present values,
- Estimate the construction cost of each improvement alternative,
- Estimate the safety benefits for each improvement alternative,
- Estimate the penalty for not resurfacing,
- Estimate the safety penalty for each improvement alternative that involves resurfacing without other geometric improvements,
- Estimate the traffic-operational benefits for each improvement alternative,
- Determine the net benefits for each improvement alternative, and
- Select the most suitable improvement alternative for each site within the available budget by applying optimization logic.

Each of these components is discussed below.

1. Identify Sites to Be Considered

The resource allocation process is intended for application to a specific identified set of highway sections. These would typically be sites that have been selected for resurfacing as part of a highway agency's resurfacing program for a specific year or a larger set of sites, each expected to be in need of resurfacing within a period of several years. The sites could represent all suitable resurfacing candidates statewide, all suitable candidates within a particular highway district or geographical area, all suitable candidates on a particular roadway system, or all suitable candidate sites eligible for a particular funding source, or some combination of these. The process is based on the following two assumptions:

- The sites considered represent all sites eligible for improvement with funds from a particular budget and
- The budget being considered is the only source of funding for the improvements being considered.

If these assumptions are not met, then the set of sites, the range of improvement alternatives, and/or the size of the budget considered might need to be expanded until the assumptions are met.

The following data, at a minimum, will be needed for each highway section under consideration to apply the resource allocation process:

- County,
- Route Number,
- Site Description (text description of project limits or mileposts),

- Area type (urban/rural),
- Length (mi),
- Number of lanes (count through travel lanes only),
- Presence of median (divided/undivided),
- ADT (veh/day),
- Number of nonintersection-related accidents per year,
- Number of intersection-related accidents per year,
- Estimated average travel speed (mph),
- Existing lane width (ft),
- Existing shoulder width (ft),
- Existing shoulder type (paved/gravel/turf/composite), and
- Estimated time remaining before mandatory resurfacing (years).

Additional data inputs are required if the candidate improvements for a site include horizontal curves, roadside features, intersections, or other user-defined improvement alternatives.

Most of the input data listed above should be readily available to highway agencies. To keep the process as simple as possible, it is best if each highway section considered is relatively homogeneous with respect to area type, AADT, and cross-section geometrics. Minor variations within a section in cross section, for example, may be permitted, but when distinct subsections with different cross sections are present, it will usually be desirable to divide these into separate sites. Site boundaries should also be based on pavement type and condition considerations, which might warrant different resurfacing treatments. The process addresses only nonfreeway facilities.

Expected accident experience could be based on predictive models, such as those developed by Zegeer et al. (*15*) or by Vogt and Bared (*40*). However, RSRAP users are encouraged to supply safety estimates based on actual accident histories for the sites in question. Default values from predictive models necessarily represent average conditions. However, the site-to-site variations in accident experience observed in actual experience (even between sites that are nominally similar) may have important implications for the cost-effectiveness of particular safety improvements, and, therefore, accident data for the specific sites in question are vital to the objectives of the optimization process. For this reason, the program does not estimate the safety performance of candidate sites and requests the user to provide this information as input. Furthermore, we recommend that the safety performance estimate be based on an average of a 5-year history.

Still better estimates can be developed with the Empirical Bayes (EB) approach, which provides a weighted average of model predictions and actual accident histories. Tools to apply the EB approach are currently being developed for FHWA's Interactive Highway Safety Design Model Crash Prediction Module software and FHWA's *SafetyAnalyst* software. These software tools will complement RSRAP and should become available over the next several years.

2. Identify Improvement Alternatives to Be Considered

The next step in the process is to define the set of improvement alternatives to be considered for each site. The appropriate candidate improvements will vary from site to site depending on the existing site conditions. The objective of this step in the process is to include all alternatives that might potentially be the most appropriate improvement for the site, that is, to be as inclusive as possible while remaining within the scope of projects eligible for the particular funding source being considered. Improvement alternatives selected at this stage, which later prove not cost-effective or less cost-effective than some other alternative will be eliminated at a later stage in the process.

The process is capable of considering the following types of improvements:

- Pavement resurfacing,
- Lane widening,

- Shoulder widening,
- Shoulder paving,
- Horizontal curve improvements,
- Roadside improvements,
- Intersection left- and right-turn lane improvements, and
- Other user-defined alternatives.

The resource allocation process is capable of considering the safety effects of these individual improvement types, as well as the best available estimate of their effects in combination. The software developed to implement the process includes default methods for estimating the effects of each of the improvement types listed above, with the exception of user-defined alternatives. However, when a default safety effectiveness estimate is supplied by RSRAP, the user has the option to replace that value with a more appropriate value based on local experience. Default values of safety effectiveness can be replaced either for all sites or for any specific site.

The following improvement alternatives will be considered by default for each site evaluated:

- Do nothing.
- Resurface pavement.
- Resurface pavement and widen lanes for all sites with lanes less than 12 ft in width (widening of lanes is considered in increments of 1 ft; therefore, for a site with 9-ft lanes, widening by 1, 2, and 3 ft will be considered).
- Resurface pavement and widen shoulders for all sites with shoulders less than 8 ft in width (widening of shoulders will be considered in increments of 2 ft; therefore, for a site with 2-ft shoulders, widening by 2, 4, and 6 ft will be considered).
- Resurface pavement and pave shoulder (if shoulder is currently unpaved).
- Resurface pavement with all feasible combinations of lane widening, shoulder widening, and shoulder paving.

Other improvement types and combinations of improvement types may be added at each site based on user assessment of appropriate improvement needs for that site (e.g., horizontal curve, roadside, or intersection improvements). This will require user analysis of improvement needs outside the scope of the resource allocation process.

3. Convert Future Costs and Benefits to Present Values

All costs and benefits in the optimization process are converted to their present values for comparison. The use of the net present value method has been accepted for many years in highway economic analyses, first in the AASHTO *Manual on User Benefit Analyses for Highway and Bus Transit Improvements* (*27*) and later in the MicroBENCOST program (*42*).

One-time costs or benefits in a specific future year are reduced to their present values using the single-amount present worth factor:

$$(P/F,\ i,\ n) = \frac{1}{(1+i)^n} \tag{45}$$

where

$(P/F, i, n)$ = single-amount present worth factor to convert an amount in a specific future year to its present value;

i = minimum attractive rate of return expressed as a decimal fraction (i.e., for a 4-percent minimum attractive rate of return, $i = 0.04$); and

n = number of years until amount is paid or received.

Future benefits and costs that will recur annually over the service life of the improvement are reduced to their present values by the uniform-series present worth factor:

$$(P/A,\ i,\ n) = \frac{(1+i)^n - 1}{i(1+i)^n} \tag{46}$$

where

$(P/A, i, n)$ = uniform-series present worth factor to convert a series of uniform annual amounts to its present value and
n = number of years that amounts are paid or received.

The discount rate, or minimum attractive rate of return (i), used in computing these factors represents the rate of return that could be earned on alternative investments. Highway expenditures are expected to exceed this minimum attractive rate of return to represent good investments for taxpayers. Federal policy recommends the use of a minimum attractive rate of return of 7 percent per year (or $i = 0.07$) in investments of public funds (*43*). However, this 7-percent return includes the effect of inflation. Because the future costs and benefits derived below are expressed in constant dollars (i.e., they do not include any effects of inflation), inflation should be excluded from the minimum attractive rate of return as well. The current inflation level is approximately 3 percent per year, so a minimum attractive rate of return of 4 percent per year ($i = 0.04$) appears to be appropriate for use in the resource allocation process. AASHTO has indicated in the past that they consider 4 percent per year above the inflation rate to represent the real long-term cost of capital (*27*).

The number of years until amount is paid or received (n), mentioned above, represents the life of the safety improvement, not the service life of the pavement. Therefore, we recommend a period of 20 years instead of 10 years.

Although the number of years and discount rate are offered as default values, they may be changed on a global or site-specific basis. However, it is recommended that these values are used and remain consistent for all sites for analysis purposes.

4. Estimate Construction Cost of Each Improvement Alternative

The construction cost of each improvement alternative is estimated by RSRAP based on the input site condition data and default unit construction cost values. Default methods for computing improvement construction costs are provided in RSRAP for the following improvement types:

- Pavement resurfacing,
- Lane widening,
- Shoulder widening,
- Shoulder paving, and
- Installation of intersection left- and right-turn lanes.

The default cost estimates are based on average cost data supplied by highway agencies. They consist of building subgrade and overlay costs. Users must supply the improvement construction costs for horizontal curve improvements, roadside improvements, and other user-defined alternatives because the costs of these alternatives are generally too site-specific to use a global default value.

Users have the option to replace the default construction cost estimates determined in RSRAP with their own data, either globally, for all sites, or just for specific sites. In the global defaults provided with the program (see below), the cost of shoulder widening does not include the cost of right-of-way acquisition. Therefore, if right-of-way needs to be purchased when widening the shoulders of a specific site, the shoulder-widening cost per foot (SWcost in Table 22) should be changed accordingly to reflect the increase in widening cost

Table 22. Default unit construction cost estimates used in the RSRAP

Area Type	Default unit costs ($/ft²)				
	Rescost	LWcost	SWcost	Srescost	Reconcost
Rural	1.07	3.93	5.32	0.47	12.10
Urban	1.80	3.93	5.32	0.47	12.10

Notes: Rescost = cost for pavement resurfacing only ($/ft^2)
LWcost = lane widening cost ($/ft^2)
SWcost = shoulder widening cost ($/ft^2)
Srescost = shoulder paving cost ($/ft^2)
Reconcost = total pavement replacement cost ($/ft^2)

for that specific site. Management and administrative costs can also be incorporated into these amounts.

Construction costs represent expenditures at the beginning of the analysis period, so no conversion to present value is required.

Table 22 presents the default construction cost values used in the RSRAP.

For intersection improvements, RSRAP estimates the construction cost of adding a left- or right-turn lane ($CC_{TurnLane}$). For rural areas $CC_{TurnLane}$ is $60,000. For urban areas $CC_{TurnLane}$ is $112,000.

The total estimated construction cost for each improvement alternative combines the construction cost estimates for all specific improvement types that are part of that alternative.

When entering the cost for a horizontal curve improvement, the user should develop that cost assuming that no lane widening, shoulder widening, or shoulder paving will be needed. The RSRAP program will supply the additional costs for these widening and paving alternatives as they are considered.

5. Estimate Safety Benefits for Each Improvement Alternative—PSB

An estimate of the safety benefits of each improvement alternative considered for each site is determined by RSRAP for use in the resource allocation process. Default methods for estimating safety benefits are provided within RSRAP for each improvement type considered with the exception of other user-specified alternatives. To consider a user-specified alternative in the resource allocation process, the user must be able to supply an accident reduction effectiveness estimate for the improvement.

The benefits attributable to accidents reduced by a geometric or traffic control improvement were estimated using a safety benefit equation that takes into account the following variables: expected number of annual accidents for location type *m* at site *j* (N_{jm}), accident modification factor for improvement alternative *k* at location type *m*, expressed as decimal fraction (AMF_{mk}), proportion of total accidents to which AMF_{mk} applies expressed as a decimal fraction and based on severity levels (RF_{ms}), and accident reduction cost by severity level (AC_s). These variables and subscripts are described below.

Subscripts

The index variable *m* represents two location types at which accident reduction benefits are estimated separately:

- nonintersection locations (m = 1) and
- intersections (m = 2).

The index variable *s* represents two accident severity levels for which accident costs differ:

- fatal and injury accidents ($s = 1$) and
- property-damage-only accidents ($s = 2$)

The index variable k represents the improvement alternative considered (e.g., an improvement alternative may be 1 ft increase in lane width, 2 ft increase in shoulder width, and paving shoulder).

The index variable j represents the site at which a particular improvement is being made.

Accident Modification Factors for Specific Improvement Types—AMF_{mk}

The incremental effects on safety of specific geometric design and traffic control elements are represented by accident modification factors—AMFs. The AMF for the nominal or base value of each geometric design traffic control feature has a value of 1.0. Any feature associated with higher accident experience than the nominal or base condition has an AMF with a value greater than 1.0; any feature associated with lower accident experience than the base condition has an AMF with a value less than 1.0.

For any improvement being evaluated, the ratio of the appropriate AMF after the improvement to the appropriate AMF before the improvement represents an AMF for the improvement itself. Thus, an improvement with an AMF of 0.95 would be expected to decrease accident frequency by 5 percent, whereas an improvement with an AMF of 1.05 would be expected to increase accident frequency by 5 percent.

The AMFs used in RSRAP for two-lane highway improvements are those presented in a recent FHWA report entitled, *Prediction of the Expected Safety Performance of Rural Two-Lane Highways* (*7*). AMFs for intersection left- and right-turn lanes from another recent FHWA study (*20*) have also been incorporated in RSRAP. For multilane highways, slightly modified versions of the two-lane highway AMFs for lane widening and horizontal curve improvements were developed in NCHRP Project 3-56. The AMFs for lane widening, shoulder widening, and shoulder paving apply only to related accident types (which include single-vehicle run-off-road, multiple-vehicle same-direction sideswipe accidents and multiple-vehicle opposite-direction accidents). AMFs for other improvement types apply to total accidents. Quantitative values of the AMFs used by RSRAP are presented in Chapter 5 (Part 1) of this report.

As mentioned earlier, the user has the capability to substitute AMFs based on local experience for the default AMFs supplied with RSRAP. Default values may be replaced either globally, for all sites, or for specific sites chosen by the user.

Accident Severity Distribution

The AMFs for the various improvement types discussed above apply equally to accidents of all severity levels. Knowledge of the safety effects of geometric improvements has not yet progressed to the point that it is possible to reliably estimate such effects separately for each accident severity level. However, RSRAP does use default levels of the accident severity distribution for roadway segments and intersections to estimate the reduction in accident frequency separately for each of two accident severity levels:

- fatal and injury accidents and
- property-damage-only accidents.

The fatal and injury severity levels are combined so that the random occurrence of a single fatal accident does not influence the evaluation process.

Table 23 provides the estimates of the accident severity distribution for roadway segments and at-grade intersections. The default accident severity distribution in Table 23 is

Table 23. Default distribution for accident severity level used in RSRAP (*7*)

Accident severity level	Proportion of total accidents	
	Roadway segments	Intersections
Fatal and injury	0.321	0.397
Property damage only	0.679	0.603
TOTAL	**1.000**	**1.000**

based on data from the FHWA Highway Safety Information System (HSIS) for Illinois, Michigan, Minnesota, and North Carolina (*7*).

Expected Annual Accident Frequency—N_{jms}

The number of expected annual accidents for the roadway section, N_{j1}, and for at-grade intersections, N_{j2}, are user-input values. These accidents are then proportionally divided based on the severity levels into annual accident frequency N_{j1s} and N_{j2s} using the accident severity level proportions presented in Table 23.

Determination of Safety Benefits

The general formulation of the nonintersection accident prediction frequency used in the RSRAP algorithm is presented below:

$$N_{\text{non int}} = N_{j1}(AMF_1 \times AMF_2 \ldots \times AMF_n) \tag{47}$$

where

$N_{\text{non int}}$ = total number of nonintersection accidents per year after application of accident modification factors,
N_{j1} = expected number of nonintersection accidents per year at site *j*, and
AMF_k = accident modification factors calculated for each improvement *k*.

The general formulation of the intersection accident prediction frequency used in the RSRAP algorithm is presented below:

$$N_{int} = N_{j2} \bullet AMF_{\text{intersection}} \tag{48}$$

where

N_{int} = total number of intersection accidents per year after application of accident modification factors,
N_{j2} = expected number of total roadway segment accidents per year for location type *m* at site *j*, and
$AMF_{\text{intersection}}$ = final accident modification factor calculated for all intersections of a particular site.

The total predicted accident frequency for an entire project or an extended highway section is determined using the following equation:

$$N_t = \sum_{\text{all segments}} N_{\text{non int}} + \sum_{\text{all intersections}} N_{\text{int}} \tag{49}$$

where

N_t = predicted accident frequency for an entire project or an extended highway section.

Accident Reduction Cost—AC_s

The safety benefits of specific improvements evaluated in RSRAP are expressed in monetary terms using accident cost estimates published by FHWA. The most recent FHWA estimates, published in 1994 (*43*), and a 2002 update to those estimates developed in the research, are shown below.

	1994	2002
Fatal accident (F):	$2,600,000	$3,000,000
Incapacitating injury accident (A):	180,000	208,000
Serious injury accident (B):	36,000	42,000
Minor injury accident (C):	19,000	22,000
Property-damage-only accident (PDO):	2,000	2,300

These 2002 values of accident cost are used as default values in the RSRAP software.

For analysis purposes, all of the fatal and injury accident levels have been combined into a single accident cost level. It is generally inappropriate to treat fatal accident costs separately when analyzing specific sites because the occurrence of a fatal accident at any particular site may be simply random. The (A), (B), and (C) injury levels have been combined because not all potential users of the resource allocation process have accident records systems that classify accident severity in this way. The accident cost estimates used as default values in RSRAP are the following:

AC_1—Fatal or injury accident (F/A/B/C)—$103,000/accident.
AC_2—Property-damage-only accident (PDO)—$2,300/accident.

These accident cost estimates may be replaced by users with alternative values used by their agency.

6. Estimate Penalty for Not Resurfacing—PNR

Option 1 of the resource allocation process does not require any consideration of resurfacing benefits because, under the assumptions of Option 1, the decision to resurface the roadway sections in question has already been made. Option 2, however, is intended to allow resurfacing to compete with safety improvements for available funds. This option does require consideration of resurfacing benefits.

The nature of 3R programs is that one of three approaches must be selected for every site considered: (1) do nothing, (2) resurface only, or (3) resurface plus implement one or more additional safety improvements. Safety improvements have specific quantifiable benefits in terms of reduced accidents, reduced delays, and/or reduced vehicle operating costs. However, the only direct user benefits or costs of resurfacing are short-term operational benefits caused by increased speeds and possible short-term increases in accidents if resurfacing is not accompanied by geometric improvements. If only these costs and benefits were considered, the resurfacing projects selected would generally be those with the greatest potential for accompanying safety improvements. Such an approach gives no consideration to the pavement condition and the criticality of the need for resurfacing. If resurfacing of a roadway section is postponed too long, it may require a thicker (and more expensive) overlay. Postponing resurfacing until failure occurs may require complete replacement of the pavement structure down to the subgrade.

To give the need for resurfacing its proper weight in RSRAP, a penalty for not resurfacing in terms of future pavement overlay or replacement costs is assigned to the do-nothing alternative. This value varies with the present condition of the roadway section, being higher where the present condition of the pavement is worse. The penalty for not resurfacing a roadway section for n years (when it will require complete replacement) can be represented by the present value of future pavement replacement cost:

$$PNR_{jk} = \begin{cases} -aRB_j & \text{for do-nothing alternative} \\ 0 & \text{for all other alternatives} \end{cases} \quad (50)$$

where

PNR_{jk} = present value of not resurfacing alternative k at site j (future pavement replacement cost),
RB_j = pavement replacement cost to be incurred in year n for site j, and
a = coefficient based on number of years until pavement failure (number of years and default a values are given below).

Number of years	**Default *a* values**
1 yr or less	1
2 yr	0.8
3 yr	0.6
4 yr	0.4
5 yr	0.2
6 yr or more	0

The default values of a shown above can be changed by the user.

7. Estimate Safety Penalty for Resurfacing Without Other Geometric Improvements for Each Improvement Alternative—PRP

The effect of resurfacing on safety has been a matter of controversy for years. Some researchers have maintained resurfacing of a road increases speeds, which, in turn, may increase accidents. Others have contended that such an effect is unproven.

Research by Hauer, Terry, and Griffith (*11*) has demonstrated that such an effect of resurfacing on safety exists but has a relatively short duration (30 months for nonintersection accidents and 12 months for intersection accidents). Research in NCHRP Project 17-19(2) found an inconsistent resurfacing effect: resurfacing had a negative effect on safety in some states, but a positive effect on safety in others. Because the NCHRP 17-9(2) research was inconclusive, a decision was reached to incorporate the Hauer, Terry, and Griffith results in RSRAP. However, the user has an option whether to consider this effect in RSRAP.

According to research by Hauer, Terry, and Griffith (*11*), resurfacing without accompanying geometric improvements may result in a short-term (approximately 12- to 30-month) increase in accident experience. RSRAP allows the user to determine whether or not the safety penalty for resurfacing without accompanying geometric improvements should be included in the analysis. If the user decides to consider this penalty, the penalty amount is added to alternatives that include resurfacing and have existing lane and shoulder width less than 11 and 6 ft, respectively, when these geometric elements were not improved. The default value of the resurfacing effect is an increase in nonintersection accidents of 21 percent over the first 30 months after resurfacing and an increase in intersection accidents of 35 percent over the first 12 months after resurfacing. When geometric improvements (which in RSRAP include lane and shoulder width larger than 11 and 6 ft, respectively) are made in conjunction with a resurfacing project, *PRP* is set equal to zero.

8. Estimate Traffic-Operational Benefits for Each Improvement Alternative—PTOB

Research in NCHRP Project 3-56 has demonstrated that there is a small, but statistically significant, speed increase of approximately 1 mph that accompanies resurfacing. This represents an average value of speed changes for approximately 40 sites that were resurfaced, whose average values were affected by resurfacing over a range from a 4-mph decrease in speed to a 7-mph increase in speed. The average 1-mph increase in speed represents a traffic-operational benefit that may partially offset the increase in accident frequency caused by resurfacing discussed above. This effect of resurfacing on traffic operations is included in the RSRAP software, but the user has the option whether to consider it. Normally, the effect of resurfacing on speed (*PTOB*) should be considered only when the effect of resurfacing on safety (*PRP*) is also considered.

The traffic-operational benefit caused by increased speed is considered to last for 30 months after resurfacing. Its present value is calculated taking into account the site length, speed of travel, average daily traffic (ADT), and monetary value of time to the driver (the default value is $10/hr). The default value of the increase in speed with resurfacing is 1 mph although this may be varied by the user. When the user chooses to consider the speed benefits (*PTOB*), RSRAP adds the *PTOB* value to the benefits of all alternatives except the do-nothing alternative.

9. Determine Net Benefits for Each Alternative

The next step in the resource allocation process is to determine the net benefits for each improvement alternative at each site. The formulation of the net benefits depends on which RSRAP analysis options have been selected by the user.

The net benefit equations to be used for each option selected are presented below.

Option 1A—Safety benefits considering safety improvements only

$$NB_{jk} = PSB_{jk} + PRP_{jk} - CC_{jk} \tag{51}$$

Option 2A—Safety benefits considering both resurfacing and safety improvements

$$NB_{jk} = PSB_{jk} + PNR_{jk} + PRP_{jk} - CC_{jk} \tag{52}$$

Option 1B—Safety and speed benefits considering safety improvements only

$$NB_{jk} = PSB_{jk} + PTOB_{jk} + PRP_{jk} - CC_{jk} \tag{53}$$

Option 2B—Safety and speed benefits considering both resurfacing and safety improvements

$$NB_{jk} = PSB_{jk} + PTOB_{jk} + PNR_{jk} + PRP_{jk} - CC_{jk} \tag{54}$$

where

NB_{jk} = net benefit for improvement alternative *k* at site *j*,
PSB_{jk} = present value of safety benefits of improvement alternative *k* at site *j* (using the AMFs),
$PTOB_{jk}$ = present value of travel time reduction benefits for improvement alternative *k* at site *j*,
PNR_{jk} = present value of penalty for not resurfacing improvement alternative *k* at site *j* (only present in do-nothing alternative),
PRP_{jk} = present value of short-term safety penalty for resurfacing without accompanying geometric improvements for improvement alternative *k* at site *j*, and
CC_{jk} = construction cost for improvement alternative *k* at site *j*.

If the user has specified that the safety penalty for resurfacing without accompanying safety improvements should be considered, then PRP_{jk} in Equations 51 through 54 is set equal to zero in all cases.

It should be noted that in all formulations of the equation for net benefits, each term has already been converted to a present value except the construction cost term, which is, by nature, already a present value.

10. Select the Most Suitable Improvement Alternative for Each Site Within the Available Budget

An integer programming approach is used to select the most suitable improvement alternative for each site within the available budget. The integer program to provide the optimum mix of improvement alternatives is as follows:

$$\text{Maximize } TB = \sum_{j=1}^{y}\sum_{k=1}^{z} NB_{jk}X_{jk} \tag{55}$$

subject to the following constraints:

$$\sum_{k=1}^{z} X_{1k} = 1$$

$$\sum_{k=1}^{z} X_{2k} = 1$$

$$\vdots$$

$$\sum_{k=1}^{z} X_{2k} = 1$$

$$\sum_{j=1}^{y}\sum_{k=1}^{z} CC_{jk}X_{jk} \le B$$

where

TB = total benefits from all selected improvements,
y = total number of sites,
z = total number of improvement alternatives for a given site,
X_{jk} = an indicator value whose value is 1 if alternative improvement k at site j is selected as part of the optimum allocation of funds and whose value is 0 if alternative improvement k at site j is not selected as part of the optimum allocation of funds (for each site, exactly one alternative should be selected), and
B = improvement budget or maximum funding available for improvement of the sites under consideration.

Equation 55 is the objective function of the integer program, which represents the total benefits to be maximized. The values of NB_{jk} for each improvement alternative at each site would be determined with Equations 51, 52, 53, or 54, depending upon the user's objective in analyzing the resource allocation problem.

The constraints on the optimal solution are represented by the equalities and inequalities presented below the objective function. They require that one and only one improvement alternative can be selected for each site. The last inequality constrains the total expenditure on improvements to be less than or equal to the available budget.

The optimal solution to the integer program is the group of improvement alternatives that provides the maximum total benefit. This optimum solution consists of the improvement alternative for each site for which the value of X_{jk} in the integer program is equal to one. The total net benefits for this group of alternatives can be determined with Equation 55, and the total expenditures on improvements required to achieve those benefits can be determined with the equation used for calculating the cost constraint (expressed as an equality rather than an inequality).

The integer programming procedure used for optimization is performed using the Solver program, which comes as a standard feature of the Microsoft Excel spreadsheet package. The version of the Solver program supplied with Excel is limited in the size of problems it can solve, but larger versions of the Solver program that also work with Excel are available commercially at additional cost.

SECTION 4

INSTALLATION OF AND UPDATES TO THE RSRAP SOFTWARE

INSTALLATION

The following procedure should be used to install the RSRAP software (provided on CD-ROM with this report) on a computer:

1. Copy the entire folder entitled RSRAP on the installation CD to the hard drive (usually this drive is called the C drive) so that it becomes a folder known as C:\RSRAP.
2. Clear the “Read Only” file property of every file in C:\RSRAP and C:\RSRAP\Old Projects. This is done by right-clicking on selected files, choosing Properties from the pop-up menu, and clicking the attribute check box labeled “Read Only” on the General tab.
3. To run RSRAP, follow the procedures in Section 7 and click on the file named C:\RSRAP\RSRAP.mdb

Alternative installation procedures for RSRAP may be found in Appendix E. Additionally, Appendix F provides installation and upgrade information for the Solver program.

SYSTEM REQUIREMENTS

Because RSRAP is an Access database that links to Excel during execution, system requirements for the RSRAP software are essentially the same as those for the Microsoft Office Suite; please consult installation requirements for these products for more detailed information. Further, an additional 17,710 KB (or 18,135,040 bytes) of memory are needed for this program before data entry. Adding a site to the database, including consideration of all alternatives for that site, requires at least 4,046 bytes of additional storage. The storage required would increase with the number of intersections and curves entered for a site.

SECTION 5

ACCESS 97 BASICS

GETTING STARTED

RSRAP is an Access database program that operates within Microsoft Windows environments: Windows 95, Windows NT 4.0, or later versions of Windows. RSRAP has been developed for Access 97 or later versions of Microsoft Access. RSRAP also uses the capabilities of Microsoft Excel and its add-on Solver program. Section 4 of this guide provides instructions for installation of RSRAP on a personal computer. Instructions for installation of Access and Excel are provided by Microsoft.

Like many Microsoft applications, Access is easily started in various ways. From the Start button located on the task bar at the bottom of the screen, click on the Programs option and then on Microsoft Access. Click once with the left mouse button, and, in a few moments, the Access screen appears. There may also be an icon on the desktop or on a toolbar that can be clicked to start Access. RSRAP can also be started from Windows Explorer by browsing to find RSRAP's file location and double-clicking its icon.

ACCESS NAVIGATION

Open RSRAP from its file location by using the Open option in the File menu. As with all Windows programs, Access provides a host of ways to control program operations. The mouse, keyboard, menus, dialog boxes, command buttons, key combinations, and more can be used. With RSRAP, there are three types of navigation: navigation among forms, among records on forms, and among fields in a record.

In RSRAP, navigation between data display and entry forms is handled via command buttons. They are generally labeled “Ok” or “Exit.” The “Exit RSRAP” menu item is to exit the application rather than the current screen.

Data input and result display forms/screens show information for one item or record at a time, whether it's a site, intersection, or curve. RSRAP has two methods for displaying the next item in the list or record. Record navigation keys, shown in Figure 5, can be found at the bottom of the data result forms. These buttons represent, from left to right, first record, previous record, next record, and last record. For data input screens, records appear by name in a list box (see Figure 6). Selecting/clicking the desired record in the list will cause Access to display that record's information.

The Tab key provides the primary method of navigating through the fields of a given form (the Enter key will work too). Tab movement generally goes from left to right or top to bottom across a screen. To reverse the direction, or return to the previous cell, press Shift + Tab. Arrow keys, located by the numeric keypad, can also be used to move from one cell to the next. Finally, one can also move from one field to another by moving the mouse pointer to the desired field and clicking the left mouse button.

ENTERING DATA

Most data in RSRAP are entered in labeled cells called text boxes, in which information may simply be typed. Some data are gathered through pop-up input boxes; these data

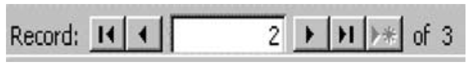


Figure 5. Record selector.

include site name, intersection name, and budget. After typing information in a pop-up input box, press the Ok button (or the Enter key), and Access automatically stores it in the correct location.

The final type of data entry cell is a combo box. A combo box looks like a text box, but on entry a down arrow appears on the right side of the box. Information entered in this box is limited to a list of choices shown on a drop-down menu. The mouse may be used to click the arrow and select the choice. Alternatively, typing the first few characters of the intended entry will cause the cell to automatically select the closest match from the list. Entering data not in the list, including blank spaces, will result in an error. If the error persists, but the cell appears empty, pressing the Esc key will undo the last entry.

Tabbing through a text box or combo box that has been flagged as required data will generate a prompt for information. A description of the desired information can be found on the status bar. Similarly, if invalid data are entered, such as text characters in a numeric field, Access will issue a warning message.

If an error is made while entering data, simply use the Backspace key to delete the error and then retype the value. To edit existing or incomplete data, click an insertion point in the offending field and use normal editing techniques to make the correction. (This includes the Delete key, which removes the selected characters or characters to the right of the cursor.)

Unlike many applications that wait for the user to save information, Access saves the values in a new or edited record as soon as the user moves to another record. Additionally, closing a form saves information. Therefore, there is no need to explicitly save data, except to save a copy of data to an external file (see description below).

SAVING DATA

RSRAP performs optimization for a set of sites for which data must be supplied by the user. Site data sets are created by entering data, as described above. When RSRAP is restarted, any site data used in the previous session will still be present. A custom menu located on the toolbar provides three utility programs to clear, save, and retrieve site data files used in RSRAP. These three utility programs are the following:

- **Clear Site Data**. This program erases all site data from memory so that the user can begin entering data for a new set of sites. The program will offer an option to save the current data set before it is cleared.
- **Save Site Data**. This program saves the current site data set in an external file with a user-selected name.
- **Retrieve Site Data**. This program retrieves previously entered site data from an external file that the user identifies by name. Any site data currently in memory will be lost, so the program will offer an option to save the current data set before it is cleared.

Figure 6. List box.

EXTRA TIPS

Arrow keys and key combinations in Access are, for the most part, identical to those used in other Windows applications. For example, Access allows for use of Microsoft's standard copy and paste techniques. A user may select information to be copied by clicking and dragging over the desired text. Press Ctrl + C to copy the text, move to the field/site where the information is to be copied by clicking the mouse cursor in the field (or tabbing to it), and then press Ctrl + V to paste.

If a form is placed incorrectly on the screen so that the entire form cannot be seen, then move the form by clicking and dragging its title bar. Scroll bars can also be used to view, use, or enter information on hidden sections of a form. Lastly, the min/max buttons on a form may be used to view unseen sections.

The Esc key backs out of menu commands and cancels dialog boxes. Esc is a good key to press if what is happening on the screen is not desired.

Access has some unique key combinations as well. For example, pressing Ctrl + ' (apostrophe) will duplicate the value from the same field of the preceding record in the active field. Also, pressing Shift + F2 while in a text box opens a zoom box, making data entry easy for long entries.

PRINTING INPUT DATA

Clicking the Print Summary Site Input Report command button on the Sites screen will print the data values appearing on the first tab of this form for all sites. Similarly, clicking the Print Detailed Site Input Report command button will print all input values for each site.

ENDING AN ACCESS SESSION

When work with Access is finished, just quit by clicking Exit RSRAP on the menu bar. Information in open database tables does not need to be explicitly saved; Access updated the table files one record at a time as records were entered or edited. To quit Access, click the close button at the right end of the Access title bar.

SECTION **6**

RUNNING RSRAP

The following sequence of steps should be followed to optimize the benefits of a resurfacing program using RSRAP:

Step 1—Start Microsoft Access.
Step 2—Start RSRAP.
Step 3—Choose data entry options (proceed to Step 4 or 5).
Step 4—Change global default values used to determine improvement benefits and costs (optional).
Step 5—Enter site data:
- Add site to database,
- Enter basic site data,
- Identify improvement alternatives to be considered, and
- Change site-specific default values (optional).

Step 6—Choose optimization and analysis options.
Step 7—Review summary form.
Step 8—Edit data as needed prior to analysis (optional).
Step 9—Enter improvement budget and start RSRAP optimization process.
Step 10—Review optimization results.

Procedures for Steps 1 through 7 are presented in Section 7 of this guide, and Steps 8 and 9 are addressed in Sections 8 and 9.

SECTION 7

INPUT DATA PROCEDURES

This section describes the forms and message boxes used to enter input data for an RSRAP optimization problem. These forms and message boxes implement Steps 1 through 7 of the RSRAP procedure sequence as listed below.

- Start Microsoft Access (Step 1).
- Start RSRAP (Step 2).
- Select an option from the RSRAP Main Options screen (Step 3).
- Proceed to Defaults form (Step 4), which includes two data entry screens on separate tabs:
  - Global Accident Modification Factor (AMF) Defaults and
  - Global Cost Defaults.
- Proceed to Sites form (Step 5), which allows the user to add or delete sites and has seven data entry screens on separate tabs:
  - Site screen,
  - Alternatives screen,
  - Roadside Improvements screen,
  - Horizontal Curves screen,
  - Intersections screen,
  - Site-specific AMF Defaults screen, and
  - Site-specific Cost Defaults screen.
- Choose optimization and analysis options (Step 6).
- Go to Summary of Analysis Selections form (Step 7).
- If desired, edit data before beginning Step 8, the optimization.

Each of these forms is described below.

START MICROSOFT ACCESS—STEP 1

As stated in Section 5, Microsoft Access can be started from the Start button by clicking on the Programs option, and then on Microsoft Access. There may also be an icon on the desktop or on a toolbar that can be clicked to start Access.

START RSRAP—STEP 2

RSRAP can be started from within Access by clicking on the File menu, then clicking on the Open option, then browsing to find the RSRAP file location, and clicking on the RSRAP file name.

It is also possible to use Windows Explorer from the computer desktop to find the RSRAP file location. Clicking on the RSRAP file name will automatically open Access (if it is not already open) and start RSRAP. Thus, with Windows Explorer the user can bypass Step 1 and go directly to Step 2.

It is also possible to set up an RSRAP icon (shortcut) on the computer desktop to start RSRAP without directly opening Access first. A shortcut of this type can be created from the Programs option in the Start menu or from Windows Explorer. It can then be moved to the computer desktop.

RSRAP MAIN OPTIONS SCREEN—STEP 3

After starting the RSRAP application, a screen labeled RSRAP Main Options appears. This is the main control screen for RSRAP and guides the user through the data entry steps and then to the optimization procedure.

Initially, when no site data have been entered, the user has access only to the Cost Defaults and AMF Defaults screens and the Site screen. At this stage, the RSRAP Main Options Screen appears, as shown in Figure 7.

When the user has entered data in the Site screen or has retrieved an existing site data file from memory, an Optimize Improvements button will appear on the RSRAP Main Options screen. After this point, the optimization process can be started at any point at which the user is satisfied that all needed data have been entered. The Options screen then appears as shown in Figure 8.

Figure 7. RSRAP Main Options screen—before site data are entered.

Figure 8. RSRAP Main Options screen—after site data are entered.

DEFAULTS FORM—STEP 4

There are two types of default data:

- *Accident Modification Factor* (AMF) defaults are values that control the determination of the accident reduction benefits of lane widening, shoulder widening, shoulder paving, roadside improvements, horizontal curve improvements, and installation of intersection turn lanes. The values supplied with RSRAP (the "original defaults") have been established through safety research, and it is not recommended that they be changed unless an agency has better and more recent research results available.
- *Cost* defaults include values used to determine the construction costs of resurfacing and geometric design improvements, the cost savings per accident reduced (by severity level), and the cost savings for travel time reduction. These cost defaults can and should be adjusted to agree with actual highway agency practice and experience.

RSRAP comes with both the AMF and Cost defaults set to values that appear suitable for use by highway agencies. The AMF Defaults and Cost Defaults screens described below can be used to make global changes to any of these default values. Once changed, the revised default values will be used in creating any new sites for which data are entered into RSRAP; sites that have already been entered are not affected. In Step 5, the user can change the AMF and Cost defaults for a particular site or can elect to use the current global defaults for a site that was entered before the latest change in defaults.

Two buttons are provided at the upper left of the default form:

- **Restore Original Defaults** changes the global AMF and Cost defaults back to the original values supplied with RSRAP.
- **Exit Defaults** leaves the Defaults form and allows the user to begin entering site data using the new defaults.

The screens for AMF Defaults and Cost Defaults are described below.

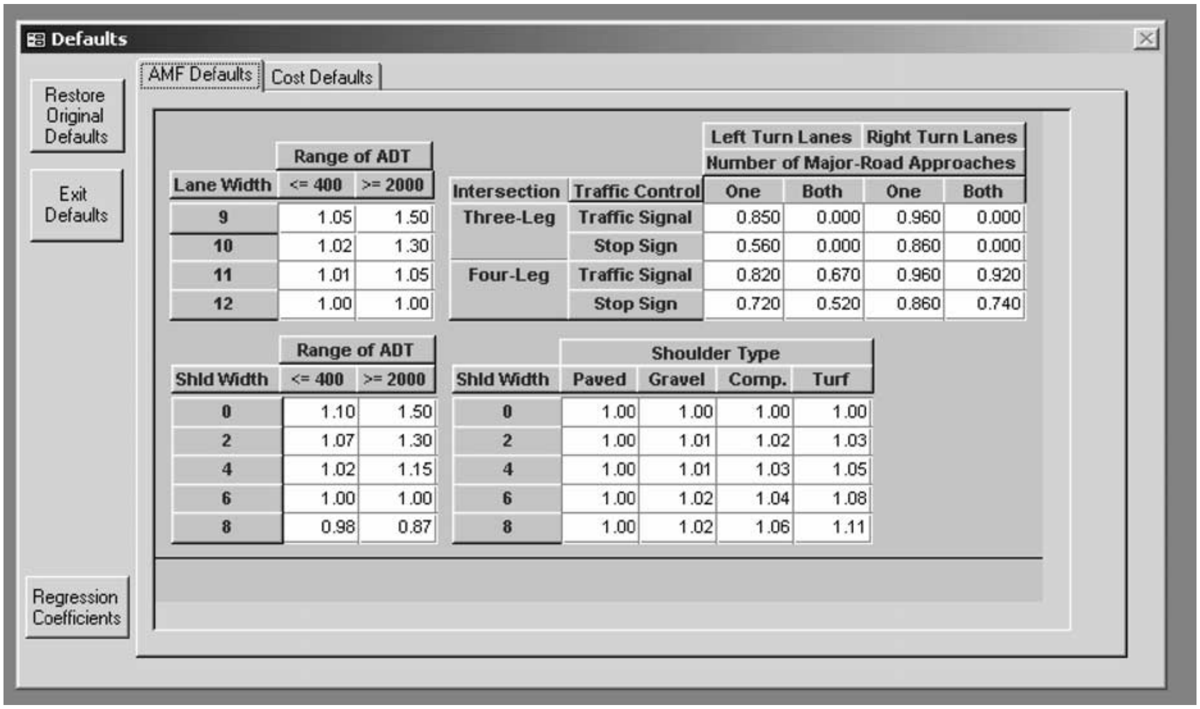
AMF Defaults

The first tab on the AMF Defaults screen (see Figure 9) allows for editing of global AMF defaults. AMFs appearing on this screen are used to determine the incremental safety impacts of geometric design and safety improvements.

AMFs appear on this screen for improvements in lane width, shoulder width, shoulder type, and installation of intersection turn lanes. To edit values appearing on the AMF Defaults screen, simply click in the desired cell, delete the old value, and retype the new. Return edited entries to the original values by clicking the Return to Original Defaults command button. Clicking this command button will restore both the AMF defaults and the Cost defaults, not just highlighted or selected ones. However, it will not change values for sites already entered in Step 5.

The Regression Coefficients command button on this screen provides access to coefficient values for calculating AMFs for roadside design and horizontal curve design. The auxiliary form used to change these values is shown in Figure 10. Access to this screen is password protected to prevent changes by the casual user. This is because substantial research would be needed to refit the regression models from which the coefficients are derived.

AMFs for roadside design and horizontal curve improvements are determined by exponential regression functions. Parameter values a, b, and c appearing in Table 24 are the coefficients for geometric variables used in the appropriate regression equations, which are shown in Chapter 5 in the first part of this report. The AMFs for roadside design and horizontal improvements are calculated from the regression results using procedures described in Chapter 5 in the first part of this report. The AMFs for roadside design and horizontal curve improvements apply to total accidents, not just related accident types.



Lane Width	Range of ADT <= 400	Range of ADT >= 2000
9	1.05	1.50
10	1.02	1.30
11	1.01	1.05
12	1.00	1.00

Intersection	Traffic Control	Left Turn Lanes: One	Left Turn Lanes: Both	Right Turn Lanes: One	Right Turn Lanes: Both
		Number of Major-Road Approaches			
Three-Leg	Traffic Signal	0.850	0.000	0.960	0.000
	Stop Sign	0.560	0.000	0.860	0.000
Four-Leg	Traffic Signal	0.820	0.670	0.960	0.920
	Stop Sign	0.720	0.520	0.860	0.740

Shld Width	Range of ADT <= 400	Range of ADT >= 2000
0	1.10	1.50
2	1.07	1.30
4	1.02	1.15
6	1.00	1.00
8	0.98	0.87

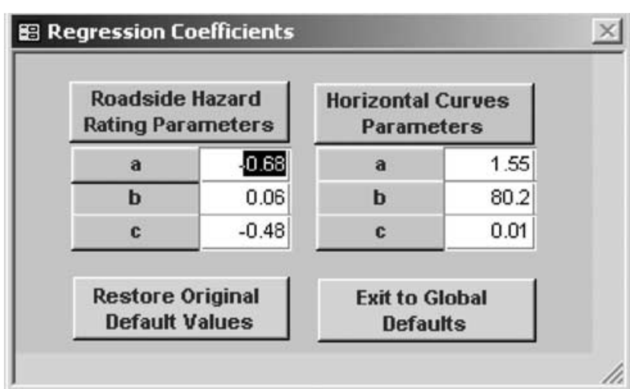
Shld Width	Shoulder Type: Paved	Gravel	Comp.	Turf
0	1.00	1.00	1.00	1.00
2	1.00	1.01	1.02	1.03
4	1.00	1.01	1.03	1.05
6	1.00	1.02	1.04	1.08
8	1.00	1.02	1.06	1.11

Figure 9. AMF Defaults screen.

Lane- and Shoulder-Width AMFs

The lane- and shoulder-width AMFs are relative factors for which a base, or typical geometric design, has a value of 1.0. An AMF greater than 1.0 represents a geometric condition that would be expected to experience more accidents than the base condition. For example, an AMF of 1.30 corresponds to a condition that would be expected to experience 30 percent more accidents than the base condition. By contrast, an AMF of 0.87 indicates a condition that would be expected to experience 13 percent fewer accidents than the base condition.

Lane-width AMFs are supplied for lane widths from 9 to 12 ft. Shoulder-width AMFs are supplied for shoulder widths from 0 to 8 ft. The base condition used in AMF determination is a 12-ft lane and a 6-ft shoulder. Lane width and shoulder width are supplied for two ADT



	Roadside Hazard Rating Parameters	Horizontal Curves Parameters
a	-0.68	1.55
b	0.06	80.2
c	-0.48	0.01

Figure 10. Auxiliary form used to change regression coefficient values.

TABLE 24 Regression equation parameters for roadside design and horizontal curves

Roadside hazard rating		Horizontal curves	
a	Regression constant	a	Length of circular portion of curve(mi)
b	Roadside hazard rating for segment	b	Radius of curvature (ft)
c	AMF for roadside hazard rating 3	c	Spiral Transition curve

ranges (less than or equal to 400 veh/day and greater than or equal to 2,000 veh/day). AMFs for sites with ADTs between 400 and 2,000 veh/day are determined by linear interpolation.

The lane-width and shoulder-width AMFs apply only to related accident types (single-vehicle, run-off-road and multiple-vehicle, opposite-direction, collision accidents) that represent approximately 35 percent of total accidents.

Shoulder-Type AMFs

The shoulder-type AMFs are similar in nature to the lane- and shoulder-width AMFs. The base condition is a paved shoulder, but AMFs are also provided for gravel, composite, and turf shoulders. Like the lane- and shoulder-width AMFs, the shoulder-type AMFs apply only to related accident types that represent approximately 35 percent of total accidents.

Intersection Turn Lane AMFs

AMFs for installation of left- and right-turn lanes at intersections are provided with RSRAP. Only turn lanes on major-road approaches are considered, and only one turn lane per approach is considered, resulting in a maximum of one or two turn lanes for each intersection. AMFs for both types of turn lanes are provided for three- and four-leg intersections and for signal-controlled and stop-controlled approaches. At four-leg intersections, turn lanes on either one or both major road approaches may be considered. At three-leg intersections, by definition, only one major-road left- or right-turn lane may be installed. The AMFs for intersection turn lane improvements apply to total accidents, not just related accident types.

To view the cost default values, click the Cost Defaults tab. To exit the Defaults Form, click the Exit Defaults command button.

Cost Defaults

The Cost Defaults tab consists of values for calculating construction costs, safety benefits (represented by the variable *PSB*), speed benefits (represented by the variable *PTOB*), and resurfacing penalties (represented by the variables *PNR* and *PRB*). (For more information on equations and variables used in the resource allocation process, see Chapter 5 in Part 1 of this report).

Construction Costs

Construction costs for resurfacing and widening are given for rural and urban areas and represent unit costs per square foot. For installation turn lanes, unit construction costs are per turn lane installed.

The construction cost defaults on the Cost Defaults screen (see Figure 11) include the following:

- Resurfacing cost per ft^2 (appropriate for a 1- or 2-in. hot mix overlay),
- Widening cost per ft^2 (not including placement of the wearing surface),

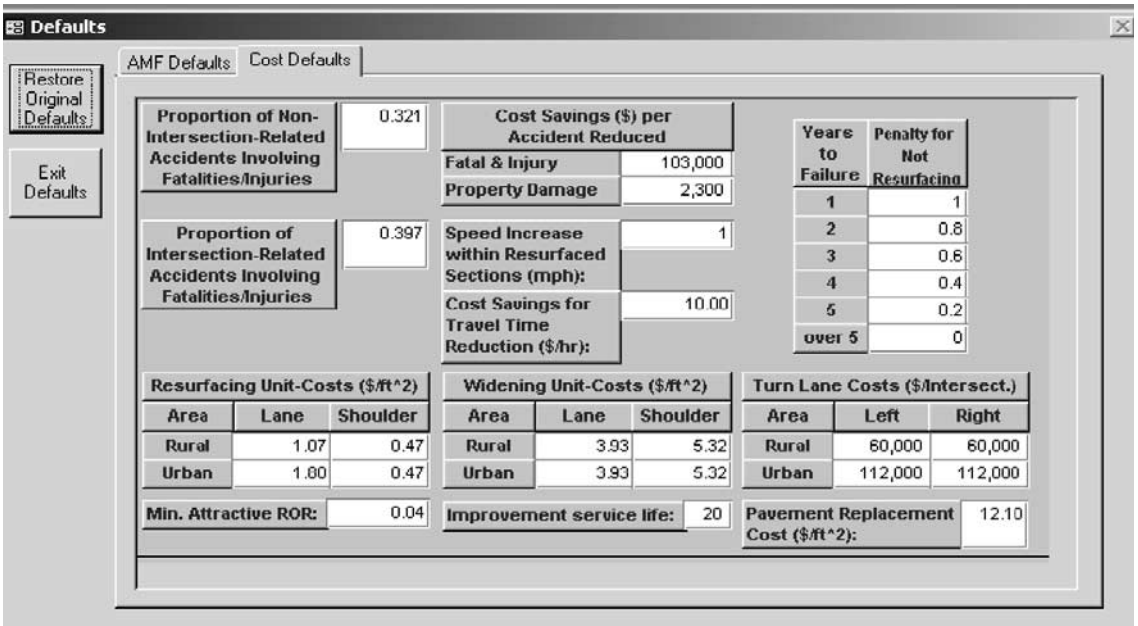


Figure 11. Cost Defaults screen.

- Turn lane installation cost per turn lane, and
- Pavement replacement cost per ft[2] (replacement of pavement structure down to the subgrade, including placement of the wearing surface).

The default data supplied with RSRAP are based on the experience of one particular highway agency. Other agencies may wish to substitute cost data based on their own experience.

Accident Cost Savings

Cost savings per accident reduced are provided based on the latest FHWA estimates. Highway agencies may substitute values based on their own practice or experience. Fatal and injury accidents are combined into a single cost category to prevent decisions from being biased by occurrence of a single fatal accident at a given site. Cost savings attributable to geometric design and safety improvements may be partially or wholly offset by a short-term (12- to 30-month) increase in accidents related to resurfacing.

Accident Severity Proportions

The Cost Defaults screen includes default values for the proportion of fatal and injury accidents in total nonintersection-related accidents and total intersection-related accidents. These default values are used when site-specific data are not provided by the user. Please note that when retrieving saved data, these values will be rounded to two decimal places instead of three. They can be restored by using the Restore Original Defaults button.

Travel Time Savings

The short-term increase in accidents associated with resurfacing is thought to result from a short-term increase in speed ensuing from resurfacing. This increase in speed is assumed to persist for the same short-term period as the increase in accidents (12 to 30 months). If the user elects the appropriate option in Step 3, the traffic-operational (travel time reduction) benefits will be considered in the optimization procedure. The default values associated with traffic-operational benefits are the following:

- Speed increase within resurfaced sections (default value = 1 mph based on recent research) and
- Cost savings from travel time reduction (default value = $10/hr of travel time reduced).

Both of these default values can be changed if better values, based on local experience, are available.

Present Values of Future Benefits

Benefits or cost savings that occur over time must be reduced to their present values for comparison with construction costs in an economic value. Two default values are used in determining the present values of future cost savings. These are the following:

- The minimum attractive rate of return, also known as the discount rate (default value = 0.04, which is equivalent to 4 percent); and
- The improvement service life in years, which represents the service life of the geometric design and safety improvements (default value = 20 years), not the service life of the pavement.

Both of these default values may be changed based on local practice and experience. However, it is recommended that the same values are used for all sites.

Penalty for Not Resurfacing

To encourage resurfacing of pavements approaching the point of possible failure, RSRAP incorporates a penalty for not resurfacing a pavement that is in need of resurfacing. The penalty for not resurfacing a pavement that could fail (and require pavement reconstruction) within the next year is equal to the cost of reconstructing and replacing the entire pavement structure down to the subgrade. This penalty is discussed further in Chapter 5 in the first part of this report. The Cost Defaults screen shows the following penalties for not resurfacing:

Years until failure	Penalty for not resurfacing
1 yr or less	100% of full penalty
2 yr	80% of full penalty
3 yr	60% of full penalty
4 yr	40% of full penalty
5 yr	20% of full penalty
6 yr or more	No penalty

These percentages of the full penalty for not resurfacing may be changed by the user on the Cost Defaults screen.

SITES FORM—STEP 5

The Sites form (see Figure 12) has seven tabs or screens where site-specific information will be entered. Location description, traffic volume, and the accident history for a given site will be entered on the first screen, Site. The next screen, Alternatives, allows the user to select which improvement alternatives will be considered for a site. Lane and shoulder

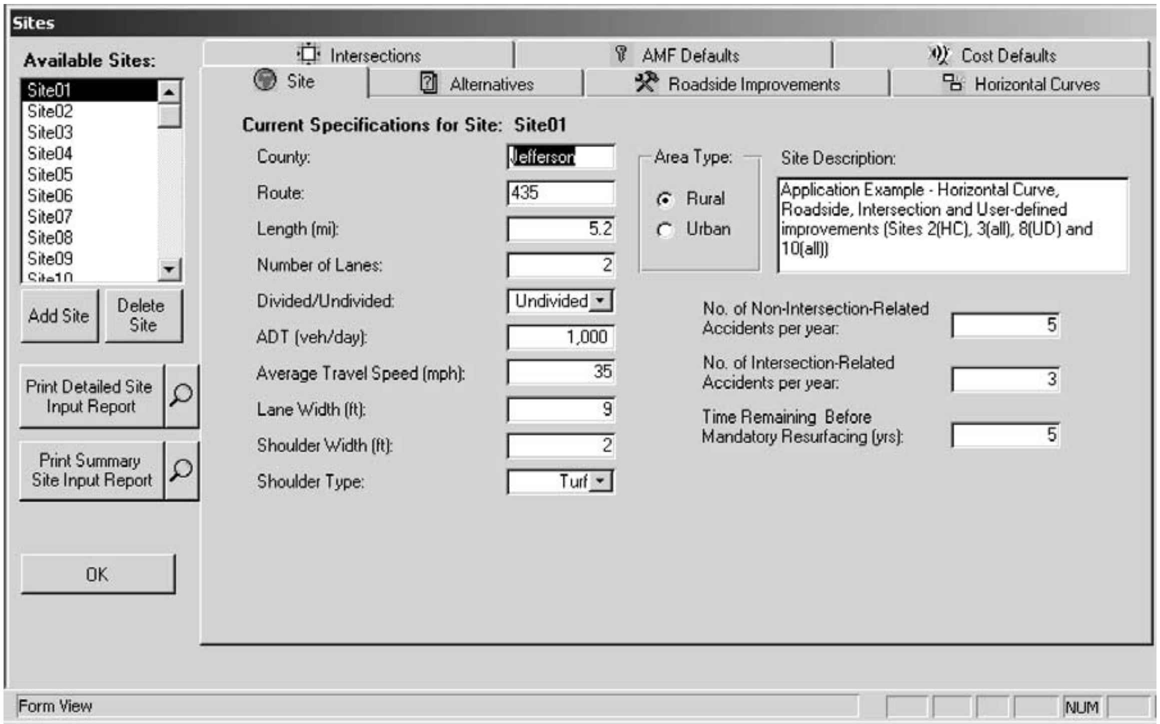


Figure 12. Sites form showing data for one specific site.

widening and shoulder paving are considered, when appropriate, for all sites. However, intersection, roadside, and horizontal curve improvements are optional and must be activated here before their respective screens are available. In addition, the Alternatives tab provides an opportunity for the user to create user-defined alternatives, or alternatives that otherwise would not have been considered. The Roadside Improvements, Horizontal Curves, and Intersection screens contain data that must be entered whenever those types of improvements are considered. The final two Defaults tabs display RSRAP defaults that may be edited or tailored for specific sites. The user can switch to another Site screen by clicking the title of the tab wanted.

Edit checks are incorporated in the program to prevent users from entering invalid data that would prevent the program from operating properly. For example, edit checks prevent users from entering zero values in fields that are later used as denominators of equations used in the optimization calculations. These checks are necessary because division by zero would interrupt the program operation.

Table 25 summarizes the screens used to enter site-specific information.

Adding and Deleting Sites

To begin entering data on the Sites form for a site that is not already in the database, click the Add Site command button (see Figure 13).

An input box entitled Add New Site (see Figure 14) will appear requesting the site name. As indicated, the site name should be unique and six characters in length. The examples presented here use Site 01, Site 02, and so forth as site names, but this is not necessary; any set of unique six-character names may be used. After successful entry, the site name will appear in the list box entitled Available Sites in the upper left corner of the screen. If the site name has already been used, a message box will appear indicating an error (see Figure 15). Begin again by clicking the Add Site command button and entering a site name that is not already in use. To eliminate a site from the database, highlight it in the Available Sites list and then

TABLE 25 Screens for entering site-specific information

Screen	Function/Purpose
Site	Entry for location description, traffic volume, cross-section geometrics, accident history, and comments for individual sites.
Alternatives	Screen for selecting improvement alternatives to be considered at site as well as providing data entry for user-defined improvement alternatives.
Roadside Improvements	Roadside design characteristics (ratings) for existing roadside features and proposed improvements.
Horizontal Curves	Geometric design characteristics for existing horizontal curves and proposed improvements.
Intersections	Geometric design characteristics for existing intersections and proposed improvements.
AMF Defaults	Screen displays default AMF calculation figures and allows site-specific revisions to default values.
Cost Defaults	Screen displays default cost/benefit calculation figures and allows site-specific revisions to default values.

click the Delete Site command button. The Delete Site confirmation box illustrated in Figure 16 will appear before deleting a site. Clicking Yes will permanently delete all information associated with the site. To enter data for the newly created site, or to enter or edit data for any other site, highlight the site name in the Available Sites list.

Site Screen

The Site screen allows for entry of location description, traffic volume, cross-section geometrics, accident history, and comments. Entry may begin by clicking the cell or tabbing to the cell and typing. Editing techniques are discussed in Section 5.

Table 26 summarizes input for this screen.

Highway sections that have been selected as candidates for improvement should be as homogeneous as possible; therefore, data input for many site characteristics is limited to only one choice. For example, it is assumed that the lane and shoulder width are the same in both directions of travel for the length of the site. However, as safety impacts of improvements

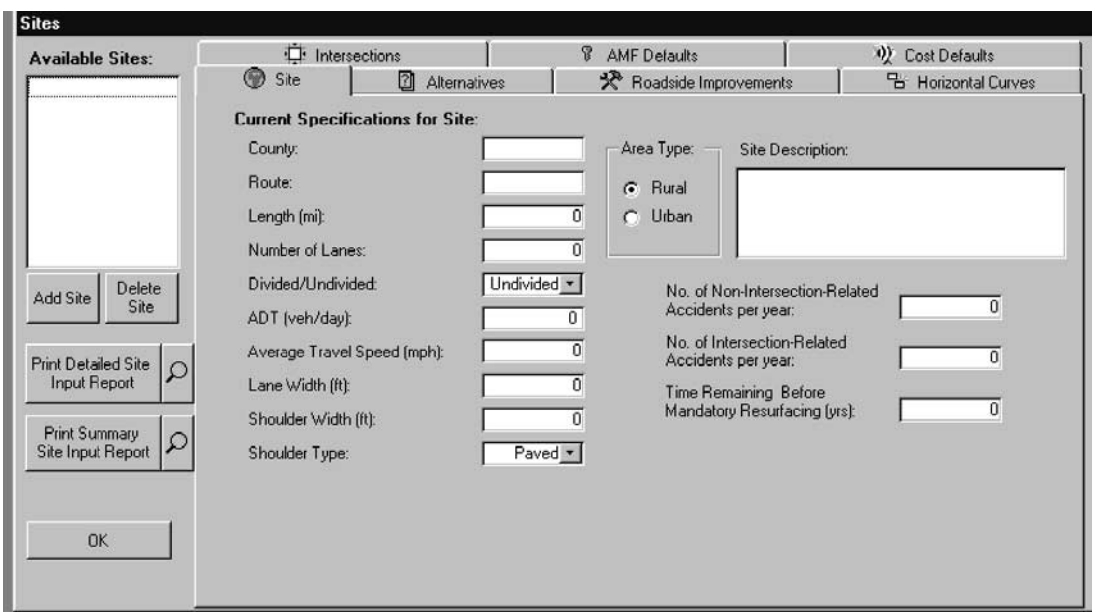


Figure 13. Sites form without data.

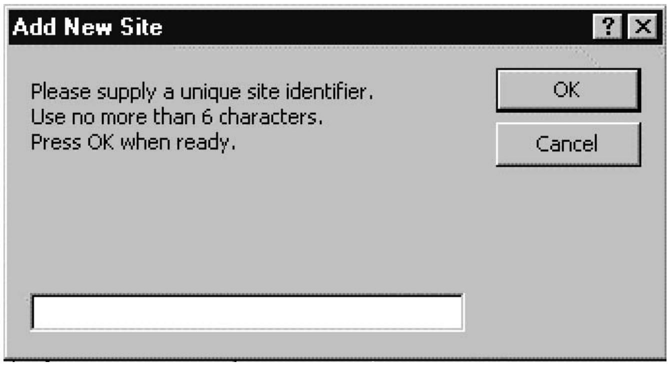


Figure 14. Add New Site input box.

Figure 15. Add New Site input box error message.

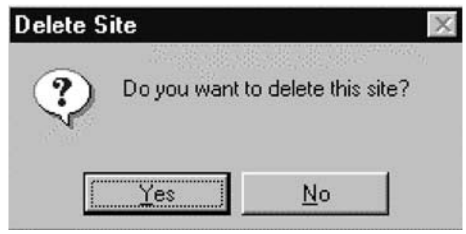


Figure 16. Delete Site confirmation box.

for lane and shoulder widening are measured in whole number increments, entered widths are rounded down for selection of benefits. Therefore, a 9.6-ft lane should be entered as a 10-ft lane. Lane widths above 12 ft will be considered as equal to 12 ft in the safety benefit calculations, but construction costs will vary with the lane width.

If there are significant variations in lane width, shoulder width, or shoulder type within a site, consider breaking the site apart into two or more separate sites. Variations in roadside design, horizontal alignment, or intersection design within a site are permitted and do not require a site to be subdivided.

The estimated accident frequencies entered on the Site screen should be based on as long a history as possible, but should not include periods before or during the most recent resurfacing or reconstruction of the site. The use of 5 years of accident data to calculate the annual accident frequency is recommended whenever possible. Default values of the accident severity distribution are provided in the RSRAP default data; these default values can be modified by the user based on local data. If the accident severity distribution for a given site differs from the default values, a site-specific accident severity distribution can be entered on the site-specific Cost Defaults screen.

Saving Site Data

The input data entered for a set of sites may be saved at any time for later retrieval using the button at the top of the screen marked Save Site Data. The data will be saved under a user-selected file name.

Clearing Site Data

The Clear Site Data button at the top of the screen may be used to clear all currently entered site data from memory so that a new data set can be entered. When the user opts to clear the site data from memory, the user will be offered an option to save the data currently in memory under a user-selected file name.

TABLE 26 Input for the Site screen

Data input	Field type	Description
Site Name	Text	Enter unique site identifier, entered with Add Site command button.
County	Text	Enter county in which the site is located (up to 30 characters in length).
Route	Text	Enter name or number of route on which the site is located (up to 30 characters in length).
Length	Numeric	Enter total length of site in miles.
Number of Lanes	Numeric	Enter total number of through travel lanes for both directions of travel combined; do not include auxiliary or turning lanes.
Divided/Undivided	Numeric	Select median type.
ADT	Numeric	Enter current ADT as veh/day.
Number of Nonintersection-Related Accidents Per Year	Numeric	Enter estimated annual number of nonintersection-related accidents per year.
Number of Intersection-Related Accidents Per Year	Numeric	Enter estimated annual number of intersection-related accidents per year; generally, only intersection-related accidents that occur within 250 ft of the intersection should be included. (NOTE: The sum of intersection-related and nonintersection-related accidents per year should equal the estimated total accidents per year for the site.)
Average Travel Speed	Numeric	Enter the estimated current average speed of traffic in miles per hour.
Lane Width	Numeric	Enter the existing lane width in feet.
Shoulder Width	Numeric	Enter the existing shoulder width in feet.
Shoulder Type	Numeric	Enter the existing shoulder type (paved/gravel/turf/composite).
Time Remaining Before Mandatory Resurfacing	Numeric	Years remaining until pavement failure (if the number of years remaining until pavement failure is 6 or more, entry of any number greater than or equal to 6 will provide the same result).
Area Type	Numeric	Area type (rural/urban).

Retrieving Site Data

The Retrieve Site Data button at the top of the screen can be used to retrieve a data set that was previously saved. Because any site data currently in memory will be lost, the user will be offered an option to save the current data before the stored data are retrieved.

Printing Input Data

At any time during the process of entering site data, the site input data may be printed in a detailed or summary report. These reports can be generated by the buttons on the screen labeled Print Detailed Site Input Report and Print Summary Site Input Report. Examples of these reports are presented in Appendix D.

Alternatives Screen

The Alternatives screen provides the user with an opportunity to select which improvement alternatives are to be considered for a given site (see Figure 17). To access this screen, click the Alternatives tab, then select alternatives by clicking the check box to the right of

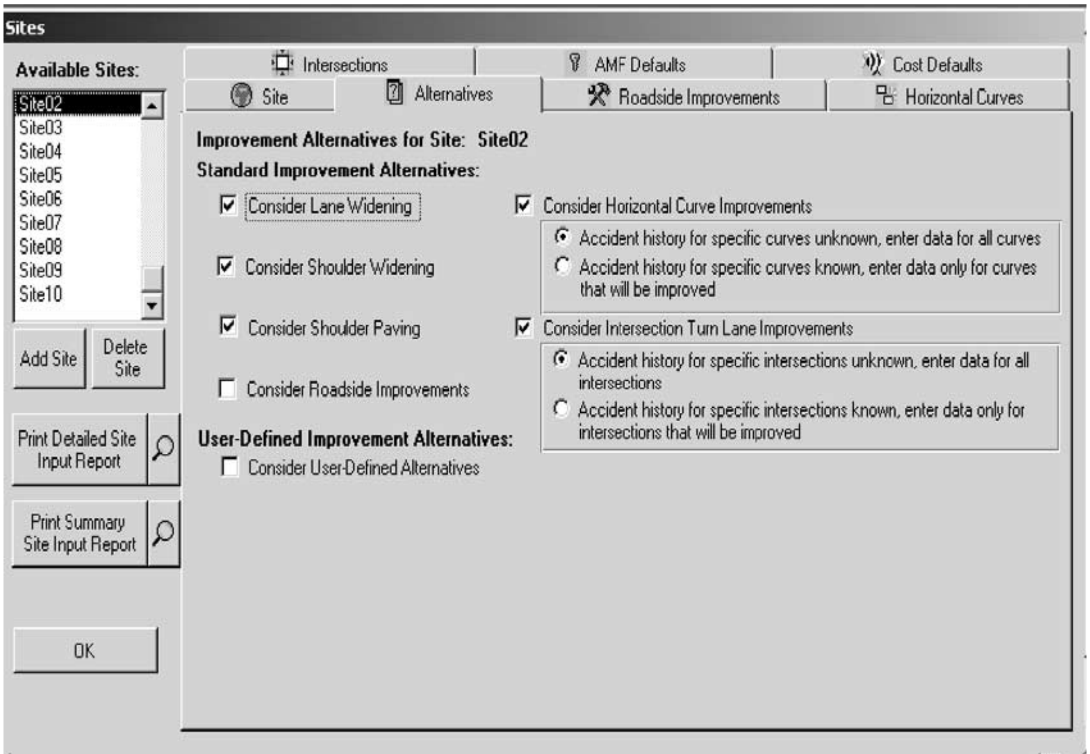


Figure 17. Alternatives screen.

any alternative. Click again to deselect that alternative. Lane widening, shoulder widening, and shoulder paving are automatically selected for each site.

If horizontal curve improvements are selected, the user must make a choice between two options:

- Enter data for all curves and
- Enter data only for curves that will be improved.

The first option is the default; geometric data must be entered for every curve within the site, but no accident data for specific curves are required. This option requires more geometric data, but does not require the user to determine the accident experience of individual curves. The second option may be used when the accident experience of individual curves is known. The user only needs to enter geometric data for curves that are to be improved, but accident data must also be entered for each individual curve to be improved. These data are entered on the Horizontal Curve Improvements screen.

Intersection turn lane improvements are handled with similar options. The user must choose either to enter geometric design and traffic volume data for all intersections or to enter geometric design, traffic volume, and accident data only for the specific intersections that will be improved. The first option is the default and should be used when accident data for individual intersections are not available. Data for individual intersections are entered on the Intersection Improvements screen.

If roadside, horizontal curve, or intersection improvements are selected on the Alternatives screen, screens appearing on their respective tabs will change from the screen marked Not Considered (see Figure 18) to a data entry screen.

Similarly, if the user indicates that user-defined alternatives will be considered for a site, a data entry form will appear in the lower portion of the screen for descriptions of the user-defined alternatives to be entered (see Figure 19).

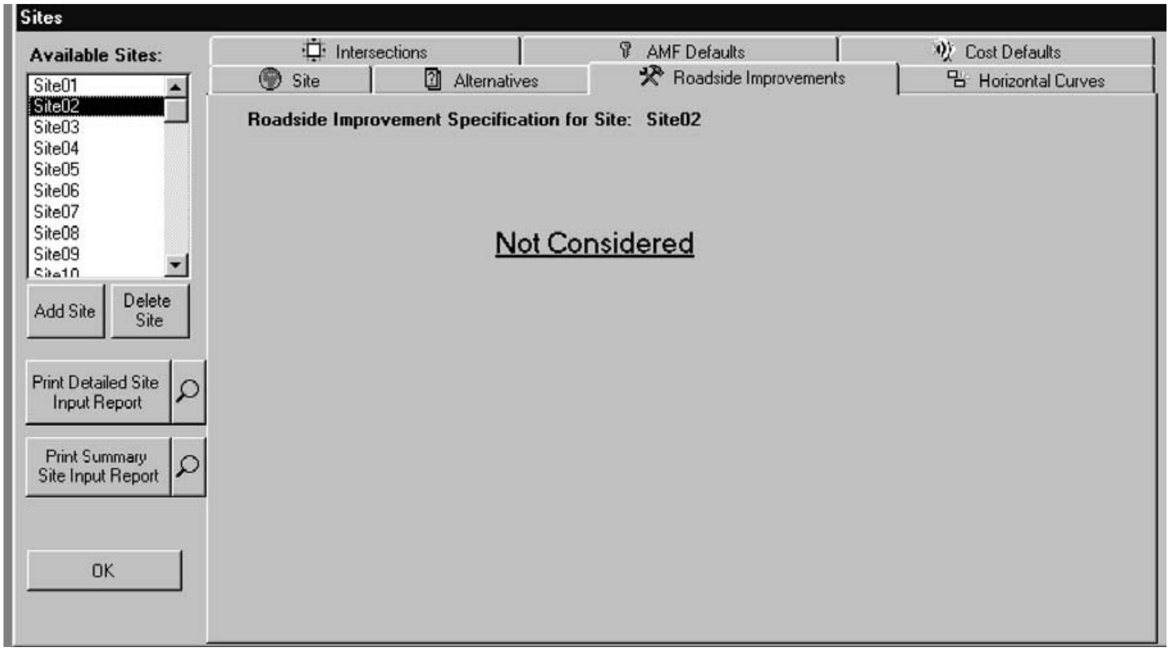


Figure 18. Roadside Improvements screen when roadside improvements have not been selected on the Alternatives screen.

User-Defined Alternatives on the Alternatives Screen

A user-defined alternative is any alternative with the potential to improve safety that the user wishes to consider in addition to the six "built-in" improvement alternatives: lane widening, shoulder widening, shoulder paving, roadside design alternatives, horizontal curve improvements, and intersection turn lane improvements. For a user-defined alternative to be considered, the user must be able to supply its construction cost and its accident reduction effectiveness. A maximum of five user-defined alternatives are permitted per site.

Typical user-defined alternatives include access management projects, median modifications, and rumble strips. However, adding a lane or completely reconstructing the roadway is beyond the scope of a 3R project; therefore, it should not be a user-defined alternative.

To begin entering a user-defined alternative, click the Add Alternative command button. As in the Add Sites function, an input box will appear requesting a unique name (up to 30 characters in length) for the user-defined alternative (see Figure 20). Once entered, it will be placed in the Available Alternative list box. A user-defined alternative could be identified by a name like Alt01 or by a description of the improvement type, such as "Add Shoulder Rumble Strips."

A message box will warn the user of duplicate names and will warn the user if the number of user-defined alternatives exceeds five (see Figure 21).

Table 27 summarizes data to be entered for a user-defined alternative.

Data entry for percent reduction should be a whole number between 0 and 100 rather than a proportion.

If a given user-defined alternative is to be considered at more than one site, it must be reentered at each site. Therefore, the cost and accident reduction effectiveness for a given user-defined alternative may be the same for all sites or may vary from site to site.

Roadside Design Improvements Screen

After selecting roadside improvements on the Alternatives screen, the screen shown in Figure 22 will appear the next time the Roadside Improvements tab is selected.

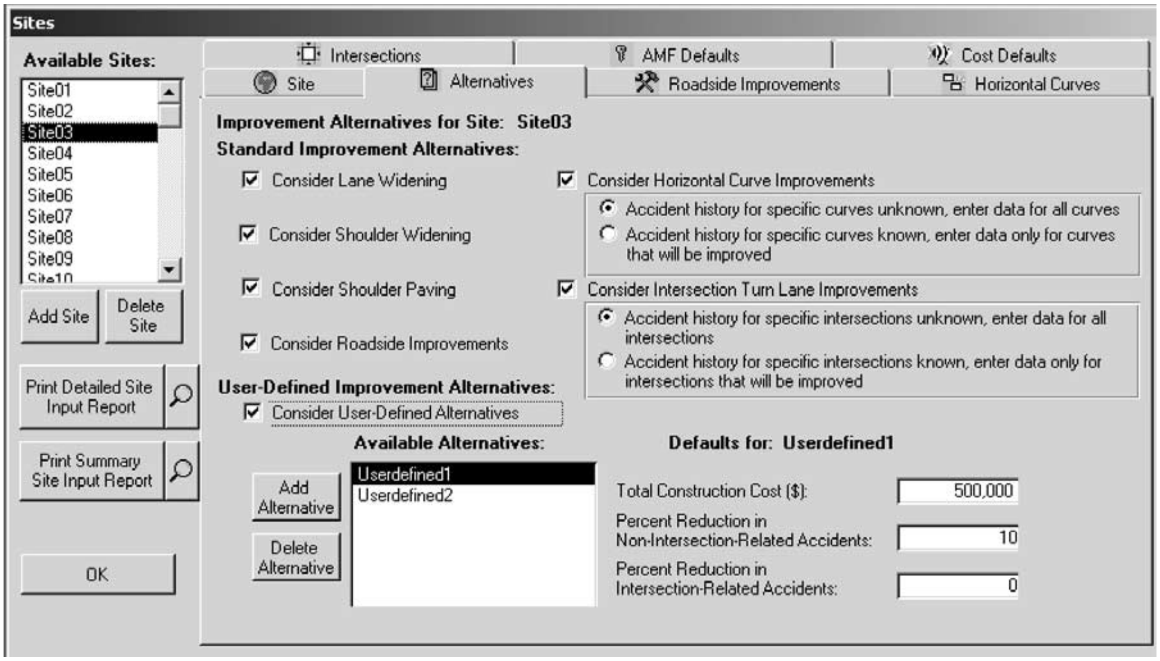


Figure 19. Alternatives screen with user-defined alternatives data entry form.

The relative safety of roadside designs is rated on a scale developed in previous research by Zegeer et al. (*15*). The roadside hazard ratings range from 1 (best roadside) to 7 (worst roadside).

The screen shown in Figure 22 includes 14 roadside design categories defined by clear zone width, roadside slope, and type and location of roadside obstacles. The screen also shows the roadside hazard rating that corresponds to each of these categories. The user describes any proposed roadside design improvement by entering the percentage of roadway length in each of the 14 categories both before and after the proposed improvement. The before and after percentages should each total 100.

The total construction cost of the proposed roadside design improvement at this site must also be entered on this screen.

Horizontal Curve Improvements Screen

The Horizontal Curves data entry screen is used to provide data for horizontal curve improvements. This screen appears after horizontal curve improvement has been selected

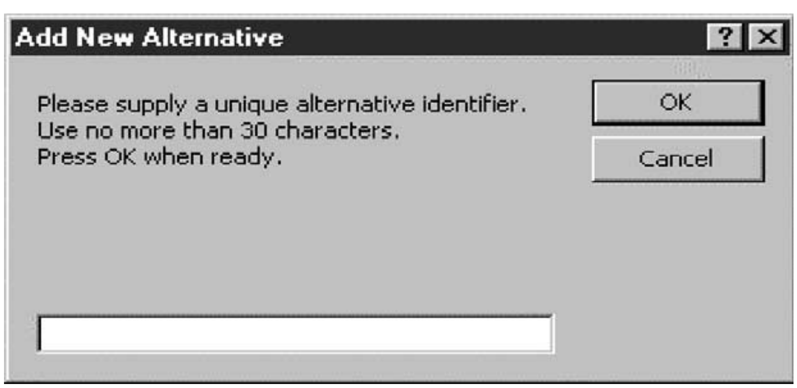


Figure 20. Add New Alternative input box.

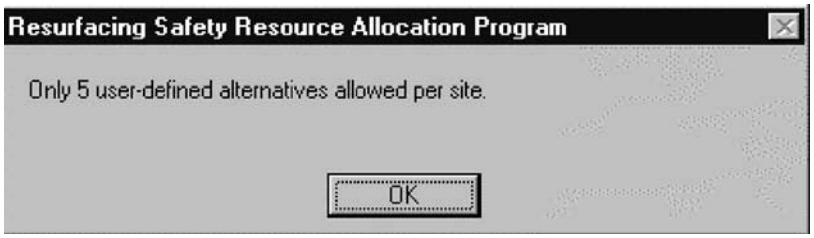


Figure 21. Message box displayed if too many user-defined alternatives are entered.

on the Alternatives screen, the accident history determined, and the Horizontal Improvements tab clicked (see Figure 23).

The approach used by RSRAP to evaluate horizontal curves is dependent on the availability of data on the accident histories for the specific curves proposed for improvement. A choice between data entry approaches, based on data availability, must be made on the Alternatives screen. If the accident history for each improved curve is known, a text box for entry of accident data will be displayed for each curve on the Horizontal Curves screen. Using this option, accident and geometric data are entered only for those specific horizontal curves that are proposed for improvement. The required geometric data include the length and radius of each curve and the presence or absence of spiral transitions both before and after the proposed improvement. If a curve is proposed for flattening as part of an improvement project, its length will generally be longer and its radius larger after the improvement than it was before the improvement. If a curve is not to be modified as part of the proposed improvement, then the same geometric data should be entered for the periods before and after the improvement.

On the other hand, to evaluate a horizontal curve improvement when the specific accident history of each curve is not known, geometric data must be provided for all horizontal curves within the site, whether they are proposed for improvement or not. However, in this case, no text box to enter accident data for individual curves will appear, and no entry of accident data for individual curves is required. Instead, RSRAP will use accident predictive models to estimate the expected accident frequencies of the curves that will be improved.

Data entry for horizontal curve improvements begins like user-defined alternatives, by clicking the Add Curve command button. An input box will appear requesting a unique name for the curve, up to 15 characters in length. Although any unique name can be used for each curve, names like Curve01, Curve02, and so forth, may make for convenient data entry. Once entered, the curve name will be placed in the Available Curves list box. Data

TABLE 27 Data entered for a user-defined alternative

Data input	Field type	Description
User-Defined Alternative Name	Text	Enter unique alternative identifier (up to 30 characters in length).
Total Construction Cost ($)	Numeric	Enter construction cost for this user-defined alternative improvement at this site.
Percent Reduction in Nonintersection-Related Accidents	Numeric	Enter expected percentage reduction in nonintersection-related accidents for this alternative at this site.
Percent Reduction in Intersection-Related Accidents	Numeric	Enter expected percentage reduction of intersection-related accidents for this alternative at this site.

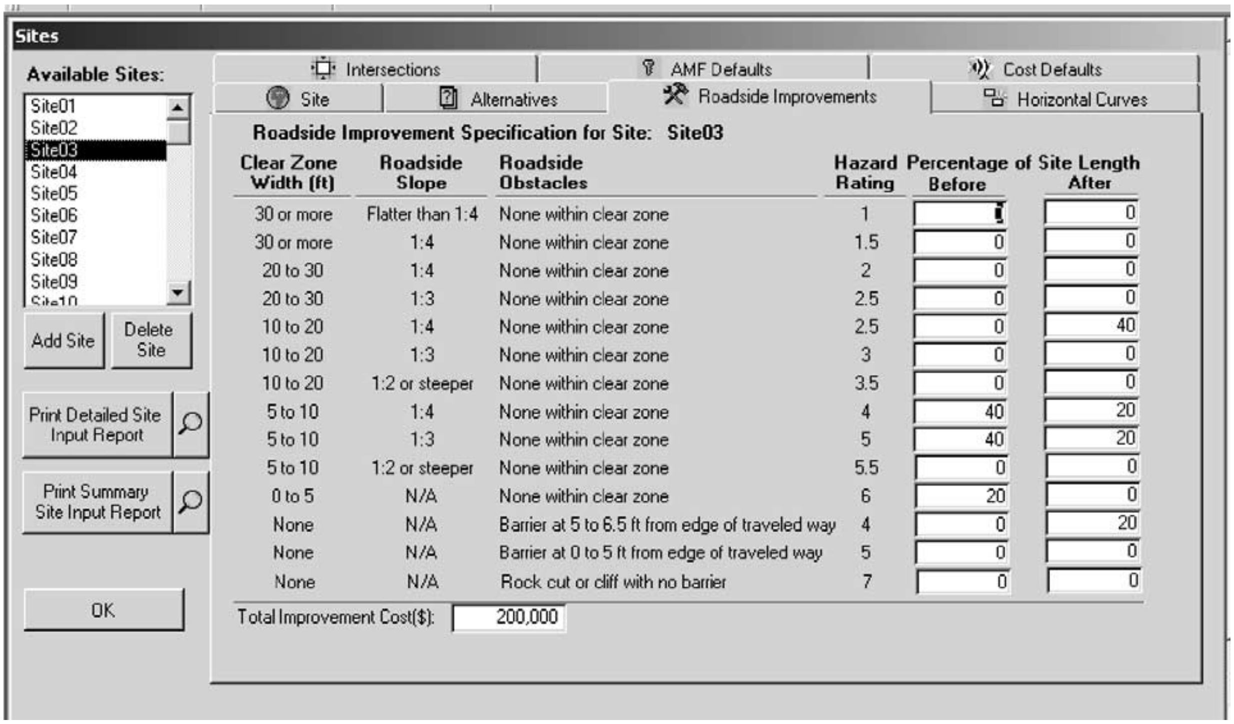


Figure 22. Roadside Improvements screen.

for the curve can be entered or edited by highlighting the curve name in the Available Curves list box and entering or changing data in the fields to the right of the list box. The number of horizontal curves for which data may be entered for a given site is unlimited, but only one set of horizontal curve improvements per site may be considered.

The sum of the lengths for all horizontal curves entered for a given site, obviously, must be less than or equal to the total site length. There is currently no formal check on the total length of horizontal curves, so the user is responsible for accurate data entry.

Table 28 summarizes the geometric data that must be entered to determine the safety impact of horizontal curve improvements.

Repeat the same fields for the condition after improvement.

The total construction cost for improving all curves on the site that are proposed for improvement should be entered at the bottom of the form. This cost should include all costs for improving the curves including right-of-way, earthwork/grading, paving, and surfacing. The total construction cost must include the cost of placing the wearing surface on the improved curve or subsequent RSRAP calculations may be inaccurate.

Intersection Improvements Screen

Like other alternative tabs, data input for geometric specifications of intersections will appear on entry to this screen after appropriate selection on the Alternatives tab and determination of accident histories (see Figure 24).

Similar to horizontal curves, there are two data entry options for intersection turn lane improvement. As explained above, the user must choose between the options on the Alternatives screen. For one option, the user must have available and enter accident data for each individual intersection. With this option, data are entered only for intersections where turn lane improvements are proposed. As in the overall site data, accident data for any given intersection should include all intersection-related accidents that have occurred within 250 ft of the intersection. For the other option, accident data for individual intersections

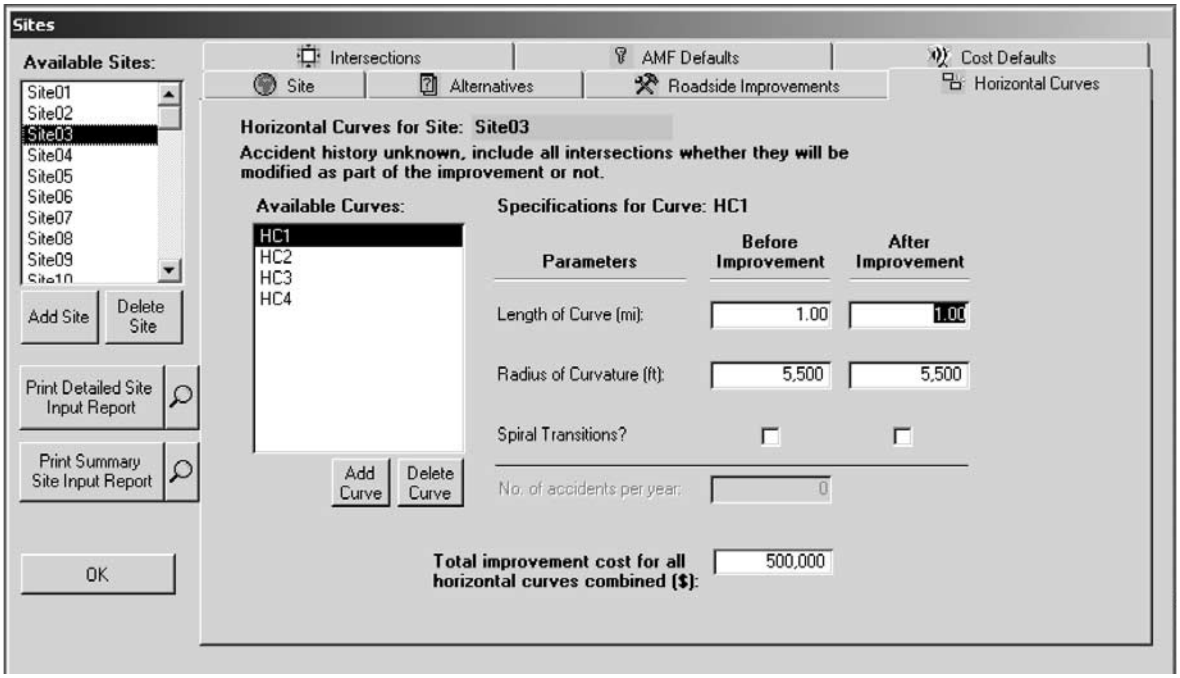


Figure 23. Horizontal Curves Improvements screen.

need not be entered, but the user must then enter geometric and traffic volume data for every intersection on the site, whether an intersection will be improved or not.

Clicking the Add Intersection command button begins data entry for intersection improvements. An input box will appear requesting a unique name for the intersection, up to 25 characters in length. Although any unique name can be used for each intersection, names like Intersection 1, Intersection 2, and so forth, may make for convenient data entry. Once entered, the intersection name will be placed in the list box. Data for the intersection can be entered or edited by highlighting the intersection name in the Available Intersections list box and entering or changing data in the fields to the right of the list box.

The number of intersections for which data may be entered for any given site is unlimited.

Table 29 summarizes the geometric data that must be entered to determine the safety impact of intersection improvements. Repeat the same fields for the condition after improvement.

The maximum number of turn lanes on a major-road approach is one, since no double- or triple-turn lanes are considered. Therefore, the maximum number of left- or right-turn lanes for an intersection is two. Input for traffic control and ADT level both refer to the minor road; ADT data for the major road have already been entered on the Site screen. If the intersection has four legs, then ADT and traffic control are assumed to be the same for both directions of travel on the minor road. ADT level for the minor road should be selected as based on the values presented in Table 30.

AMF and Cost Defaults Screens

Information appearing on the AMF and Cost Default screens replicates data input appearing on the Global Default screens. These screens on the Site form may be used to adjust defaults for a site to create site-specific defaults, except for regression coefficients and the minimum attractive rate of return (see Figures 25 and 26). All new sites are created with figures from the current global defaults. To change these global defaults for a specific site, simply edit the data appearing on these screens to apply them for a highlighted (selected) site. If global defaults were changed after the creation of a site, then new global defaults can be copied into the site by clicking the Use Current Global Defaults command button.

TABLE 28 Geometric data inputs for determining the safety impact of horizontal curve improvements

Data input	Field type	Description
Curve Name	Text	Enter a unique curve identifying number (up to 15 characters in length).
Length of Curve—Before	Numeric	Enter length of curve before improvement in miles.
Radius of Curvature—Before	Numeric	Enter radius of curvature before improvement in feet.
Spiral Transitions—Before	Yes/No	Enter YES if spiral transitions were present before improvement; otherwise enter NO.
Accidents	Numeric	Enter average number of annual accidents when known.

Similarly, if global defaults were changed prior to the creation of the site, then the defaults may be returned to RSRAP's original values by clicking the Use Original Defaults command button.

SPECIFY NEW ANALYSIS FORM—STEP 6

After all site data have been entered, the user should click the Ok command button at the lower left of the Site form to return to the RSRAP Main Options screen. The Optimize Improvements button will now appear on this screen. Clicking this button begins the sequence of actions that performs the optimization.

The first of the steps is the Choose Optimization and Analysis Options form. This form prompts the user to choose the optimization and analysis options to be performed during the optimization process. The form appears as shown in Figure 27. One of two optimization options must be selected:

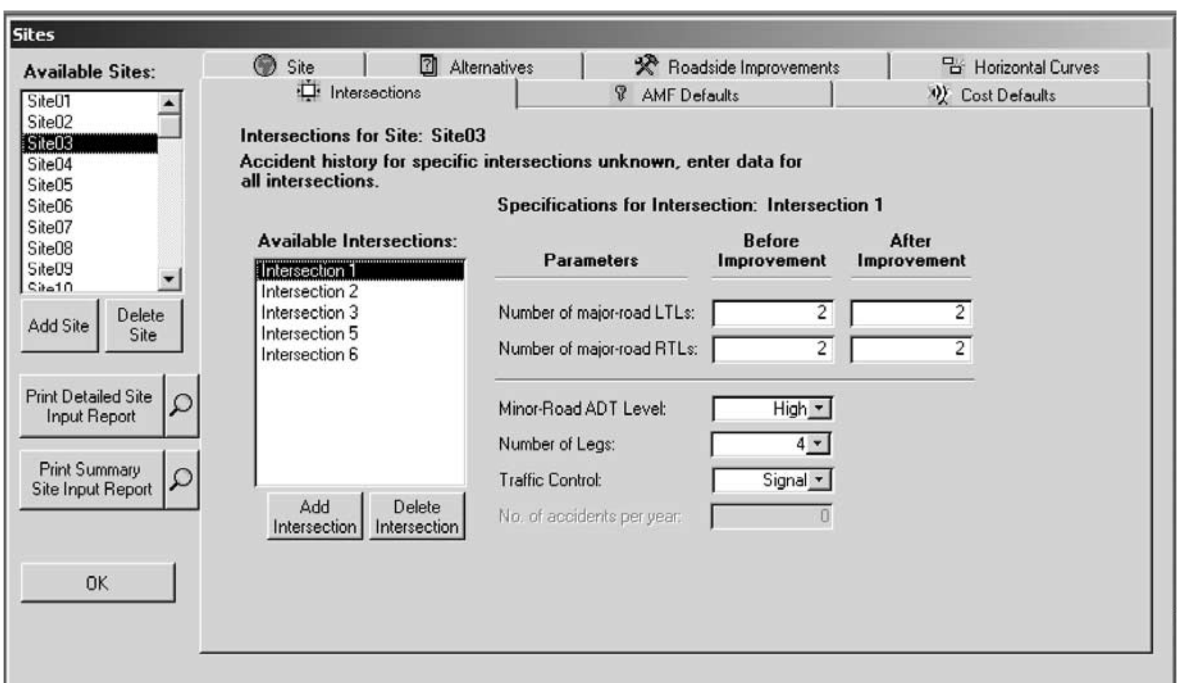


Figure 24. Intersection Improvements screen.

TABLE 29 Geometric data inputs for determining the safety impact of intersection improvements

Data input	Field type	Description
Intersection Name	Text	Enter unique intersection number (up to 25 characters in length).
Number of Left-Turn Lanes—Before	Numeric	Enter the before improvement number of Major-Road Left-Turn Lanes.
Number of Right-Turn Lanes—Before	Numeric	Enter the before improvement number of Major-Road Right-Turn Lanes.
Minor Road ADT Level	Numeric	Enter ADT level of minor road by selecting high, medium, or low.
Number of Legs	Numeric	Enter number of intersection legs (3 or 4 legs).
Traffic Control	Numeric	Enter traffic control by selecting Signal or Stop.
Accidents	Numeric	Enter average number of annual accidents when known.

TABLE 30 ADT levels for minor roads

ADT level	Vehicles per day
Very high	10,000 or more
High	5,000 to 10,000
Medium	2,000 to 5,000
Low	400 to 2,000
Very low	400 or less

- *Optimize Both Resurfacing and Safety Improvements*. With this option, RSRAP will make a recommendation for each site. RSRAP will recommend whether or not that site should be resurfaced in the coming year. If RSRAP recommends that the site be resurfaced, it will also recommend whether or not other geometric design or safety improvements should be made in conjunction with resurfacing. If this option is selected, the maximum budget specified in Step 8 must include funds for resurfacing and for geometric design and safety improvements. If, as a matter of department policy, hydraulic improvements or other similar improvements are going to be made at each site under consideration, the maximum budget entered should be reduced accordingly.
- *Optimize Safety Improvements Only*. With this option, RSRAP assumes that a decision has already been made to resurface all of the user-specified sites in the coming year. RSRAP will make a recommendation as to which sites should also have geometric design and safety improvements in conjunction with resurfacing. If this option is selected, the maximum budget specified in Step 8 should include funds available for geometric design and safety improvements only. Funds for resurfacing costs should not be included in the budget because a decision to resurface these sites has already been made.

One of two analysis options must be selected:

- *Consider Safety Benefits Only*. With this option, the benefit-cost analysis used in the optimization process considers only safety benefits. The safety benefits considered include the accident reduction benefits of the candidate geometric design and safety improvements. The benefits may be partially offset by a short-term (12- to 30-month) increase in accidents resulting from increased speeds following resurfacing.
- *Consider Both Safety and Speed Benefits*. With this option, safety benefits are determined in a manner identical to the previous option. However, in addition to the short-term increase in accidents following resurfacing, the analysis also considers the traffic-operational benefits of the short-term increase in speeds following resurfacing.

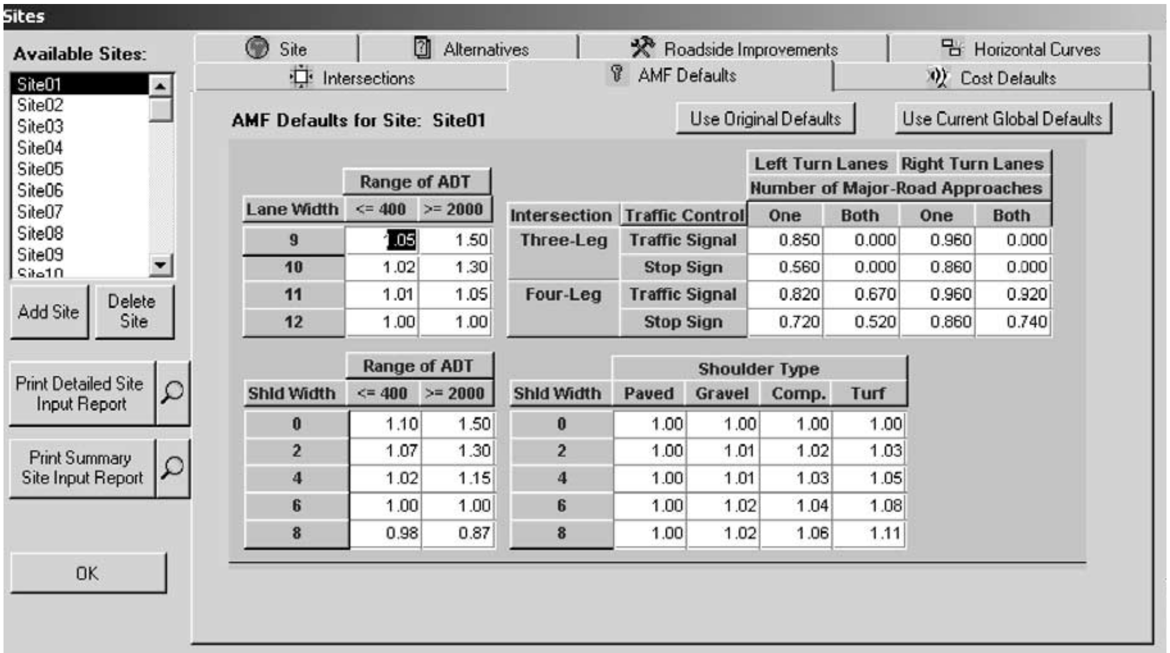


Figure 25. AMF Defaults screen for entering site-specific AMFs.

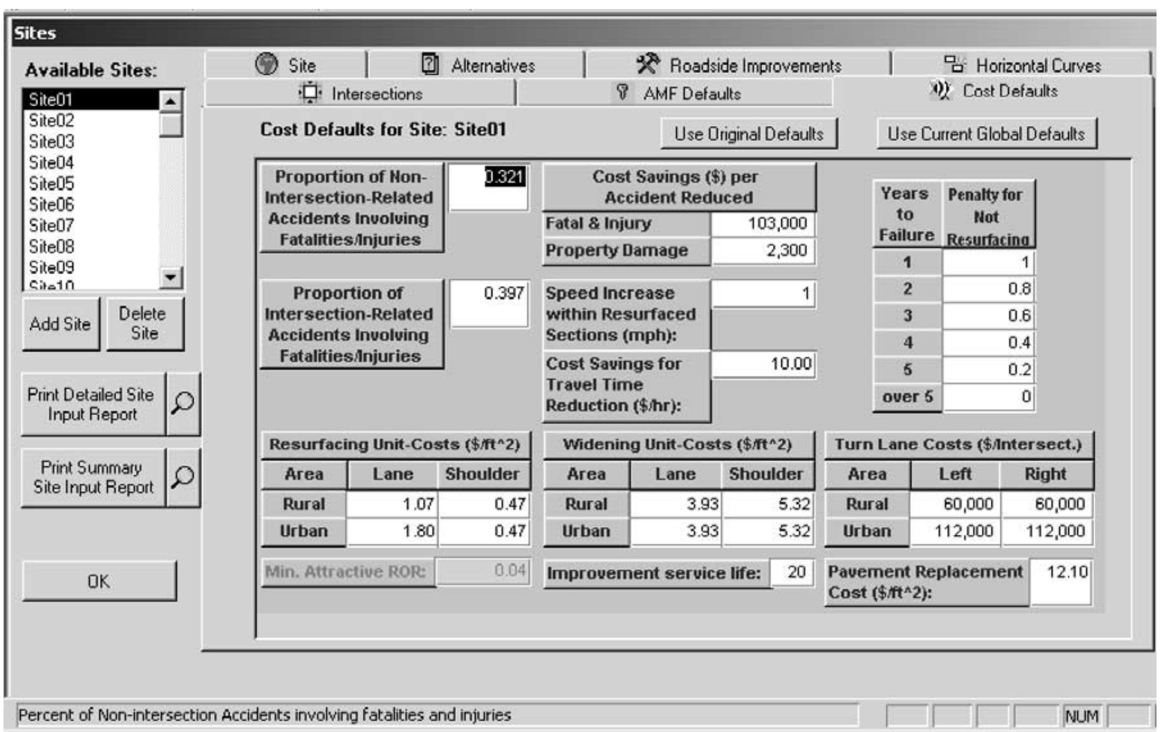


Figure 26. Cost Defaults screen for entering site-specific cost data.

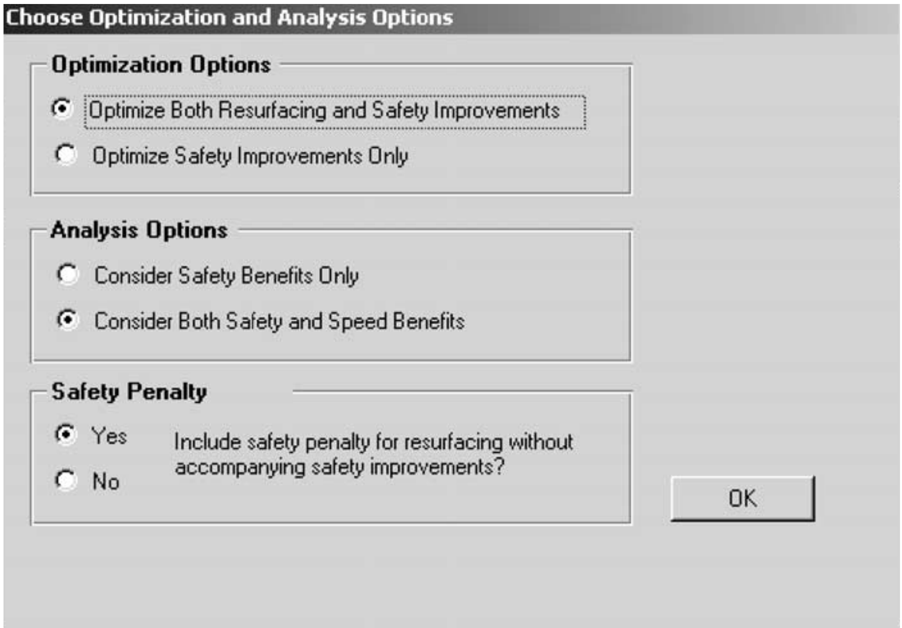


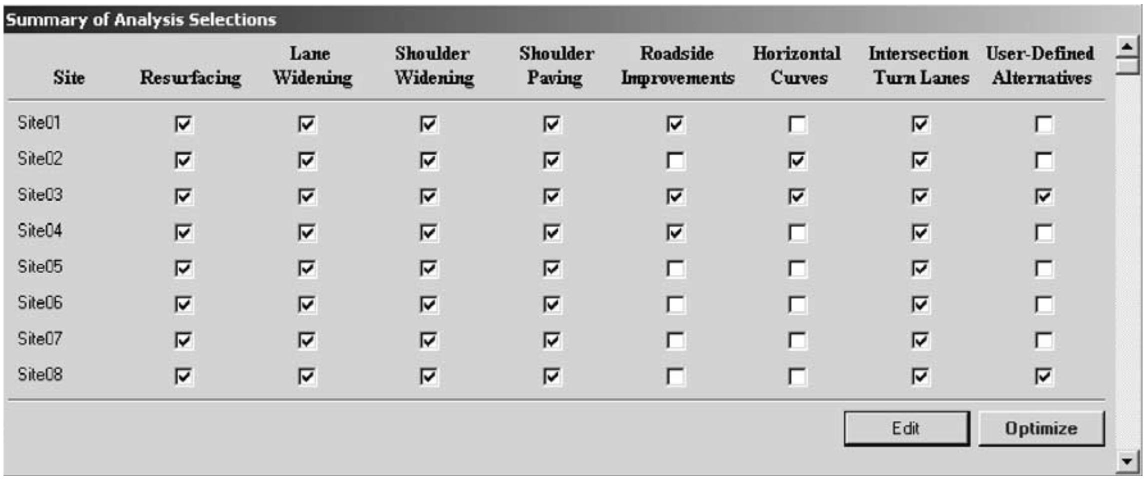
Figure 27. Choose Optimization and Analysis Options form.

Finally, the user must specify whether the safety penalty for resurfacing without accompanying geometric improvements should be included in the net benefit calculations. Caution should be exercised if selecting “No” for this option, as speed benefits and this penalty are based on similar research results. It is recommended that if the user selects “No,” the user should also select safety benefits only for the analysis option.

After selecting the optimization and analysis options, click Ok.

REVIEW SUMMARY FORM—STEP 7

After the optimization and analysis options have been selected, the user should click the Ok command button at the lower left of the Choose Optimization and Analysis Options form to open the Summary of Analysis Selections form. The form summarizes the alternative selections made during the site data entry process. If the user is satisfied that the data


Summary of Analysis Selections

Site	Resurfacing	Lane Widening	Shoulder Widening	Shoulder Paving	Roadside Improvements	Horizontal Curves	Intersection Turn Lanes	User-Defined Alternatives
Site01	☑	☑	☑	☑	☑	☐	☑	☐
Site02	☑	☑	☑	☑	☐	☑	☑	☐
Site03	☑	☑	☑	☑	☑	☑	☑	☑
Site04	☑	☑	☑	☑	☑	☐	☑	☐
Site05	☑	☑	☑	☑	☐	☐	☑	☐
Site06	☑	☑	☑	☑	☐	☐	☑	☐
Site07	☑	☑	☑	☑	☐	☐	☑	☐
Site08	☑	☑	☑	☑	☐	☐	☑	☑

Edit Optimize

Figure 28. Summary of Analysis Selections form.

have been entered correctly and if the selected alternatives summarized on this form appear to be correct, the user should click the Optimize command button to begin the process of selecting the optimum set of alternatives for all the sites (Step 8). However, if the user wants to review the data already entered or if the user sees an error in the alternatives selected, the user can perform further editing of the data (Step 7) by clicking the Edit command button on the Summary of Analysis Selections form (see Figure 28).

The Edit command button will reopen the RSRAP Main Options form and will allow the user to repeat Steps 3 through 6. This form has command buttons to go to the Global Defaults screen (Step 4) and the data entry screens (Step 5).

SECTION **8**

OPTIMIZATION PROCESS—STEP 8

The first step in the optimization process is to enter the improvement budget for the analysis. This figure will be used as a constraint in the optimization process.

Depending on the optimization option chosen by the user on the previous screen, one of two screens will appear (see Figures 29 and 30). When optimizing both resurfacing and safety improvements, the dialog box shown in Figure 29 will appear. The budget entered should include the funds available for both resurfacing and safety improvements. When optimizing safety improvements only, the dialog box shown in Figure 30 will appear. The budget entered should include only the funds available for safety improvements and should not include funds already obligated for pavement resurfacing. If nonsafety improvements will be made to any site as a matter of policy (e.g., drainage improvements), the cost of those improvements should *not* be included in the budget under either option.

After the improvement budget is entered, the RSRAP Optimization message box appears during the remainder of the optimization process (see Figure 31). During this process, a series of computations, described below, are being conducted in the background in a manner transparent for the user. The calculations may take several minutes, depending on the speed of the computer being used.

The optimization process begins with the calculation and generation of alternatives for each of the sites. Then, a reduction algorithm reduces the list of alternatives by eliminating alternatives “dominated” by other alternatives. An alternative dominates another if it costs less and has more benefit.

Dominated alternatives are eliminated before the optimization process begins to reduce the number of alternatives considered and, thus, minimize the importance of the size limitations on the Solver program. If too many alternatives for the Solver program supplied with Excel must be considered, versions of the Solver program with greater capacity are commercially available.

After eliminating dominated alternatives, a modified alternatives table in Access is converted by RSRAP into an Excel spreadsheet. Once this spreadsheet is created, the optimization process proceeds using integer linear programming to pick the combination of alternatives that provides the maximum benefit. This functional process is done by the Excel add-in program called Solver.

Solver uses a Branch and Bound method for solving integer linear programming problems. In this method, Solver finds an optimum solution first without the integer constraints. If this solution happens to also satisfy the integer constraints, then no further processing is required (this is considered the optimum solution). Otherwise, “branches” or subproblems are created for each variable having a nonintegral solution. After solving these new branches, the process is repeated until a solution is found that satisfies integer conditions and is within 5 percent of the optimal solution. Because this solution may or may not be the true optimum solution, it is possible another solution exists. The 5-percent tolerance is a compromise to ensure a reasonable answer using minimal processing time.

Model options selected in Solver for this problem include maximum time, maximum iterations, “assume linear,” and “assume scaling.” The maximum time Solver will run before it stops, including setup time and total time taken to solve all subproblems explored by the Branch and Bound method, was set at 1,000 seconds. It was intentionally set to be larger than the default value of 100 seconds. The maximum number of iterations for any one subproblem

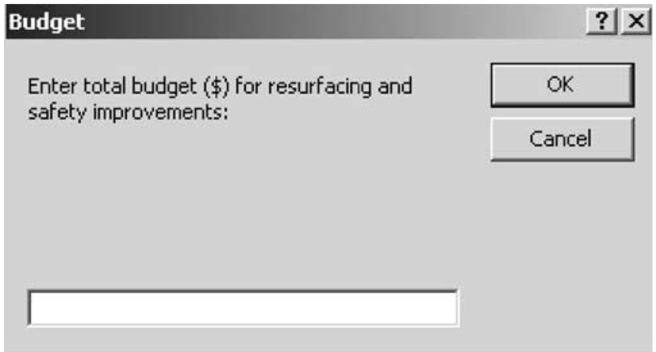


Figure 29. Improvement Budget input box for evaluating resurfacing and safety improvements.

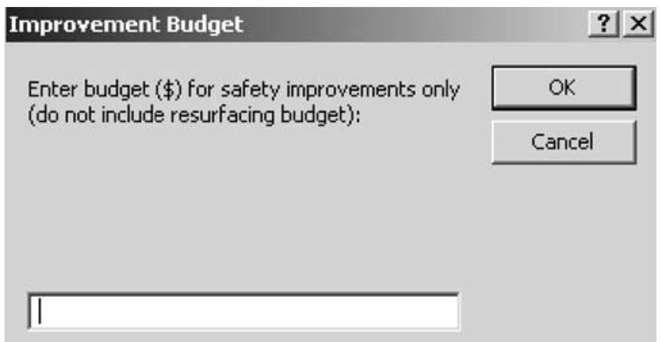


Figure 30. Improvement Budget input box for evaluating safety improvements only.

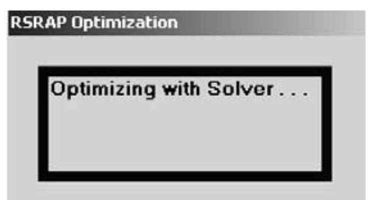


Figure 31. RSRAP Optimization message box.

Figure 32. Message appearing after Solver selects the optimal set of alternatives for each site.

has been set at 500, up from a default value of 100 iterations. Both of these options may need to be increased for larger problems.

As the values of the objective and constraint functions differ by several orders of magnitude, “assume linear and scaling” options were used. These are needed because the precision of computer arithmetic of greatly varied numbers may lead to errors when Solver performs a linearity test before presenting a solution. Information on changing these values and options can be found in Section 4.

After Solver selects the optimal set of alternatives for each site, this information is transferred from Excel back to Access. The message shown in Figure 32 appears after completion of this process. Click Ok to view the optimization results.

SECTION 9

OUTPUT REPORTS—STEP 9

After the optimization process is complete, summary results are displayed in the screen shown in Figure 33.

For each site, the Optimization Results screen displays the strategy that contributes to the maximum overall benefit for the resurfacing program.

The report of optimization results displayed on the computer screen by RSRAP is shown in Figure 33. This screen identifies the improvement alternative for each site that serves as part of the optimal strategy. The column headed Strategy Selected uses the codes listed and defined in Table 31 to identify project recommendations for each site as part of the optimal strategy.

The Optimization Results report also includes the following cost and benefit information for the recommended improvement at each site:

- Resurfacing costs,
- Safety improvement costs,
- Total improvement costs,
- Safety benefits,
- Traffic-operational benefits,
- Total benefits, and
- Anticipated percentage reduction in accident frequency.

The screen shown in Figure 33 does not provide all of the detail that would be useful to users. For example, when these reports use the code LW11, there is no direct indication on the screen whether the site in question has existing 11-ft lanes that are not being widened or whether the site has 9- or 10-ft lanes that are to be widened to 11 ft. To obtain such details, the user has two options. Clicking View Site Results on the Optimization Results screen brings up a series of screens with details on the location of the sites and their existing and recommended geometrics. Alternatively, the user can click the button on the Optimization Results screen labeled Print Detailed Report and obtain a printout that includes the specific recommended improvements for each site.

If the user clicks the View Site Results button, a series of screens that summarizes the input data and the analysis results for each specific site will appear. This series of screens is labeled Site Results; an example of the Site Results screen is shown in Figure 34. This screen presents the location and description of the site, the geometrics and safety performance of the site before improvement, and the geometrics and safety performance of the site after improvement for the improvement option selected. The screen also shows cost and benefit data for all alternatives that were considered for the site.

The Print Summary Report button and Print Detailed Report button initiate printing of the reports documenting the recommended optimal resurfacing and safety improvement strategy. The output for each of these options is shown in Figures 35 and 36.

When horizontal curves are selected for improvement, the safety improvement cost shown here will not equal the cost entered on the Horizontal Curves input screen. This occurs because the program subtracts the portion of the curve reconstruction cost attributable to resurfacing cost and moves that cost into the resurfacing column.

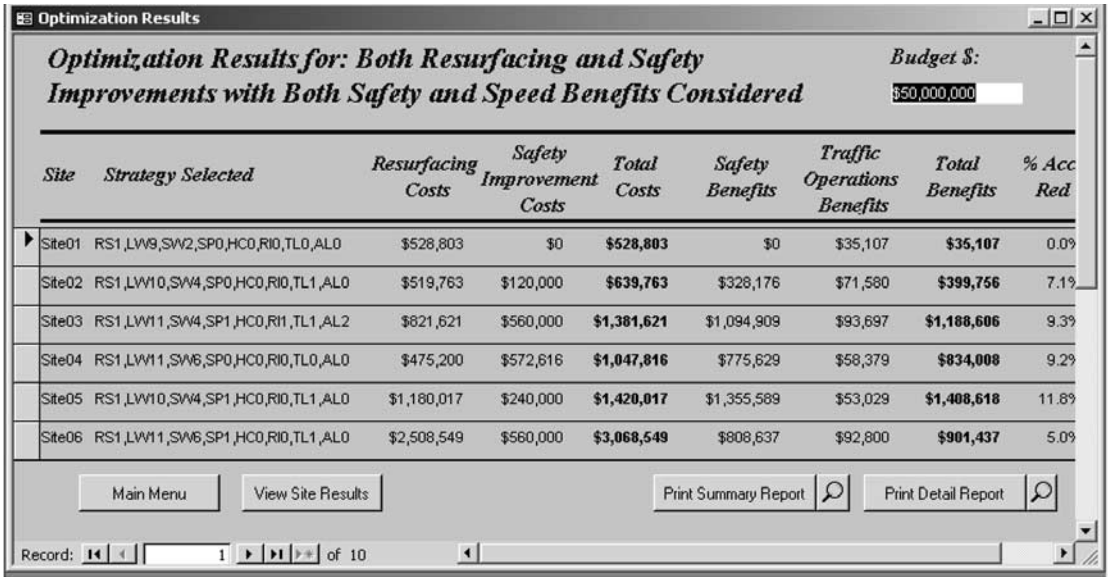


Figure 33. Optimization Results screen.

TABLE 31 Codes to identify project recommendations

Code	Definition
RS0	Do not resurface site
RS1	Resurface site
LW9, LW10, LW11, LW12	Use lane width of 9, 10, 11, or 12 ft
SW0, SW2, SW4, SW6, SW8	Use shoulder width of 0, 2, 4, 5, or 8 ft
SP0	Retain unpaved shoulders
SP1	Use paved shoulders
HC0	Do not improve horizontal curves
HC1	Improve horizontal curves
RI0	Do not improve roadside
RI1	Improve roadside
TL0	Do not install intersection turn lanes
TL1	Install intersection turn lanes
AL0	No user-specified alternative selected
AL1, AL2, AL3, AL4, AL5	User-specified alternatives selected*

* If more than one user-specified alternative is selected, codes like AL12 or AL123 will be displayed. The numbers 1, 2, 3, etc. correspond to the order in which the user-specified alternative is presented in the Alternatives screen (first, second, third, etc.).

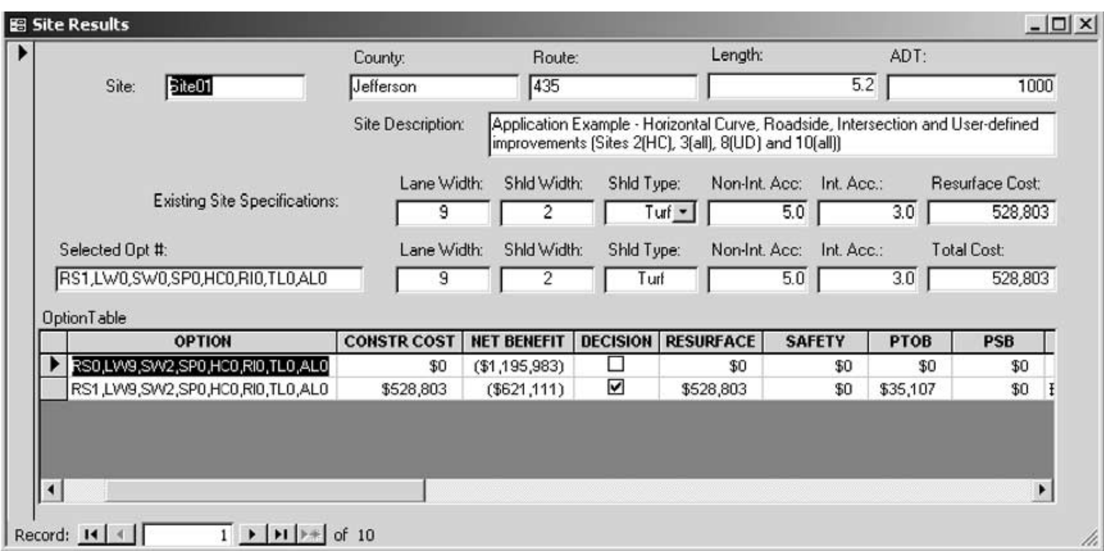


Figure 34. Site Results screen.

Optimization Results for: Both Resurfacing and Safety Improvements with Both Safety and Speed Benefits Considered

Budget: $50,000,000.00

Site	Strategy Selected	Resurfacing Costs	Safety Improvement Costs	Total Costs	Safety Benefits	Traffic Operations Benefits	Total Benefits	% Acc Red
Site01	RS1,LW9,SW2,SP0,HC0,RI0,TL0,AL0	$528,803	$0	**$528,803**	$0	$35,107	**$35,107**	0.0%
Site02	RS1,LW10,SW4,SP0,HC0,RI0,TL1,AL0	$519,763	$120,000	**$639,763**	$328,176	$71,580	**$399,756**	7.1%
Site03	RS1,LW11,SW4,SP1,HC0,RI1,TL1,AL2	$821,621	$560,000	**$1,381,621**	$1,094,909	$93,697	**$1,188,606**	9.3%
Site04	RS1,LW11,SW6,SP0,HC0,RI0,TL0,AL0	$475,200	$572,616	**$1,047,816**	$775,629	$58,379	**$834,008**	9.2%
Site05	RS1,LW10,SW4,SP1,HC0,RI0,TL1,AL0	$1,180,017	$240,000	**$1,420,017**	$1,355,589	$53,029	**$1,408,618**	11.8%
Site06	RS1,LW11,SW6,SP1,HC0,RI0,TL1,AL0	$2,508,549	$560,000	**$3,068,549**	$808,637	$92,800	**$901,437**	5.0%
Site07	RS1,LW11,SW4,SP1,HC0,RI0,TL1,AL0	$1,503,237	$360,000	**$1,863,237**	$947,234	$93,407	**$1,040,641**	6.3%
Site08	RS1,LW12,SW8,SP1,HC0,RI0,TL1,AL2	$1,398,989	$680,000	**$2,078,989**	$1,119,938	$150,118	**$1,270,056**	6.5%
Site09	RS1,LW10,SW2,SP1,HC0,RI0,TL1,AL0	$1,365,302	$336,000	**$1,701,302**	$1,071,895	$81,348	**$1,153,243**	7.8%
Site10	RS1,LW11,SW6,SP1,HC1,RI0,TL1,AL0	$1,488,369	$1,052,781	**$2,541,150**	$2,329,256	$80,186	**$2,409,442**	15.7%
Grand Total		*$11,789,849*	*$4,481,397*	*$16,271,247*	*$9,831,263*	*$809,651*	*$10,640,914*	

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Figure 35. Summary report of optimization results.

Site	Selected Improvement		County	Route	Site Length	Site Description
Site01	RS1,LW9,SW2,SP0,HC0,RI0,TL0,AL0		Jefferson	435	5.2	Application Example - Horizontal Curve,
	Proposed Site Improvements	*Resurface site*			*Do not improve horizontal curves*	
		Lane width unchanged			*Do not improve roadside*	
		Shoulder width unchanged			*Do not improve turn lanes*	
		Shoulder will remain turf			*No User-Defined Alternatives*	
Site02	RS1,LW10,SW4,SP0,HC0,RI0,TL1,AL0		Jefferson		4.6	HC alternative is considered
	Proposed Site Improvements	*Resurface site*			*Do not improve horizontal curves*	
		Lane width unchanged			*Do not improve roadside*	
		Shoulder width unchanged			*Implement turn lane improvement(s)*	
		Shoulder will remain composite			*No User-Defined Alternatives*	
Site03	RS1,LW11,SW4,SP1,HC0,RI1,TL1,AL2		Jefferson		5.7	HC, Roadside improvement, and User-de
	Proposed Site Improvements	*Resurface site*			*Do not improve horizontal curves*	
		Lane width unchanged			*Implement roadside improvement(s)*	
		Shoulder width unchanged			*Implement turn lane improvement(s)*	
		Retain paved shoulders			*Implement User-Defined Alternative(s): 2*	
Site04	RS1,LW11,SW6,SP0,HC0,RI0,TL0,AL0		Jefferson		2.5	Roadside improvement considered
	Proposed Site Improvements	*Resurface site*			*Do not improve horizontal curves*	
		Widen lane from 10 to 11 ft.			*Do not improve roadside*	
		Widen shoulders from 4 to 6 ft.			*Do not improve turn lanes*	
		Shoulder will remain gravel			*No User-Defined Alternatives*	

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Figure 36. Detailed site improvement report.

	Proposed Site Improvements	*Resurface site*			*Do not improve horizontal curves*
		Lane width unchanged			*Do not improve roadside*
		Shoulder width unchanged			*Implement turn lane improvement(s)*
		Retain paved shoulders			*No User-Defined Alternatives*
Site06	RS1,LW11,SW6,SP1,HC0,RI0,TL1,AL0		Jefferson	5.6	
	Proposed Site Improvements	*Resurface site*			*Do not improve horizontal curves*
		Lane width unchanged			*Do not improve roadside*
		Shoulder width unchanged			*Implement turn lane improvement(s)*
		Retain paved shoulders			*No User-Defined Alternatives*
Site07	RS1,LW11,SW4,SP1,HC0,RI0,TL1,AL0		Jefferson	5.6	
	Proposed Site Improvements	*Resurface site*			*Do not improve horizontal curves*
		Lane width unchanged			*Do not improve roadside*
		Shoulder width unchanged			*Implement turn lane improvement(s)*
		Retain paved shoulders			*No User-Defined Alternatives*
Site08	RS1,LW12,SW8,SP1,HC0,RI0,TL1,AL2		Jefferson	4.5	User-difined alternative is considered
	Proposed Site Improvements	*Resurface site*			*Do not improve horizontal curves*
		Lane width unchanged			*Do not improve roadside*
		Shoulder width unchanged			*Implement turn lane improvement(s)*
		Retain paved shoulders			*Implement User-Defined Alternative(s): 2*

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Figure 36. (Continued)

Site	Selected Improvement		County	Route	Site Length	Site Description
Site09	RS1,LW10,SW2,SP1,HC0,RI0,TL1,AL0		Jefferson		3.5	
	Proposed Site Improvements	*Resurface site*			*Do not improve horizontal curves*	
		Lane width unchanged			*Do not improve roadside*	
		Shoulder width unchanged			*Implement turn lane improvement(s)*	
		Retain paved shoulders			*No User-Defined Alternatives*	
Site10	RS1,LW11,SW6,SP1,HC1,RI0,TL1,AL0		Jefferson		2.3	HC, Roadside improvement, and User-de
	Proposed Site Improvements	*Resurface site*			*Implement horizontal curve improvement(s)*	
		Lane width unchanged			*Do not improve roadside*	
		Widen shoulders from 4 to 6 ft.			*Implement turn lane improvement(s)*	
		Retain paved shoulders			*No User-Defined Alternatives*	

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Figure 36. (Continued)

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GLOSSARY OF ACRONYMS

AADT: annual average daily traffic
ADA: Americans with Disabilities Act
ADT: average daily traffic
AMF: accident modification factor
$CC_{TurnLane}$: the construction cost of adding a left- or right-turn lane
EB: Empirical Bayes
HCM: *Highway Capacity Manual*
HIAP: Highway Investment Analysis Process
IMRA: interactive multiobjective resource allocation
ISTEA: Intermodal Surface Transportation Efficiency Act of 1991
MCCBA: multicriteria cost-benefit analysis
NHS: National Highway System
PDO: property-damage-only accident
PIAP: Performance Investment Analysis Process
R&P: reconditioning and preservation
RHR: roadside hazard rating
RSRAP: Resurfacing Safety Resource Allocation Program
STAA: Surface Transportation Assistance Act of 1982
STP: Surface Transportation Program
TEA-21: Transportation Equity Act for the 21st Century
VBA: Visual Basic for Applications
3R: resurfacing, restoration, and rehabilitation
4R: resurfacing, restoration, rehabilitation, and reconstruction

APPENDIXES A THROUGH C

UNPUBLISHED MATERIAL

Appendixes A through C as submitted by the research agency are not published herein. For a limited time, they are available for loan on request to NCHRP. Their titles are as follows:

Appendix A: Questionnaire Used for State Highway Agency Survey on 3R Policies and Practices
Appendix B: Summary of State Highway Agency Geometric Criteria for 3R Projects
Appendix C: Vehicle Speeds Before and After Resurfacing

APPENDIX D

INPUT AND OUTPUT REPORTS FROM RSRAP SOFTWARE FOR APPLICATION EXAMPLE

This appendix presents input and output reports from the Resurfacing Safety Resource Allocation Program (RSRAP) software for the application example presented in Chapter 6 of this report. There are three parts of this appendix:

- Summary and detailed input reports,
- Output reports for $50,000,000 budget level, and
- Output reports for $10,000,000 budget level.

SUMMARY AND DETAILED INPUT REPORTS

Summary and detailed reports for the application example presented in Chapter 6 of this report are shown in Figures D-1 and D-2.

OUTPUT REPORTS FOR $50,000,000 BUDGET LEVEL

Output reports for a $50,000,000 budget level are shown in Figures D-3 and D-4.

OUTPUT REPORTS FOR $10,000,000 BUDGET LEVEL

Output reports for a $10,000,000 budget level are shown in Figures D-5 and D-6.

Site Input Report

Site	Area Type	Roadway Type	No. of Lanes	ADT (veh/day)	Avg. Speed	Length (mi)	Lane Width (ft)	Shld. Width (ft)	Shld. Type	Accidents Non-Int.	Accidents Intersect.
Site01	Rural	Undivided	2	1,000	35	5.2	9	2	Turf	5.0	3.0
Site02	Rural	Undivided	2	3,000	40	4.6	10	4	Composite	4.0	4.0
Site03	Rural	Undivided	2	4,000	45	5.7	11	4	Paved	11.0	11.0
Site04	Urban	Divided	2	7,000	50	2.5	10	4	Gravel	15.0	3.0
Site05	Rural	Undivided	4	4,000	55	4.8	10	4	Paved	10.0	10.0
Site06	Urban	Undivided	4	6,000	55	5.6	11	6	Paved	14.0	14.0
Site07	Rural	Divided	4	5,000	50	5.6	11	4	Paved	13.0	13.0
Site08	Rural	Divided	4	10,000	50	4.5	12	8	Paved	15.0	15.0
Site09	Urban	Undivided	4	10,000	60	3.5	10	2	Paved	12.0	12.0
Site10	Urban	Divided	6	15,000	60	2.3	11	4	Paved	14.0	14.0

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Figure D-1. Summary site input report for the application example.

Detailed Site Input Report

Site	County	Route	Site Description
Site01	Jefferson	435	Application Example - Horizontal Curve, Roadside, Intersection and User-defined improvements (Sites 2(HC), 3(all), 8(UD) and

Area Type	Roadway Type	No. of Lanes	ADT (veh/day)	Avg. Speed	Length (mi)	Lane Width (ft)	Shld. Width (ft)	Shld. Type	Accidents Non-Int.	Accidents Intersect.	Yrs. to failure
Rural	Undivided	2	1,000	35	5	9	2	Turf	5.0	3.0	5

☑ *Consider Lane Widening* ☐ *Consider Roadside Improvements*

☑ *Consider Shoulder Widening* ☐ *Consider Horizontal Curve Improvements*

☑ *Consider Shoulder Paving* ☑ *Consider Turn Lane Improvements*

☐ *Consider User-Defined Alternatives*

Intersections -- Accident History Unknown

Intersection Name	Minor Road ADT	No. of Legs	Traffic Control	Before LTLs	Before RTLs	After LTLs	After RTLs
Intersection 1	Low	3	STOP	0	0	1	1
Intersection 2	Medium	4	Signal	1	0	2	1
Intersection 3	Low	4	Signal	1	1	1	1
Intersection 4	Low	3	Signal	1	0	1	0
Intersection 5	Very Low	4	STOP	0	0	0	0

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Figure D-2. Detailed site input report for the application example.

Site	*County*	*Route*	*Site Description*
Site02	Jefferson		HC alternative is considered

Area Type	*Roadway Type*	*No. of Lanes*	*ADT (veh/day)*	*Avg. Speed*	*Length (mi)*	*Lane Width (ft)*	*Shld. Width (ft)*	*Shld. Type*	*Accidents Non-Int.*	*Accidents Intersect.*	*Yrs. to failure*
Rural	Undivided	2	3,000	40	5	10	4	Composite	4.0	4.0	5

- ☑ *Consider Lane Widening*
- ☑ *Consider Shoulder Widening*
- ☑ *Consider Shoulder Paving*
- ☐ *Consider Roadside Improvements*
- ☑ *Consider Horizontal Curve Improvements*
- ☑ *Consider Turn Lane Improvements*
- ☐ *Consider User-Defined Alternatives*

Horizontal Curves -- Accident History Unknown

	Before Improvement			*After Improvement*			
Curve Name	*Length*	*Radius*	*Spiral Trans.*	*Length*	*Radius*	*Spiral Trans.*	*Horizontal Curve Cost*
HC1	0.4	2,000	☐	0.5	2,500	☑	$800,000
HC2	0.5	3,000	☑	0.5	3,000	☑	
HC3	0.3	1,500	☐	0.5	2,500	☐	

Intersections -- Accident History Unknown

Intersection Name	*Minor Road ADT*	*No. of Legs*	*Traffic Control*	*Before LTLs*	*Before RTLs*	*After LTLs*	*After RTLs*
Intersection 1	High	4	Signal	1	2	2	2
Intersection 2	Very Low	4	STOP	0	0	0	0
Intersection 3	Medium	3	Signal	0	0	1	0
Intersection 4	Low	3	STOP	1	1	1	1

Figure D-2. (Continued)

Site	County	Route	Site Description
Site03	Jefferson		HC, Roadside improvement, and User-defined alternatives are considered

Area Type	Roadway Type	No. of Lanes	ADT (veh/day)	Avg. Speed	Length (mi)	Lane Width (ft)	Shld. Width (ft)	Shld. Type	Accidents Non-Int.	Accidents Intersect.	Yrs. to failure
Rural	Undivided	2	4,000	45	6	11	4	Paved	11.0	11.0	5

☑ *Consider Lane Widening* ☑ *Consider Roadside Improvements*

☑ *Consider Shoulder Widening* ☑ *Consider Horizontal Curve Improvements*

☑ *Consider Shoulder Paving* ☑ *Consider Turn Lane Improvements*

☑ *Consider User-Defined Alternatives*

Roadside Hazards

Improvement Rating	1	1.5	2	2.5	3	3.5	4	5	5.5	6	7	Cost
Before Improvement Rating	0	0	0	0	0	0	40	40	0	20	0	$200,000
After Improvement Rating	0	0	0	40	0	0	40	20	0	0	0	

Horizontal Curves -- Accident History Unknown

	Before Improvement			After Improvement			Horizontal Curve Cost
Curve Name	Length	Radius	Spiral Trans.	Length	Radius	Spiral Trans.	
HC1	1.0	5,500	☐	1.0	5,500	☐	$500,000
HC2	0.4	1,500	☑	0.8	3,500	☑	
HC3	0.7	2,100	☐	0.7	2,100	☐	
HC4	0.3	2,200	☐	0.3	2,200	☐	

Intersections -- Accident History Unknown

Intersection Name	Minor Road ADT	No. of Legs	Traffic Control	Before LTLs	Before RTLs	After LTLs	After RTLs
Intersection 1	High	4	Signal	2	2	2	2
Intersection 2	High	3	Signal	1	1	1	1
Intersection 3	Medium	4	Signal	1	0	2	0
Intersection 5	Low	3	STOP	1	0	1	0
Intersection 6	Very Low	4	STOP	0	0	0	0

User-Defined Alternatives

Alternative Name	Percent of Intersection Accidents Reduced	Percent of Non-Intersection Accidents Reduced	Cost
Userdefined1	0	10	$500,000
Userdefined2	5	0	$300,000

Figure D-2. (Continued)

Site	***County***	***Route***	***Site Description***
Site04	Jefferson		Roadside improvement considered

Area Type	***Roadway Type***	***No. of Lanes***	***ADT (veh/day)***	***Avg. Speed***	***Length (mi)***	***Lane Width (ft)***	***Shld. Width (ft)***	***Shld. Type***	***Accidents Non-Int.***	***Accidents Intersect.***	***Yrs. to failure***
Urban	Divided	2	7,000	50	3	10	4	Gravel	15.0	3.0	5

☑ ***Consider Lane Widening***

☑ ***Consider Shoulder Widening***

☑ ***Consider Shoulder Paving***

☑ ***Consider Roadside Improvements***

☐ ***Consider Horizontal Curve Improvements***

☑ ***Consider Turn Lane Improvements***

☐ ***Consider User-Defined Alternatives***

Roadside Hazards

Improvement Rating	***1***	***1.5***	***2***	***2.5***	***3***	***3.5***	***4***	***5***	***5.5***	***6***	***7***	***Cost***
Before Improvement Rating	0	0	0	0	0	40	0	30	30	0	0	$400,000
After Improvement Rating	0	0	0	0	0	70	0	30	0	0	0	

Intersections -- Accident History Unknown

Intersection Name	***Minor Road ADT***	***No. of Legs***	***Traffic Control***	***Before LTLs***	***Before RTLs***	***After LTLs***	***After RTLs***
Intersection 1	High	4	Signal	0	0	2	2
Intersection 2	Medium	4	STOP	0	0	0	0
Intersection 3	Very High	4	Signal	1	1	2	2
Intersection 4	High	3	Signal	1	1	1	1

Figure D-2. (Continued)

Site	*County*	*Route*	*Site Description*
Site05	Jefferson		

Area Type	*Roadway Type*	*No. of Lanes*	*ADT (veh/day)*	*Avg. Speed*	*Length (mi)*	*Lane Width (ft)*	*Shld. Width (ft)*	*Shld. Type*	*Accidents Non-Int.*	*Accidents Intersect.*	*Yrs. to failure*
Rural	Undivided	4	4,000	55	5	10	4	Paved	10.0	10.0	5

- ☑ *Consider Lane Widening*
- ☑ *Consider Shoulder Widening*
- ☑ *Consider Shoulder Paving*
- ☐ *Consider Roadside Improvements*
- ☐ *Consider Horizontal Curve Improvements*
- ☑ *Consider Turn Lane Improvements*
- ☐ *Consider User-Defined Alternatives*

Intersections -- Accident History Unknown

Intersection Name	*Minor Road ADT*	*No. of Legs*	*Traffic Control*	*Before LTLs*	*Before RTLs*	*After LTLs*	*After RTLs*
Intersection 1	Medium	3	Signal	1	1	1	1
Intersection 2	Low	4	STOP	0	0	2	0
Intersection 3	Low	3	STOP	0	1	0	1
Intersection 4	Medium	4	Signal	0	0	2	0
Intersection 5	Medium	3	STOP	1	0	1	0
Intersection 6	Very Low	4	STOP	2	0	2	0

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Figure D-2. (Continued)

Site	*County*	*Route*	*Site Description*
Site06	Jefferson		

Area Type	*Roadway Type*	*No. of Lanes*	*ADT (veh/day)*	*Avg. Speed*	*Length (mi)*	*Lane Width (ft)*	*Shld. Width (ft)*	*Shld. Type*	*Accidents Non-Int.*	*Accidents Intersect.*	*Yrs. to failure*
Urban	Undivided	4	6,000	55	6	11	6	Paved	14.0	14.0	5

☑ *Consider Lane Widening*

☑ *Consider Shoulder Widening*

☑ *Consider Shoulder Paving*

☐ *Consider Roadside Improvements*

☐ *Consider Horizontal Curve Improvements*

☑ *Consider Turn Lane Improvements*

☐ *Consider User-Defined Alternatives*

Intersections -- Accident History Unknown

Intersection Name	*Minor Road ADT*	*No. of Legs*	*Traffic Control*	*Before LTLs*	*Before RTLs*	*After LTLs*	*After RTLs*
Intersection 1	Medium	4	Signal	0	0	0	0
Intersection 2	Low	3	Signal	1	0	1	0
Intersection 3	Medium	4	STOP	1	1	2	2
Intersection 4	Medium	4	Signal	1	1	2	2
Intersection 5	Low	3	STOP	0	0	0	0
Intersection 6	High	4	Signal	2	1	2	2
Intersection 7	Medium	3	Signal	1	1	1	1

Figure D-2. (Continued)

Site	*County*	*Route*	*Site Description*
Site07	Jefferson		

Area Type	*Roadway Type*	*No. of Lanes*	*ADT (veh/day)*	*Avg. Speed*	*Length (mi)*	*Lane Width (ft)*	*Shld. Width (ft)*	*Shld. Type*	*Accidents Non-Int.*	*Accidents Intersect.*	*Yrs. to failure*
Rural	Divided	4	5,000	50	6	11	4	Paved	13.0	13.0	5

☑ *Consider Lane Widening*

☑ *Consider Shoulder Widening*

☑ *Consider Shoulder Paving*

☐ *Consider Roadside Improvements*

☐ *Consider Horizontal Curve Improvements*

☑ *Consider Turn Lane Improvements*

☐ *Consider User-Defined Alternatives*

Intersections -- Accident History Unknown

Intersection Name	*Minor Road ADT*	*No. of Legs*	*Traffic Control*	*Before LTLs*	*Before RTLs*	*After LTLs*	*After RTLs*
Intersection 1	Low	3	STOP	0	1	0	1
Intersection 2	Medium	4	STOP	1	0	2	2
Intersection 3	Medium	4	Signal	0	0	0	0
Intersection 4	High	3	Signal	1	1	1	1
Intersection 5	High	4	Signal	2	2	2	2
Intersection 6	High	4	Signal	2	1	2	2
Intersection 7	Low	4	STOP	0	0	0	0
Intersection 8	Very Low	3	STOP	0	0	0	0
Intersection 9	Medium	4	Signal	0	0	2	0

Figure D-2. (Continued)

Site	*County*	*Route*	*Site Description*
Site08	Jefferson		User-difined alternative is considered

Area Type	*Roadway Type*	*No. of Lanes*	*ADT (veh/day)*	*Avg. Speed*	*Length (mi)*	*Lane Width (ft)*	*Shld. Width (ft)*	*Shld. Type*	*Accidents Non-Int.*	*Accidents Intersect.*	*Yrs. to failure*
Rural	Divided	4	10,000	50	5	12	8	Paved	15.0	15.0	5

☑ *Consider Lane Widening*
☐ *Consider Roadside Improvements*
☑ *Consider Shoulder Widening*
☐ *Consider Horizontal Curve Improvements*
☑ *Consider Shoulder Paving*
☑ *Consider Turn Lane Improvements*
☑ *Consider User-Defined Alternatives*

Intersections -- Accident History Unknown

Intersection Name	*Minor Road ADT*	*No. of Legs*	*Traffic Control*	*Before LTLs*	*Before RTLs*	*After LTLs*	*After RTLs*
Intersection 1	Very High	4	Signal	2	2	2	2
Intersection 2	High	3	Signal	1	0	1	1
Intersection 3	Very High	3	Signal	0	0	1	1

User-Defined Alternatives

Alternative Name	*Percent of Intersection Accidents Reduced*	*Percent of Non-Intersection Accidents Reduced*	*Cost*
UD1	0	10	$1,200,000
UD2	7	0	$500,000

Figure D-2. (Continued)

Site	*County*	*Route*	*Site Description*
Site09	Jefferson		

Area Type	*Roadway Type*	*No. of Lanes*	*ADT (veh/day)*	*Avg. Speed*	*Length (mi)*	*Lane Width (ft)*	*Shld. Width (ft)*	*Shld. Type*	*Accidents Non-Int.*	*Accidents Intersect.*	*Yrs. to failure*
Urban	Undivided	4	10,000	60	4	10	2	Paved	12.0	12.0	5

☑ *Consider Lane Widening*
☐ *Consider Roadside Improvements*
☑ *Consider Shoulder Widening*
☐ *Consider Horizontal Curve Improvements*
☑ *Consider Shoulder Paving*
☑ *Consider Turn Lane Improvements*
☐ *Consider User-Defined Alternatives*

Intersections -- Accident History Unknown

Intersection Name	*Minor Road ADT*	*No. of Legs*	*Traffic Control*	*Before LTLs*	*Before RTLs*	*After LTLs*	*After RTLs*
Intersection 1	Very High	4	Signal	1	1	2	1
Intersection 2	High	3	Signal	1	1	1	1
Intersection 3	High	4	Signal	0	0	2	0
Intersection 4	Medium	3	Signal	0	0	0	0
Intersection 5	Medium	4	STOP	2	1	2	1
Intersection 6	Low	4	STOP	0	0	0	0

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Figure D-2. (Continued)

Site	*County*	*Route*	*Site Description*
Site10	Jefferson		HC, Roadside improvement, and User-defined alternatives are considered

Area Type	*Roadway Type*	*No. of Lanes*	*ADT (veh/day)*	*Avg. Speed*	*Length (mi)*	*Lane Width (ft)*	*Shld. Width (ft)*	*Shld. Type*	*Accidents Non-Int.*	*Accidents Intersect.*	*Yrs. to failure*
Urban	Divided	6	15,000	60	2	11	4	Paved	14.0	14.0	5

☑ *Consider Lane Widening*
☑ *Consider Shoulder Widening*
☑ *Consider Shoulder Paving*
☑ *Consider Roadside Improvements*
☑ *Consider Horizontal Curve Improvements*
☑ *Consider Turn Lane Improvements*
☑ *Consider User-Defined Alternatives*

Roadside Hazards

Improvement Rating	*1*	*1.5*	*2*	*2.5*	*3*	*3.5*	*4*	*5*	*5.5*	*6*	*7*	*Cost*
Before Improvement Rating	0	0	0	0	0	0	50	0	0	50	0	$350,000
After Improvement Rating	0	0	0	0	0	0	100	0	0	0	0	

Horizontal Curves -- Accident History Unknown

Curve Name	*Before Improvement Length*	*Radius*	*Spiral Trans.*	*After Improvement Length*	*Radius*	*Spiral Trans.*	*Horizontal Curve Cost*
HC1	0.3	1,300	☐	0.5	2,200	☐	$1,000,000
HC2	0.4	1,500	☐	0.4	1,500	☐	
HC3	0.3	1,500	☐	0.5	5,000	☐	

Intersections -- Accident History Unknown

Intersection Name	*Minor Road ADT*	*No. of Legs*	*Traffic Control*	*Before LTLs*	*Before RTLs*	*After LTLs*	*After RTLs*
Intersection 1	Very High	4	Signal	2	1	2	2
Intersection 2	Very High	4	STOP	1	1	2	2
Intersection 3	Medium	3	STOP	1	1	1	1
Intersection 4	Low	3	STOP	0	0	0	0
Intersection 5	High	4	Signal	1	1	2	1

User-Defined Alternatives

Alternative Name	*Percent of Intersection Accidents Reduced*	*Percent of Non-Intersection Accidents Reduced*	*Cost*
UD1	0	6	$400,000
UD2	7	0	$600,000

Figure D-2. (Continued)

Optimization Results for: Both Resurfacing and Safety Improvements with Both Safety and Speed Benefits Considered

Budget: $50,000,000.00

Site	Strategy Selected	Resurfacing Costs	Safety Improvement Costs	Total Costs	Safety Benefits	Traffic Operations Benefits	Total Benefits	% Acc Red
Site01	RS1,LW9,SW2,SP0,HC0,RI0,TL0,AL0	$528,803	$0	**$528,803**	$0	$35,107	**$35,107**	0.0%
Site02	RS1,LW10,SW4,SP0,HC0,RI0,TL1,AL0	$519,763	$120,000	**$639,763**	$328,176	$71,580	**$399,756**	7.1%
Site03	RS1,LW11,SW4,SP1,HC0,RI1,TL1,AL2	$821,621	$560,000	**$1,381,621**	$1,094,909	$93,697	**$1,188,606**	9.3%
Site04	RS1,LW11,SW6,SP0,HC0,RI0,TL0,AL0	$475,200	$572,616	**$1,047,816**	$775,629	$58,379	**$834,008**	9.2%
Site05	RS1,LW10,SW4,SP1,HC0,RI0,TL1,AL0	$1,180,017	$240,000	**$1,420,017**	$1,355,589	$53,029	**$1,408,618**	11.8%
Site06	RS1,LW11,SW6,SP1,HC0,RI0,TL1,AL0	$2,508,549	$560,000	**$3,068,549**	$808,637	$92,800	**$901,437**	5.0%
Site07	RS1,LW11,SW4,SP1,HC0,RI0,TL1,AL0	$1,503,237	$360,000	**$1,863,237**	$947,234	$93,407	**$1,040,641**	6.3%
Site08	RS1,LW12,SW8,SP1,HC0,RI0,TL1,AL2	$1,398,989	$680,000	**$2,078,989**	$1,119,938	$150,118	**$1,270,056**	6.5%
Site09	RS1,LW10,SW2,SP1,HC0,RI0,TL1,AL0	$1,365,302	$336,000	**$1,701,302**	$1,071,895	$81,348	**$1,153,243**	7.8%
Site10	RS1,LW11,SW6,SP1,HC1,RI0,TL1,AL0	$1,488,369	$1,052,781	**$2,541,150**	$2,329,256	$80,186	**$2,409,442**	15.7%
Grand Total		*$11,789,849*	*$4,481,397*	*$16,271,247*	*$9,831,263*	*$809,651*	*$10,640,914*	

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Figure D-3. Summary output report for the application example with a $50,000,000 budget.

Detailed Site Improvement Report

Site	Selected Improvement		County	Route	Site Length	Site Description
Site01	RS1,LW9,SW2,SP0,HC0,RI0,TL0,AL0		Jefferson	435	5.2	Application Example - Horizontal Curve,
	Proposed Site Improvements	*Resurface site*			*Do not improve horizontal curves*	
		Lane width unchanged			*Do not improve roadside*	
		Shoulder width unchanged			*Do not improve turn lanes*	
		Shoulder will remain turf			*No User-Defined Alternatives*	
Site02	RS1,LW10,SW4,SP0,HC0,RI0,TL1,AL0		Jefferson		4.6	HC alternative is considered
	Proposed Site Improvements	*Resurface site*			*Do not improve horizontal curves*	
		Lane width unchanged			*Do not improve roadside*	
		Shoulder width unchanged			*Implement turn lane improvement(s)*	
		Shoulder will remain composite			*No User-Defined Alternatives*	
Site03	RS1,LW11,SW4,SP1,HC0,RI1,TL1,AL2		Jefferson		5.7	HC, Roadside improvement, and User-de
	Proposed Site Improvements	*Resurface site*			*Do not improve horizontal curves*	
		Lane width unchanged			*Implement roadside improvement(s)*	
		Shoulder width unchanged			*Implement turn lane improvement(s)*	
		Retain paved shoulders			*Implement User-Defined Alternative(s): 2*	
Site04	RS1,LW11,SW6,SP0,HC0,RI0,TL0,AL0		Jefferson		2.5	Roadside improvement considered
	Proposed Site Improvements	*Resurface site*			*Do not improve horizontal curves*	
		Widen lane from 10 to 11 ft.			*Do not improve roadside*	
		Widen shoulders from 4 to 6 ft.			*Do not improve turn lanes*	
		Shoulder will remain gravel			*No User-Defined Alternatives*	

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Figure D-4. Detailed output report for the application example with a $50,000,000 budget.

Site	Selected Improvement		County	Route	Site Length	Site Description
Site05	RS1,LW10,SW4,SP1,HC0,RI0,TL1,AL0		Jefferson		4.8	
	Proposed Site Improvements	*Resurface site*			*Do not improve horizontal curves*	
		Lane width unchanged			*Do not improve roadside*	
		Shoulder width unchanged			*Implement turn lane improvement(s)*	
		Retain paved shoulders			*No User-Defined Alternatives*	
Site06	RS1,LW11,SW6,SP1,HC0,RI0,TL1,AL0		Jefferson		5.6	
	Proposed Site Improvements	*Resurface site*			*Do not improve horizontal curves*	
		Lane width unchanged			*Do not improve roadside*	
		Shoulder width unchanged			*Implement turn lane improvement(s)*	
		Retain paved shoulders			*No User-Defined Alternatives*	
Site07	RS1,LW11,SW4,SP1,HC0,RI0,TL1,AL0		Jefferson		5.6	
	Proposed Site Improvements	*Resurface site*			*Do not improve horizontal curves*	
		Lane width unchanged			*Do not improve roadside*	
		Shoulder width unchanged			*Implement turn lane improvement(s)*	
		Retain paved shoulders			*No User-Defined Alternatives*	
Site08	RS1,LW12,SW8,SP1,HC0,RI0,TL1,AL2		Jefferson		4.5	User-difined alternative is considered
	Proposed Site Improvements	*Resurface site*			*Do not improve horizontal curves*	
		Lane width unchanged			*Do not improve roadside*	
		Shoulder width unchanged			*Implement turn lane improvement(s)*	
		Retain paved shoulders			*Implement User-Defined Alternative(s): 2*	

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Figure D-4. (Continued)

Site	Selected Improvement		County	Route	Site Length	Site Description
Site09	RS1,LW10,SW2,SP1,HC0,RI0,TL1,AL0		Jefferson		3.5	
	Proposed Site Improvements	*Resurface site*			*Do not improve horizontal curves*	
		Lane width unchanged			*Do not improve roadside*	
		Shoulder width unchanged			*Implement turn lane improvement(s)*	
		Retain paved shoulders			*No User-Defined Alternatives*	
Site10	RS1,LW11,SW6,SP1,HC1,RI0,TL1,AL0		Jefferson		2.3	HC, Roadside improvement, and User-de
	Proposed Site Improvements	*Resurface site*			*Implement horizontal curve improvement(s)*	
		Lane width unchanged			*Do not improve roadside*	
		Widen shoulders from 4 to 6 ft.			*Implement turn lane improvement(s)*	
		Retain paved shoulders			*No User-Defined Alternatives*	

Figure D-4. (Continued)

Optimization Results for: Both Resurfacing and Safety Improvements with Both Safety and Speed Benefits Considered

Budget:
$10,000,000.00

Site	Strategy Selected	Resurfacing Costs	Safety Improvement Costs	Total Costs	Safety Benefits	Traffic Operations Benefits	Total Benefits	% Acc Red
Site01	RS1,LW9,SW2,SP0,HC0,RI0,TL0,AL0	$528,803	$0	**$528,803**	$0	$35,107	**$35,107**	0.0%
Site02	RS1,LW10,SW4,SP0,HC0,RI0,TL1,AL0	$519,763	$120,000	**$639,763**	$328,176	$71,580	**$399,756**	7.1%
Site03	RS1,LW11,SW4,SP1,HC0,RI1,TL1,AL2	$821,621	$560,000	**$1,381,621**	$1,094,909	$93,697	**$1,188,606**	9.3%
Site04	RS0,LW10,SW4,SP0,HC0,RI0,TL0,AL0	$0	$0	**$0**	$0	$0	**$0**	0.0%
Site05	RS1,LW10,SW4,SP1,HC0,RI0,TL1,AL0	$1,180,017	$240,000	**$1,420,017**	$1,355,589	$53,029	**$1,408,618**	11.8%
Site06	RS0,LW11,SW6,SP1,HC0,RI0,TL0,AL0	$0	$0	**$0**	$0	$0	**$0**	0.0%
Site07	RS1,LW11,SW4,SP1,HC0,RI0,TL1,AL0	$1,503,237	$360,000	**$1,863,237**	$947,234	$93,407	**$1,040,641**	6.3%
Site08	RS1,LW12,SW8,SP1,HC0,RI0,TL1,AL0	$1,398,989	$180,000	**$1,578,989**	$555,526	$150,118	**$705,644**	3.2%
Site09	RS0,LW10,SW2,SP1,HC0,RI0,TL0,AL0	$0	$0	**$0**	$0	$0	**$0**	0.0%
Site10	RS1,LW11,SW6,SP1,HC1,RI0,TL1,AL0	$1,488,369	$1,052,781	**$2,541,150**	$2,329,256	$80,186	**$2,409,442**	15.7%
Grand Total		*$7,440,798*	*$2,512,781*	*$9,953,579*	*$6,610,690*	*$577,124*	*$7,187,814*	

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Figure D-5. Summary output report for the application example with a $10,000,000 budget.

Detailed Site Improvement Report

Site	Selected Improvement		County	Route	Site Length	Site Description
Site01	RS1,LW9,SW2,SP0,HC0,RI0,TL0,AL0		Jefferson	435	5.2	Application Example - Horizontal Curve,
	Proposed Site Improvements	*Resurface site*			*Do not improve horizontal curves*	
		Lane width unchanged			*Do not improve roadside*	
		Shoulder width unchanged			*Do not improve turn lanes*	
		Shoulder will remain turf			*No User-Defined Alternatives*	
Site02	RS1,LW10,SW4,SP0,HC0,RI0,TL1,AL0		Jefferson		4.6	HC alternative is considered
	Proposed Site Improvements	*Resurface site*			*Do not improve horizontal curves*	
		Lane width unchanged			*Do not improve roadside*	
		Shoulder width unchanged			*Implement turn lane improvement(s)*	
		Shoulder will remain composite			*No User-Defined Alternatives*	
Site03	RS1,LW11,SW4,SP1,HC0,RI1,TL1,AL2		Jefferson		5.7	HC, Roadside improvement, and User-de
	Proposed Site Improvements	*Resurface site*			*Do not improve horizontal curves*	
		Lane width unchanged			*Implement roadside improvement(s)*	
		Shoulder width unchanged			*Implement turn lane improvement(s)*	
		Retain paved shoulders			*Implement User-Defined Alternative(s): 2*	
Site04	RS0,LW10,SW4,SP0,HC0,RI0,TL0,AL0		Jefferson		2.5	Roadside improvement considered
	Proposed Site Improvements	*No improvements to site*			*Do not improve horizontal curves*	
		Lane width unchanged			*Do not improve roadside*	
		Shoulder width unchanged			*Do not improve turn lanes*	
		Shoulder will remain gravel			*No User-Defined Alternatives*	

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Figure D-6. Detailed output report for the application example with a $10,000,000 budget.

Site	Selected Improvement		County	Route	Site Length	Site Description
Site05	RS1,LW10,SW4,SP1,HC0,RI0,TL1,AL0		Jefferson		4.8	
	Proposed Site Improvements	*Resurface site*			*Do not improve horizontal curves*	
		Lane width unchanged			*Do not improve roadside*	
		Shoulder width unchanged			*Implement turn lane improvement(s)*	
		Retain paved shoulders			*No User-Defined Alternatives*	
Site06	RS0,LW11,SW6,SP1,HC0,RI0,TL0,AL0		Jefferson		5.6	
	Proposed Site Improvements	*No improvements to site*			*Do not improve horizontal curves*	
		Lane width unchanged			*Do not improve roadside*	
		Shoulder width unchanged			*Do not improve turn lanes*	
		Retain paved shoulders			*No User-Defined Alternatives*	
Site07	RS1,LW11,SW4,SP1,HC0,RI0,TL1,AL0		Jefferson		5.6	
	Proposed Site Improvements	*Resurface site*			*Do not improve horizontal curves*	
		Lane width unchanged			*Do not improve roadside*	
		Shoulder width unchanged			*Implement turn lane improvement(s)*	
		Retain paved shoulders			*No User-Defined Alternatives*	
Site08	RS1,LW12,SW8,SP1,HC0,RI0,TL1,AL0		Jefferson		4.5	User-difined alternative is considered
	Proposed Site Improvements	*Resurface site*			*Do not improve horizontal curves*	
		Lane width unchanged			*Do not improve roadside*	
		Shoulder width unchanged			*Implement turn lane improvement(s)*	
		Retain paved shoulders			*No User-Defined Alternatives*	

Figure D-6. (Continued)

Site	Selected Improvement		County	Route	Site Length	Site Description
Site09	RS0,LW10,SW2,SP1,HC0,RI0,TL0,AL0		Jefferson		3.5	
	Proposed Site Improvements	*No improvements to site*			*Do not improve horizontal curves*	
		Lane width unchanged			*Do not improve roadside*	
		Shoulder width unchanged			*Do not improve turn lanes*	
		Retain paved shoulders			*No User-Defined Alternatives*	
Site10	RS1,LW11,SW6,SP1,HC1,RI0,TL1,AL0		Jefferson		2.3	HC, Roadside improvement, and User-de
	Proposed Site Improvements	*Resurface site*			*Implement horizontal curve improvement(s)*	
		Lane width unchanged			*Do not improve roadside*	
		Widen shoulders from 4 to 6 ft.			*Implement turn lane improvement(s)*	
		Retain paved shoulders			*No User-Defined Alternatives*	

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Figure D-6. (Continued)

APPENDIX E

ALTERNATIVE INSTALLATION

The Resurfacing Safety Resource Allocation Program (RSRAP) may be installed in a location other than a microcomputer station's hard drive (usually called the C drive). However, Visual Basic for Applications (VBA) code within the application must be changed to reflect the alternate location for every file utilized by RSRAP, or the program will not execute properly. The RSRAP database file, RSRAP.mdb, can be moved to any location without modifying code or interrupting the execution of the program. There are three types of files that are used by the RSRAP program that will need to be relocated; consequently, there are three VBA code modules in RSRAP to be modified: clsSolver, clsExportTables, and clsAlternatives.

The first module, clsSolver, contains a file path reference to the Excel spreadsheet that activates Solver. Moving the RSRAP folder, which contains this Excel spreadsheet (xlsolvera.xls), requires the new file path for the spreadsheet to be referenced in the clsSolver module. Similarly, data sets saved by RSRAP are stored in the Old Projects folder within RSRAP, so the clsExportTables module must reflect the new location of this subfolder to successfully save files from RSRAP. Finally, debugging files are generated during the creation of alternatives and are stored in the RSRAP folder, so the clsAlternatives module must be changed to reflect their new location as well. These four text files contain safety benefit and cost calculation records of each alternative, curve, intersection, or user-defined alternative generated for a site. Additionally, there is an Excel workbook in the c:\RSRAP folder called TestFiles. It contains the header row for these generated files.

To access the VBA code within RSRAP to make the necessary changes, hold down the shift key while starting RSRAP. Once the database is open, click the Modules tab, then select (by clicking) the appropriate class module, and open it in design mode (by clicking the design button). An example of the open database is shown Figure E-1.

Once the modules are open, edits are made as they would be in most text files, that is, by finding the text to change and replacing it. The changes to be made so that the correct file path is referenced are listed below.

Modules to modify	File path text to replace
clsSolver	C:\RSRAP\
clsExportTables	C:\RSRAP\OldProjects\
clsAlternatives	C:\RSRAP\

To illustrate one change, suppose the RSRAP folder is moved to a network drive, Drive F, under a folder called Transportation; in this case, lines 39 through 41 of the clsSolver module would change from

```
39 With XL
40      .Visible = False
41      .Workbooks.Open
(“C:\RSRAP\xlsolver2a.XLS”)
```

to become

```
39 With XL
40      .Visible = False
41      .Workbooks.Open
(“F:\Transportation\RSRAP\xlsolver2a.XLS”)
```

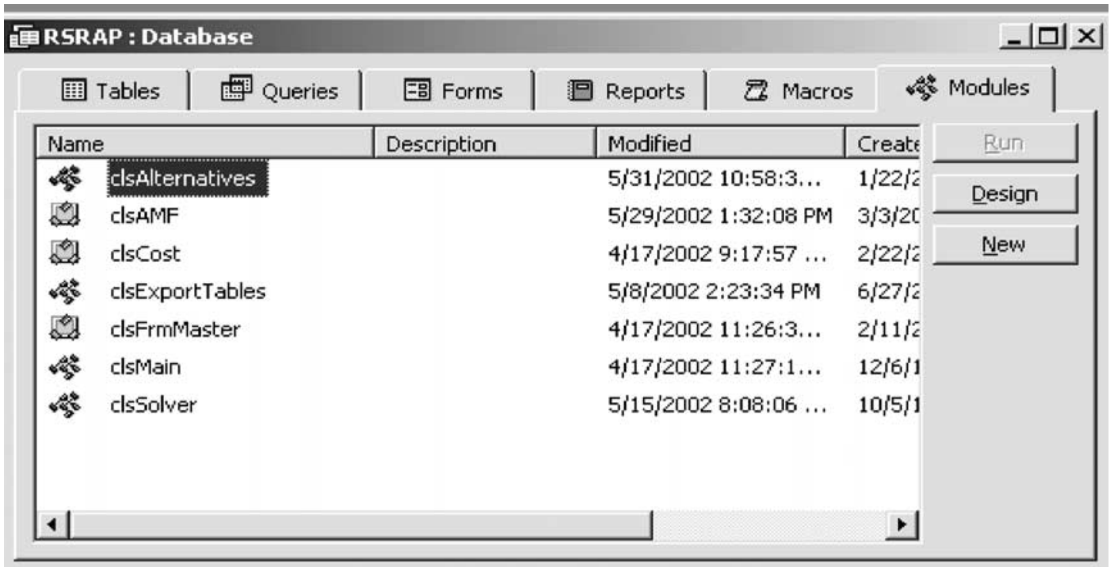

Figure E-1. RSRAP database screen.

APPENDIX F

INSTALLING AND UPGRADING THE SOLVER PROBLEM

The optimization done in the Resurfacing Safety Resource Allocation Program (RSRAP) is performed with an add-in program to Excel called Solver. Solver is not automatically installed in the standard installation of Excel; the user must manually choose it during a custom installation. (Please consult the Excel user's manual for installation of add-ins). If Solver was not installed on a computer, the user will receive an error message "Cannot find xlsolver.dll" during the optimization process.

The version of Solver that is distributed with Excel handles 200 alternatives. This version has been found to be adequate for most RSRAP applications. However, some agencies may find that their problems require a larger version of Solver. Versions of Solver that handle more than 200 alternatives may be purchased from a commercial supplier/vendor.

Once a new Solver program is installed, Excel must choose from the default Solver and the purchased one when performing an optimization problem. Therefore, the macro running Solver in xlsolvera.xls, the spreadsheet created for RSRAP, must be changed to specify a different Solver. To access the code for modification, open the Excel spreadsheet xlsolvera.xls with macros enabled. To access the visual basic editor, click the macro submenu found in the Tools menu in Excel, then select Visual Basic Editor. VBA code for this program may be viewed by double-clicking Sheet1 (Main) in the Project window (upper left corner of screen). The code to be modified is shown below.

```
Private Sub RunSolver_Click()
            ⋮
  SolverOptions _
    MaxTime:=1000, _
    Iterations:=500, _
    AssumeLinear:=True, _
    Scaling:=True
  SolverOK SetCell:=Range("TotalBenefit"), _
      MaxMinVal:=1, _
      ByChange:=Range("Decision") ', Engine:=2,
EngineDesc:="Standard Simplex LP"
```

Remove single apostrophe

The Engine and EngineDesc parameters of the SolverOk function need to be changed and activated to reflect the new Solver. This code is currently commented out and must be activated by removing the apostrophe (') character preceding the parameters. The current values for the Engine and EngineDesc parameters are:

Engine	Solver engine specified
1	Nonlinear GRG Solver
2	Simplex or LP/Quadratic Solver
3	Evolutionary Solver or Large-Scale LP Solver

EngineDesc	Solver engine specified
"Standard GRG Nonlinear"	NonlinearGRGSolver
"Standard Simplex LP"	Simplex LP Solver
"Standard LP/Quadratic"	LP/QuadraticSolver
"Standard Evolutionary"	Evolutionary Solver
"Large-Scale LP Solver"	Large-Scale LP Solver

The values for these function parameters may change as the vendor develops new Solver products. Hopefully, however, the list will be expanded instead of dramatically changed.

The other function, SolverOptions, presented earlier, may also be modified to change Solver Model options. The options that can be changed include maximum time, maximum iterations, and scaling and linear modeling (see Section 8). Information on these options may also be obtained through the vendor.

Abbreviations used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ITE	Institute of Transportation Engineers
NCHRP	National Cooperative Highway Research Program
NCTRP	National Cooperative Transit Research and Development Program
NHTSA	National Highway Traffic Safety Administration
SAE	Society of Automotive Engineers
TCRP	Transit Cooperative Research Program
TRB	Transportation Research Board
U.S.DOT	United States Department of Transportation