Guidelines for Integrating Safety and Cost-Effectiveness into Resurfacing, Restoration, and Rehabilitation (3R) Projects

DETAILS

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Introduction

Resurfacing, restoration, and rehabilitation (3R) projects are typically initiated based on current or anticipated pavement conditions that indicate the need for pavement resurfacing. In designing 3R projects, highway agencies need to decide whether to simply resurface the pavement or whether to utilize the 3R project as an opportunity to implement other desirable improvements, such as geometric design changes, to reduce crash frequency and severity and/or improve traffic operations. The approach to such decisions recommended in these guidelines for application to specific 3R projects considers current roadway and roadside design, current and anticipated future traffic volumes, crash history and anticipated future crash frequency and severity, improvement implementation costs, and other economic, environmental, and community factors that highway agencies consider in the project development process. These guidelines provide a framework for considering these factors in 3R project design decisions, so that funds are invested in geometric design improvements as part of 3R projects primarily where documented crash patterns exist or where, in the absence of a documented crash pattern, the anticipated crash reduction benefits over the service life of the project exceed the improvement implementation costs. The guidelines advise highway agencies to avoid investing funds in geometric design improvements where the improvement implementation costs exceed the anticipated crash reduction benefits, unless there is either a documented crash pattern that can be mitigated by the improvements or a documented traffic operational improvement need.

These guidelines are intended to replace the design guidelines for 3R projects presented in TRB Special Report 214, *Designing Safer Roads: Practices for Resurfacing, Restoration, and Rehabilitation* (*1*). The guidelines presented in this document are based on substantial advances in knowledge about the effects of geometric design features on crash frequency and severity since TRB Special Report 214 was published in 1987. Most specifically, the guidelines implement the safety knowledge presented in the American Association of State Highway and Transportation Officials (AASHTO) *Highway Safety Manual* (HSM) (*2,3*) and other recent safety research.

Scope of Guidelines

The scope of the guidelines is limited to projects involving only resurfacing, restoration, and/or rehabilitation. New construction and reconstruction projects are not addressed by these guidelines.

The guidelines address 3R projects initiated for any reason. Most 3R projects are initiated because of poor pavement condition that indicates a need for pavement resurfacing, but the guidelines can also be applied to projects initiated for other reasons, as long as the project does not involve new construction or reconstruction.

The guidelines address design of 3R projects on rural two-lane highways, rural multilane undivided highways, rural multilane divided nonfreeways, urban and suburban arterials, and rural and urban freeways.

The guidelines are based on the current state of knowledge concerning crash reduction effectiveness and traffic operational improvements that can result from specific design alternatives for 3R projects. The guidelines should be updated in the future as knowledge of these issues advances.

The guidelines are intended for application to 3R projects paid for from any funding source. Thus, the guidelines are not limited just to projects funded as part of the Federal 3R program. The guidelines are also applicable to 3R projects funded from other Federal sources and to projects funded entirely with state or local funds. The guidelines focus on deciding whether any specific project should be resurfaced without accompanying geometric design improvements or whether (and what) geometric design changes should be made as part of the project. The focus of the guidelines is entirely on determining the appropriate geometric design for the roadway after project implementation (either the same as the existing roadway or incorporating cost-effective changes). The guidelines do not address administrative issues such as the appropriate form of design approvals or the need for design exceptions. Such administrative issues are best addressed by the highway agencies involved. The highway community is moving toward more flexible geometric design processes, with reduced need for routine design exceptions, but such administrative issues are outside the scope of these guidelines. In any case, the cost-effectiveness approach utilized in these guidelines should provide the justification needed for design decisions within any administrative framework for design approval procedures that may be in place.

How Does the Design Process for 3R Projects Differ from the Design Process for New Construction and Reconstruction Projects?

The current design process for new construction projects is based primarily on the dimensional design criteria presented in the AASHTO *Green Book* (*4*) and in the design policies of individual highway agencies. It is appropriate to use established dimensional design criteria for new construction projects because, in such projects, there is no existing roadway with a safety and traffic operational performance history that can be used to guide the design process. Established dimensional design criteria provide an aspirational goal for design of reconstruction projects. Where a roadway is being fully reconstructed, design improvements may be feasible with limited additional cost, except where such improvements would substantially impact adjacent development, established communities, or sensitive environments; in these situations, highway agencies typically seek a design exception to minimize such impacts.

3R projects are usually initiated based on the need for pavement resurfacing and are most appropriately considered as maintenance activities. A performance-based design process provides the basis for design of 3R projects focusing on the decision about which projects should be resurfaced without accompanying design improvements and which projects should have design improvements incorporated.

The design process for 3R projects begins with the recognition that the project will be implemented on an existing road whose past safety and traffic operational performance is known and should serve as a key factor in design decisions. Unlike new construction and reconstruction projects, which are designed in accordance with dimensional design criteria presented in the AASHTO *Green Book* (*4*), these guidelines do not establish dimensional design criteria for 3R projects. Rather, 3R design decisions are based on an assessment of the safety and traffic operational performance of the existing road and the cost-effectiveness of potential design improvements. Geometric design improvements should be considered as part of a 3R project in the following situations:

- An analysis of the crash history of the existing road identifies one or more crash patterns that are potentially correctable by a specific design improvement, or
- An analysis of the traffic operational level of service (LOS) indicates that the LOS is currently lower than the highway agency's target LOS for the facility or will become lower than the target LOS within the service life of the planned pavement resurfacing (typically 7 to 12 years), or
- A design improvement would reduce sufficient crashes over its service life to be cost-effective; i.e., the anticipated crash reduction benefits over the service life of the project should exceed the improvement implementation cost.

In the absence of any of the three situations defined above, there is no indication that a design improvement is needed as part of a 3R project, and the existing roadway and roadside geometric features should remain in place. It makes little sense to invest scarce resources in design improvements as part of a 3R project where the existing roadway is performing well and where potential design improvements would not be cost-effective; the funds needed for such a project can be better invested in projects that do have documented performance concerns or where potential design improvements would be cost-effective. In particular, improvement of systemwide safety across the road network is so important that funds invested with the objective of improving safety should be directed toward projects where it can be demonstrated that safety benefits will actually be obtained.

The reliance on cost-effectiveness to guide design decisions for 3R projects has several advantages:

- Highway agencies can have confidence that funds invested in design improvements intended to reduce crashes as part of 3R projects are, in fact, likely to result in reduced crashes.
- Since crash frequency for a road generally increases with increasing traffic volume, the use of cost-effectiveness analysis as a basis for design decisions means that the likelihood of design improvements being included in a 3R project increases with increasing traffic volume. This dependence of design decisions on traffic volume levels is logical and desirable and is not fully reflected in most current dimensional design criteria for new construction and reconstruction.
- A cost-effectiveness approach will focus improvement needs on low-cost improvements with documented safety effectiveness, which are most consistent with the limited scope

of 3R projects. However, the procedures are flexible enough that higher cost improvements can be considered where benefits are sufficient to justify their implementation. If extensive geometric improvements are found to be cost-effective, consideration may be given to reclassifying the project as a reconstruction project.

The guidelines demonstrate that reliance on dimensional design criteria will result in suboptimal results, with some investments made at locations where they are not cost-effective and other investments not made at locations where they would be cost-effective.

Crash Reduction Effectiveness of 3R Improvements

The crash reduction effectiveness of design improvements that are commonly incorporated in 3R projects is documented in these guidelines based on crash modification factors (CMFs) presented in the AASHTO *Highway Safety Manual* (*2,3*) and recent research.

Benefit-Cost Analysis Procedures

The guidelines present a set of benefit-cost analysis procedures that can be applied to alternative geometric design improvements for 3R projects to determine which improvements would be cost-effective and which improvements would not be cost-effective.

Three specific benefit cost-analysis applications have a role in 3R project design decisions. These are:

- benefit-cost analysis for a single design alternative for a specific site
- benefit-cost analysis to choose among several design alternatives for a specific site
- benefit-cost analysis to develop agency-specific minimum AADT guidelines for application in design decisions

Procedures for each of these applications are presented in Section 5.5 of these guidelines.

Benefit-Cost Analysis Tools

Two spreadsheet tools for benefit-cost analysis in support of 3R project design decisions are presented in these guidelines. These include a tool for analysis of a single design alternative or combination of alternatives (Spreadsheet Tool 1) and a tool for comparison of several design alternatives or combinations of alternatives (Spreadsheet Tool 2). The spreadsheet tools apply to rural two-lane highways, rural multilane nonfreeways (including both undivided and divided highways), and rural and urban freeways. The tools do not address urban and suburban arterials because no crash reduction effectiveness estimates are available for most project types on arterials. Examples of the application of each spreadsheet tool are presented in Section 5.7 of these guidelines. User guides for the spreadsheet tools are presented in Appendices A and B.

3R Project Design Guidelines for Specific Roadway Types

General design guidelines applicable to all 3R projects are presented in Chapters 2 through 5, including an introduction to the spreadsheet benefit-cost analysis tools in Chapter 5. Specific design guidelines in Chapter 6 are presented for 3R projects on the roadway types to which the spreadsheet benefit-cost analysis tools apply, as well as for urban and suburban arterials. The specific types of 3R project improvements addressed by the guidelines include lane widening, shoulder widening and paving, horizontal curve improvements, sight distance improvements, bridge widening, passing lanes, restoration of normal pavement cross slope, rumble strip improvements, striping and delineation improvements, roadside slope flattening, removal of roadside objects, installation/rehabilitation of guardrail and other traffic barriers, intersection turn lane improvements, and other intersection improvements. A summary of the guidelines is presented in Chapter 7.

Chapter 1. Introduction

1.1 Purpose of Guidelines

The design guidelines presented in this document have been developed to assist highway agencies in making geometric design decisions as part of the project development process for resurfacing, restoration, and rehabilitation (3R) projects. The guidelines address the role of safety considerations in the design of 3R projects and the implementation of a risk-based approach to design based on cost-effectiveness analysis.

3R projects are typically initiated based on current or anticipated pavement conditions that indicate the need for pavement resurfacing. In designing 3R projects, highway agencies need to decide whether to simply resurface the pavement or whether to utilize the 3R project as an opportunity to implement other desirable improvements, such as geometric design changes, to reduce crash frequency and severity and/or improve traffic operations. The approach to such decisions recommended in these guidelines for application to specific 3R projects considers current roadway and roadside design; current and anticipated future traffic volumes; crash history and anticipated future crash frequency and severity; improvement implementation costs; and other economic, environmental, and community factors that highway agencies consider in the project development process. These guidelines provide a framework for considering these factors in 3R project design decisions, so that funds are invested in geometric design improvements as part of 3R projects primarily where documented crash patterns exist or where, in the absence of a documented crash pattern, the anticipated crash reduction benefits over the service life of the project exceed the improvement implementation costs. The guidelines advise highway agencies to avoid investing funds in geometric design improvements where the improvement implementation costs exceed the anticipated crash reduction benefits, unless there is either a documented crash pattern that can be mitigated by the improvements or a documented traffic operational improvement need.

These guidelines are intended to replace the design guidelines for 3R projects presented in TRB Special Report 214, *Designing Safer Roads: Practices for Resurfacing, Restoration, and Rehabilitation* (*1*). The guidelines presented here are based on substantial advances in knowledge about the effects of geometric design features on crash frequency and severity since TRB Special Report 214 was published in 1987. Most specifically, the guidelines implement the safety knowledge presented in the American Association of State Highway and Transportation Officials (AASHTO) *Highway Safety Manual* (HSM) (*2,3*) and other recent safety research.

1.2 Scope of Guidelines

The scope of the guidelines is limited to projects involving only resurfacing, restoration, and/or rehabilitation. New construction and reconstruction projects are not addressed by these guidelines. Section 2.1 discusses the distinctions between new construction, reconstruction, and 3R projects.

The guidelines address 3R projects initiated for any reason. Most 3R projects are initiated because of poor pavement condition that indicates a need for pavement resurfacing, but the guidelines can also be applied to projects initiated for other reasons, as long as the project does not involve new construction or reconstruction.

The guidelines address design of 3R projects on rural two-lane highways, rural multilane undivided highways, rural multilane divided nonfreeways, urban and suburban arterials, and rural and urban freeways.

The guidelines are based on the current state of knowledge concerning crash reduction effectiveness and traffic operational improvements that can result from specific design alternatives for 3R projects. The guidelines should be updated in the future as knowledge of these issues advances.

The guidelines are intended for application to 3R projects paid for from any funding source. Thus, the guidelines are not limited just to projects funded as part of the Federal 3R program. The guidelines are also applicable to 3R projects funded from other Federal sources and to projects funded entirely with state or local funds. The guidelines focus on deciding whether any specific project should be resurfaced without accompanying geometric design improvements or whether (and what) geometric design changes should be made as part of the project. The focus of the guidelines is entirely on determining the appropriate geometric design for the roadway after project implementation (either the same as the existing roadway or incorporating cost-effective changes). The guidelines do not address administrative issues such as the appropriate form of design approvals or the need for design exceptions. Such administrative issues are best addressed by the highway agencies involved. The highway community is moving toward more flexible geometric design processes, with reduced need for routine design exceptions, but such administrative issues are outside the scope of these guidelines. In any case, the crash history review and cost-effectiveness approaches utilized in these guidelines should provide justification of design decisions within any administrative framework for design approval procedures that may be in place.

1.3 History of Guidelines

Geometric design criteria have historically been established by AASHTO policies, updated most recently in the 2011 *Policy on Geometric Design of Highways and Streets*, commonly known as the *Green Book* (*4*), which apply to new construction and reconstruction projects. After each updated AASHTO policy is published, FHWA typically adopts the AASHTO geometric design criteria by regulation for application to the National Highway System (NHS) (Code of Federal Regulations, 23 CFR Part 625). In 1985, FHWA regulations identified 13 controlling criteria for geometric design; new construction and reconstruction projects on the NHS required a formal design exception to be initiated by the state or local highway agency and approved by FHWA if any of the 13 controlling criteria are not met. Based on research presented in NCHRP Report 783 (*5*), FHWA recently reduced the number of controlling criteria from 13 to 10 and no longer requires design exceptions for projects with design speeds of 45 mph or less for 8 of the 10 controlling criteria. Design exceptions for structural capacity and design speed are still required for NHS roads at all levels of design speed.

Until 1976, Federal highway funds could be used only for new construction or reconstruction projects. The Federal-Aid Highway Act of 1976 first permitted state and local highway agencies to use Federal funds for 3R projects on existing federal-aid highways. Congress specified safety as one of the criteria to be considered in designing 3R projects, but did not specify any particular set of geometric design criteria or any particular safety analysis procedures.

In 1977, AASHTO proposed a set of geometric design criteria for 3R projects that were less restrictive than the geometric design criteria in use for new construction and reconstruction (*6*). This proposal brought criticism from safety advocates who wanted all geometric elements on 3R projects to be upgraded to full new construction criteria to improve safety. Congress held hearings on this issue in 1981 and, as a result, the Surface Transportation Assistance Act of 1982 mandated a study of the cost-effectiveness of geometric design standards and the development of minimum standards for 3R projects on roads other than freeways. The result of this Congressional mandate was the formation of a study committee and the publication of TRB Special Report 214 (*1*), which proposed geometric criteria for 3R projects that have become the basis for the 3R design policies of many highway agencies. The AASHTO *Green Book* (*4*) does not present design criteria for 3R projects, but rather refers users to TRB Special Report 214.

There have been many changes in both the state of knowledge and highway agency policies since the publication of TRB Special Report 214 in 1987. Much of this new knowledge is organized in the HSM (*2,3*). The guidelines presented in this document have been developed to update the guidelines in TRB Special Report 214 based on the new knowledge that is available.

1.4 Organization of Guidelines

The remainder of the guidelines for 3R projects are organized as follows. Chapter 2 defines 3R projects and distinguishes them from new construction and reconstruction. Chapter 3 presents the process for 3R project development. Chapter 4 discusses the management of a 3R program to reduce crash frequency and severity, one of several objectives of 3R programs. Chapter 5 presents the application of benefit-cost analysis in 3R programs, including a description of two spreadsheet-based tools developed to supplement these guidelines that can be used to perform benefit-cost analyses. Chapter 6 presents specific design guidelines for 3R projects, incorporating a benefit-cost approach. Chapter 7 presents a summary of the 3R project design guidelines. Appendices A and B present user guides for the two spreadsheet-based geometric design tools. Appendix C presents updated crash cost estimates that may be used as default values in the spreadsheet tools.

Chapter 2.
What are 3R Projects?

This chapter discusses the definition of 3R projects and how they differ from new construction and reconstruction projects, the objectives of 3R projects, and typical improvements considered in 3R projects in addition to resurfacing.

2.1 New Construction vs. Reconstruction vs. 3R Projects

Understanding of the context for design of 3R projects requires understanding of the distinctions between new construction, reconstruction, and 3R work. Each of these types of projects is defined below.

2.1.1 New Construction Projects

New construction projects typically consist of projects on new alignment where no highway facility has existed before (e.g., projects on greenfield sites). Some projects on existing roads might be classified as new construction if the existing roadway is completely removed, a new alignment or cross section is developed for the facility, and the new alignment and cross section are not substantially constrained by development adjoining the existing road; this situation is rare, but can occur.

New construction projects are designed using the criteria in the AASHTO *Green Book* (*4*). The design guidelines presented here do not apply to new construction projects.

2.1.2 Reconstruction Projects

Reconstruction projects include projects on existing roads that are not considered new construction and in which:

- the entire pavement structure, down to the subgrade, is removed and replaced, for all or most of the project length,
- a substantial proportion of the existing alignment is modified, or
- the basic roadway cross section is changed (e.g., expanding an existing two-lane highway to four lanes)

Reconstruction projects are designed using the criteria in the AASHTO *Green Book* (*4*). The design guidelines presented here do not apply to reconstruction projects.

2.1.3 3R Projects

3R projects include projects in which the scope is limited to resurfacing, restoration, and/or rehabilitation of existing roads. 3R projects do not involve new construction or reconstruction, as defined above. Therefore, by definition, 3R projects do not involve a substantial amount of road construction on a new alignment, removal of the entire pavement structure down to the subgrade, realignment of substantial portions of the project, or a change in the basic roadway cross section. If only a limited or isolated portion of a project involves new construction or reconstruction, the remainder of the project can be designed as 3R work.

Projects with overlays of any depth and projects involving cold milling to remove an obsolete surface course and/or maintain a pavement surface elevation consistent with vertical clearance design may be considered 3R projects.

For purposes of the design guidelines presented in this document, projects may be classified as 3R projects regardless of whether they are funded as part of the Federal 3R program or any other designated 3R program. The design guidelines presented here are applicable to projects that are not considered new construction or reconstruction and involve only resurfacing, restoration, and/or rehabilitation, regardless of the project funding source.

Chapters 2 through 5 present general design guidance applicable to all 3R projects. Chapter 6 presents design guidelines applicable to 3R projects on specific roadway types. Chapter 7 summarizes all of the design guidelines.

2.2 Objectives of 3R Projects

The primary objective of most 3R projects is to preserve and extend the life of the pavement by resurfacing. Thus, 3R projects are normally initiated because pavement management systems indicate the need for pavement resurfacing. Furthermore, the timing of most 3R projects is set based on the timing of the need for pavement resurfacing to preserve and extend the life of the pavement structure. A few 3R projects are initiated to address needs other than pavement resurfacing and, as long as they do not involve new construction or reconstruction, they can be considered as 3R projects for design purposes.

While the primary objective of most 3R projects is pavement preservation, the development of a 3R project provides an opportunity for geometric design improvements to enhance traffic operations, reduce crashes, improve drainage, or improve the roadway or roadside in other ways. The project would still be considered 3R work as long as the design changes do not constitute new construction or reconstruction. It is to the advantage of both the highway agency and the traveling public for any needed design changes to be made in conjunction with the pavement resurfacing project; coordination of such improvements reduces implementation costs and reduces travel delays in work zones, in comparison to implementing separate projects at separate times. Federal guidelines require highway agencies to consider the need for traffic operational and safety improvements in the project development process for 3R projects funded through the Federal 3R program. The guidelines presented in this document show a structured process for considering the need for traffic operational and safety improvements in 3R projects that is intended to focus such improvements on locations where the improvement will be cost-effective. The guidelines indicate that design improvements should not necessarily be made in all 3R projects, but only when engineering analyses confirm that the proposed improvements are appropriate and cost-effective or where a specific need is otherwise demonstrated.

2.3 Typical Improvements Made in 3R Projects in Addition to Resurfacing

A broad range of highway infrastructure improvements may be considered in 3R projects in conjunction with pavement resurfacing. A recent survey found that most highway agencies routinely consider the need for specific design improvements intended to reduce crash frequency and severity in 3R projects (*7*). Another survey identified the types of design improvements most commonly cited by highway agencies as among the top five improvement types made in conjunction with 3R projects (*7,8*). These include:

- Guardrail addition or improvement (including improvement of guardrail end treatments)
- Shoulder paving, grading, or widening
- Clear zone improvements
- Signing improvements
- Shoulder or centerline rumble strips
- Striping and delineation
- Superelevation restoration
- Pavement surface condition/friction
- Intersection design/turn lanes/turn radius
- Roadway/lane widening
- Roadside slope flattening

These improvement types and others that may be incorporated in 3R projects are addressed in Chapter 6 of these guidelines.

Chapter 3.
Process for 3R Project Development

This chapter presents the process for development of 3R projects including the identification of candidate 3R projects and the role of safety and traffic operational considerations in design decisions.

3.1 How Does the Design Process for 3R Projects Differ from the Design Process for New Construction and Reconstruction Projects?

The current design process for new construction projects is based primarily on the dimensional design criteria presented in the AASHTO *Green Book* (*4*) and in the design policies of individual highway agencies. It is appropriate to use established dimensional design criteria for new construction projects because, in such projects, there is no existing roadway with a safety and traffic operational performance history that can be used to guide the design process. Established dimensional design criteria provide an aspirational goal for design of reconstruction projects. Where a roadway is being fully reconstructed, design improvements may be feasible with limited additional cost, except where such improvements would substantially impact adjacent development, established communities, or sensitive environments; in these situations, highway agencies typically seek a design exception to minimize such impacts.

3R projects are usually initiated based on the need for pavement resurfacing and are most appropriately considered as maintenance activities. A performance-based design process provides the basis for design of 3R projects focusing on the decision about which projects should be resurfaced without accompanying design improvements and which projects should have design improvements incorporated.

The design process for 3R projects begins with the recognition that the project will be implemented on an existing road whose past safety and traffic operational performance is known and should serve as a key factor in design decisions. Unlike new construction and reconstruction projects, which are designed with reference to dimensional design criteria presented in the AASHTO *Green Book* (*4*), these guidelines do not establish dimensional design criteria for 3R projects. Research has found that any set of dimensional design criteria for 3R projects is likely to produce suboptimal results in terms of crash frequency and severity reduction (*7*). Rather, 3R design decisions should be based on an assessment of the safety and traffic operational performance of the existing road and the cost-effectiveness of potential design improvements. This approach is most likely to maximize the crash frequency and severity reduction that can be obtained within any budget level for 3R projects. Geometric design improvements should be considered as part of a 3R project in the following situations:

- An analysis of the crash history of the existing road identifies one or more crash patterns that are potentially correctable by a specific design improvement, or

- An analysis of the traffic operational level of service (LOS) indicates that the LOS is currently lower than the highway agency's target LOS for the facility or will become lower than the target LOS within the service life of the planned pavement resurfacing (typically 7 to 12 years), or
- A design improvement would be expected to reduce sufficient crashes over its service life to be cost-effective; i.e., the anticipated crash reduction benefits over the service life of the project should exceed the improvement implementation cost. Procedures for evaluating the cost-effectiveness of design improvements are presented in Chapter 5 of these guidelines.

In the absence of any of the three situations defined above, there is no indication that a design improvement is needed as part of a 3R project, and the existing roadway and roadside geometric features should remain in place. It makes little sense to invest scarce resources in design improvements as part of a 3R project where the existing roadway is performing well and where potential design improvements would not be cost-effective; the funds needed for such a project can be better invested in projects that do address documented performance concerns or where potential design improvements would be cost-effective. In particular, improvement of systemwide safety across the road network is so important that funds invested with the objective of improving safety should be directed toward projects where it can be demonstrated that substantial safety benefits will likely be obtained.

One potential exception to the guidance given above occurs if the normal pavement cross slope for an existing roadway to be resurfaced is less than the dimensional design criteria for normal cross slope in the AASHTO *Green Book* (*4*) or the design policy of the responsible highway agency. For, example, the AASHTO *Green Book* recommends a normal cross slope of 1.5 to 2 percent for paved roadways. There are no existing cost-effectiveness analysis procedures to address the selection of normal cross slope values, but appropriate pavement cross slope is needed for proper drainage during precipitation and should be provided. Therefore, it is recommended that normal pavement cross slope be increased to the criteria applicable to new construction and reconstruction as part of pavement resurfacing, whenever practical. This guidance applies only to normal cross slope, but does not apply to superelevated horizontal curves. The pavement cross slope on superelevated curves for rural two-lane and multilane highways is addressed by a CMF in the AASHTO *Highway Safety Manual* (*2*). Therefore, the need for superelevation improvement/restoration for horizontal curves on these facility types can be considered through cost-effectiveness analyses.

The reliance on cost-effectiveness to guide design decisions for 3R projects has several advantages:

- Highway agencies can have confidence that funds invested in design improvements intended to reduce crashes as part of 3R projects are, in fact, likely to result in reduced crashes.
- Since crash frequency for a road generally increases with increasing traffic volume, the use of cost-effectiveness analysis as a basis for design decisions means that the likelihood of design improvements being included in a 3R project increases with increasing traffic

volume. This dependence of design decisions on traffic volume levels is logical and desirable and is not fully reflected in most current dimensional design criteria for new construction and reconstruction.

- A cost-effectiveness approach will focus improvement needs on low-cost improvements with documented safety effectiveness, which are most consistent with the limited scope of 3R projects. However, the procedures are flexible enough that higher cost improvements can be considered where benefits are sufficient to justify their implementation. If extensive geometric improvements are found to be cost-effective, consideration may be given to reclassifying the project as a reconstruction project.

Section 4.4 demonstrates that reliance on dimensional design criteria will provide suboptimal results, with some investments made at locations where they are not cost-effective and other investments not made at locations where they would be cost-effective.

3.2 How Should Candidate 3R Projects Be Identified?

Candidate 3R projects should be identified primarily on the basis of pavement condition and the need for pavement resurfacing. Most highway agencies assess pavement condition and establish resurfacing priorities with the assistance of pavement management systems. Resurfacing at the proper time in the life of the pavement prolongs the life of the pavement and avoids more costly repairs.

There are essentially three approaches that may be used in pavement management for project and treatment selection under fiscally constrained situations: ranking, prioritization, and optimization. Each of these three analysis approaches provides a method for identifying an optimal strategy for preserving the condition of the network, given any constraints that may exist.

One of the easiest methods for selecting projects is to rank needs based on some type of agency priority, such as pavement condition or traffic levels, or both. A common method of ranking needs is to list road sections in sequential order by pavement condition rating, and to fund projects with the worst pavement condition until the available funding limits have been met. This approach is commonly referred to as a “worst-first” strategy in which the pavements in the worst condition are assigned the highest priority for funding.

The next level of sophistication in project and treatment selection is a prioritization process, in which the most cost-effective use of available funding over the analysis period is identified. This approach is preferred over a ranking approach because consequences of delaying or accelerating a treatment are evaluated, and the cost-effectiveness of a treatment is taken into account in developing the program recommendations.

An optimization analysis is a more complex analysis to determine how to efficiently allocate resources so that network conditions are maximized and costs are minimized. In some cases, agencies add additional constraints to help meet agency objectives. For example, an additional constraint that prevents any interstate pavement from dropping below a particular condition level may be included as an analysis parameter. An advantage of the optimization analysis is the ability to incorporate risk into the analysis. One of the challenges associated with the use of pure optimization is the difficulty in linking network level results with project-level results. At the network level, the results of an optimization analysis typically provide the percentage of the road network that should be moved from one condition state to another through maintenance or rehabilitation actions.

While most candidate 3R projects are identified based on the need for pavement resurfacing, any project that does not involve new construction or reconstruction can be addressed with the design guidelines in this document. For example, projects on existing roads identified with crash analysis tools, congestion management systems, or any other tool can be designed as a 3R project so long as the scope of the project does not fall within the definition of reconstruction, as presented in Section 2.1.2. Thus, highway agencies have substantial flexibility to identify candidate 3R projects in any manner, so long as the resulting project falls within the definition of a 3R project. Most 3R projects, even if they are not initiated originally by pavement resurfacing needs, are scheduled for implementation in conjunction with pavement resurfacing to obtain economies of scale. However, a design improvement that falls within the definition of 3R work can be designed and implemented in accordance with the guidelines presented in this document, regardless of whether pavement resurfacing is performed as part of the project.

3.3 Assessment of Needs for Improvements in Addition to Resurfacing

As noted earlier, there are three types of assessments that are generally conducted to investigate whether a design improvement is appropriate in conjunction with pavement resurfacing. These are:

- Crash history review and analysis
- Traffic operational analysis
- Cost-effectiveness analysis

All three of these assessment approaches should be applied to every candidate 3R project. In some cases, one or more of these assessments can be applied very quickly. For example, if the crash history for a candidate project site includes no crashes, no crash history review is needed; if the candidate project site has experienced very few crashes, the crash history review should require only a limited effort. If a candidate project has a very low annual average daily traffic volume (AADT), a quick traffic operational review may be all that is needed to establish that the LOS of the project site is acceptable. Conversely, sites with high crash frequencies, or high traffic volumes, will require, and deserve, more involved analyses. Each of these assessment types is discussed below.

3.3.1 Crash History Review

A crash history review should be a routine part of the design of every 3R project. Crash history data for a period of at least three, and preferably five, years should be reviewed to identify existing crash patterns and assess the need for design improvements. Depending upon the length and complexity of the project and the number of crashes that have occurred during the assessment period, the crash history review may involve:

- review of automated crash data and/or hard copy police crash reports
- tabulation of crash severities and types overall and by location within the project, including comparison to average crash characteristics for similar corridors
- preparation of collision diagrams
- comparison of intersections and segments within the project limits to average crash frequencies of similar intersections and segments for the same facility type

The scope of the crash history review is flexible and will vary from project to project. If a candidate 3R project has experienced no crashes in the assessment period, no further crash review is needed and the assessment can move on to traffic operational assessment and cost-effectiveness analysis (see below). If only a few crashes have occurred, the crash history review can be accomplished quickly by reviewing automated crash data and/or hard copy police crash reports. The assessment should focus on determining whether there are repeated crashes of any given type or at any given location that are indicative of a crash pattern and that are potentially correctable by a design improvement. If a substantial number of crashes have occurred in the assessment period, then more effort will need to be devoted to the review, because the potential for crash patterns to be identified is greater. Tabulations of crash severities and types, overall and by location, should be prepared and collision diagrams may be useful in identifying crash patterns. Table 1 shows an example from a report in the AASHTOWare *Safety Analyst* (*9,10*) software tools illustrating the format of crash tabulations that may be useful in crash history review.

Table 1. Example Crash Type Summary from the AASHTOWare *Safety Analyst* Software (*9,10*)

Description	2008	2009	2010	2011	2012	2013	Total	Observed Percent	Average Percent
Collision with bicyclist	0	0	0	0	1	0	1	5.26	0.33
Collision with pedestrian	0	0	0	0	1	0	1	5.26	0.36
Collision with fixed object	1	0	0	0	0	0	1	5.26	13.41
Other single-vehicle collision	0	0	0	0	1	0	1	5.26	2.23
Rear-end	1	1	1	3	0	0	6	31.58	22.92
Angle	0	1	0	0	1	0	2	10.53	2.59
Sideswipe, same direction	0	0	1	0	0	0	1	5.26	5.17
Other multiple-vehicle collision	0	1	1	1	1	2	6	31.58	6.26
Total Crashes	2	3	3	4	5	2	19	100.00	100.00

Collision diagrams illustrate the crash location and the pre-crash movements and manner of collision of the vehicles involved in each crash. Pre-crash movements are illustrated with arrows showing the intended direction of travel for each vehicle and whether the vehicle was going straight ahead, turning left, turning right, or backing. Manner of collision for multiple-vehicle crashes is illustrated by the orientation at which the pre-crash movement arrows intersect and shows the classification of a crash as head-on; sideswipe, opposite direction; sideswipe, same direction; angle; or rear end. Procedures for preparing collision diagrams are presented in HSM Chapter 5. The preparation of collision diagrams can be automated with the AASHTOWare *Safety Analyst* software tools and with other commercially available software. Figure 1 shows a typical collision diagram. Collision diagrams are most commonly used to evaluate intersection crashes, as shown in the figure, but collision diagrams can be prepared for non-intersection locations as well. In particular, the AASHTOWare *Safety Analyst* software tools can automate the preparation of collision diagrams for non-intersection locations.

The crash history review should focus on fatal and serious injury crashes, which are the highest priority to address in ongoing safety programs. Crash patterns that consist primarily of property-damage-only or minor-injury crashes are not unimportant, but sites with patterns of fatal or serious injury crashes should receive priority in programming design improvements.

Chapter 5 of the AASHTO *Highway Safety Manual* (*2*) provides a good guide to the process of diagnosing crash patterns at particular sites. HSM Chapter 5 includes guidance on the use of crash tabulations, statistical tests, and collision diagrams in diagnosis of crash patterns. Use of HSM Chapter 5 enables the investigator to review quantitative results and apply quantitative tests.

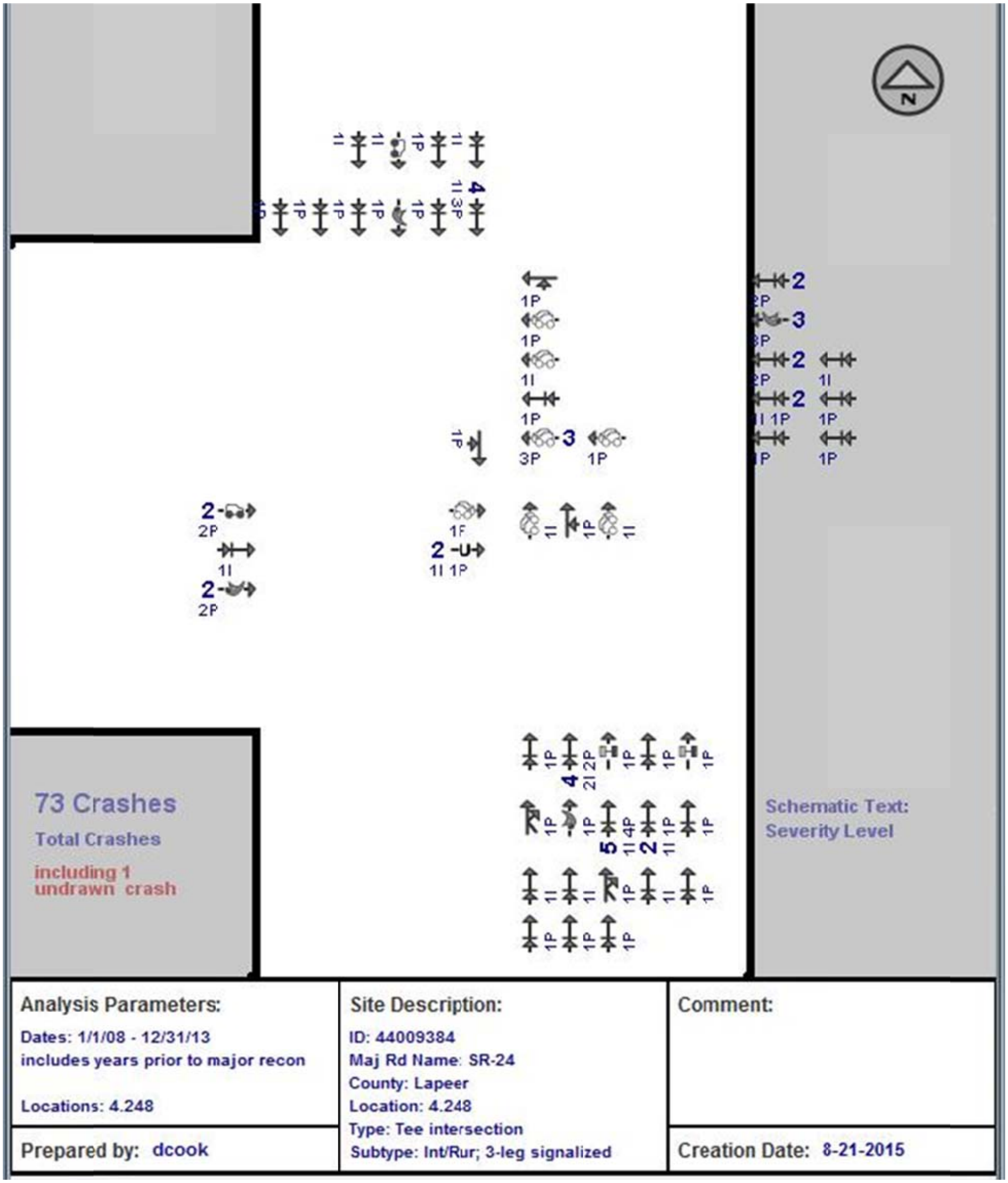


Figure 1. Example collision diagram from the AASHTOWare *Safety Analyst* Software (*9,10*)

There is no specific minimum number of crashes that constitutes a crash pattern. Identification of crash patterns depends on the context of particular sites. Engineering judgment based on highway agency experience with particular types of sites may be the best guide in identification of crash patterns. One approach that is potentially applicable to some types of sites is to apply the testing procedures in HSM Chapter 5 to determine whether crash experience at a given site exceeds the expected crash experience for sites of that particular type and traffic volume level.

HSM Chapter 6 explains how crash patterns can be used in identifying and selecting particular countermeasure types with applications likely to reduce particular crash types.

The concepts presented in HSM Chapters 5 and 6 have been automated in the AASHTOWare *Safety Analyst* software, which includes safety management tools for application to specific highway types. Use of *Safety Analyst* requires initial effort to organize a highway agency's roadway, intersection, ramp, and crash data, but the software can provide substantial benefits by automating the diagnosis and countermeasure selection process.

Economic analyses are not typically needed as part of crash history reviews. The identification of what the highway agency considers to be a potentially correctable crash pattern, especially a pattern involving severe crashes, is sufficient justification to include a design improvement in a 3R project. Cost-effectiveness analyses are typically applied where no crash patterns are found (see Section 3.3.3). However, some agencies may prefer to verify through economic analysis that correction of a specific pattern would be cost-effective. Both HSM Chapter 7 and *Safety Analyst* provide economic appraisal procedures that can be applied for this purpose.

3.3.2 Traffic Operational Analysis

If the current traffic operational level of service for a roadway, or the anticipated LOS at any time during the service life of the planned pavement resurfacing (typically 7 to 12 years), is less than the highway agency's target LOS for the roadway, then a design treatment to improve the LOS is appropriate as part of a 3R project. Examples of design treatments that may improve LOS are lane widening, shoulder widening, and addition of turn lanes. It is also appropriate to consider alternatives to design improvements, such as changes in traffic control devices that might accomplish the same objective.

Traffic operational analyses are generally performed with the procedures of the *Highway Capacity Manual* (HCM) (*11*). For any specific facility type, the HCM specifies the service measure(s) that define LOS (see Table 2), presents thresholds that define specific LOS categories, and present procedures to estimate the service measure(s) and, therefore, determine LOS. The HCM procedures provide one method to quantify the service measure(s), but other methods including field measurements and simulation modeling are also possible. Such alternatives to the HCM procedures can be applied at any site, but would normally be needed only for complex situations that fall outside the scope of the HCM procedures.

Table 2. Traffic Operational Service Measures for Specific Roadway Facility Types (*11*)

Road Type	HCM Service Measures
Rural two-lane roadway	Average travel speed Percent time-spent-following
Rural multilane highway	Traffic density
Urban and suburban arterials	Travel speed as a percentage of base free-flow speed

Intersection design improvements may also be included to improve the LOS as part of a 3R project. Delay is a service measure used to define LOS at intersections. The addition of a left- or right-turn lane may make operational sense as well as provide safety benefits.

The target LOS for any roadway is determined by the responsible highway agency. Design policies, such as the AASHTO *Green Book* or the policies of individual highway agencies, do not normally define target LOS criteria for application to specific projects. As a practical matter, most highway agencies find that appropriate target LOS levels vary with the project context, giving consideration to topography, area type (urban/rural), metropolitan area size, and project scope. Thus, the target LOS is often a project-by-project decision, and highway agencies have substantial flexibility in deciding whether to incorporate traffic operational improvements in particular 3R projects.

3.3.3 Cost-Effectiveness Analysis

Cost-effectiveness analysis of 3R projects applies a *systemic* approach to safety assessment, based on crash prediction models, as opposed to the analysis of observed crashes discussed above for the crash history review in Section 3.3.1. Every roadway section has some nonzero risk of crash occurrence, even if no crashes have actually occurred. A systemic approach considers the need for design improvements based on potential crash risk, whether that risk has resulted in crashes or not. The cost-effectiveness analysis can be based solely on assessment of *predicted* crash frequency or *predicted* and *observed* crash frequencies can be applied using the Empirical Bayes (EB) procedure to estimate the long-term *expected* crash frequency.

The type of cost-effectiveness analysis recommended for the assessment of 3R projects is benefit-cost analysis, in which the results can be expressed as benefit-cost ratios (project benefits divided by project costs) or net present benefits (project benefits minus project costs). The benefit-cost analysis procedures applicable to 3R projects are presented in Chapter 5. These procedures are tedious to apply manually, so two spreadsheet-based benefit-cost tools have been created for application by highway agencies; these benefit-cost tools are described in Chapter 5.6 of these guidelines. The benefit-cost tools can be applied by highway agencies in any of three ways:

- evaluation of an individual candidate 3R project to determine whether a specific proposed design improvement would be cost-effective
- evaluation of an individual candidate 3R project to determine whether any of a range of specific design improvements would be cost-effective

- evaluation of a set of potential improvements for generic 3R project scenarios to establish minimum AADT guidelines for consideration of specific design improvements for specific roadway types

The first two applications listed above, involving analysis of individual candidate 3R projects, are the preferred approaches to benefit-cost analysis. Chapter 5 shows why these approaches are preferred. The third application listed above, establishment of minimum AADT guidelines for specific design improvements on specific roadway types, is less desirable than the first two applications, but is an acceptable approach for highway agencies that prefer not to conduct analyses of individual projects. Procedures for application of the three approaches listed above are presented in Chapter 5.

Chapter 4.
Managing a 3R Program to Reduce Crash Frequency and Severity

3R programs are managed by highway agencies as part of their effort to preserve pavements and extend their service life. However, 3R projects also provide an opportunity to consider the need for design improvements to reduce crash frequency and severity. The Federal 3R program requires consideration of safety improvement needs in 3R projects, and most highway agencies also consider safety improvement needs in 3R projects that are not part of the Federal 3R program. This chapter shows how 3R programs can be managed not only to preserve pavements and extend their service life, but also as a key part of each highway agency's efforts to reduce the frequency and severity of traffic crashes on the roadway system. This goal can be achieved through a structured design process that considers the need for design improvements in each 3R project, with the objective of implementing such improvements where a crash history review identifies an existing crash pattern or where an economic analysis indicates that a design improvement would be cost-effective. Prioritizing improvement needs is critical to using available funds efficiently and maximizing the crash reduction benefits from 3R improvements, so it is important that design improvements be made as part of 3R projects where needed and also that design improvements not be made where there is no demonstrated need and where such improvements would not be cost-effective.

4.1 Role of 3R Projects in Overall Safety Management Programs of Highway Agencies

Highway agencies and their safety partners undertake a broad range of activities to reduce crash frequency and severity. These may include:

- Monitoring the crash history of the roadway system and making design or traffic control improvements where potentially correctable crash patterns are identified
- Conducting systemic reviews of the roadway system and making design or traffic control improvements where such improvements appear to be cost-effective based on their potential reduction of potential future crashes, whether or not there is a history of observed crashes
- Reviewing plans for highway infrastructure projects, as they develop, to identify opportunities for incorporating design or traffic control changes in specific projects to reduce crash frequency or severity
- Coordinating with law enforcement agencies to prioritize enforcement activities and focus enforcement at locations where it is most needed
- Conducting public education and driver training programs to promote highway safety awareness and safe driving practices among the traveling public
- Encouraging improvement of emergency medical services to assist crash victims in receiving on-site and in-hospital treatment as soon as practical after a crash occurs

All types of highway infrastructure improvement projects, including 3R projects, help to address the first three aspects of highway safety management listed above.

The list of highway safety activities presented above makes clear that, while highway safety management includes monitoring crash history and developing projects to address identified crash patterns, it is in no way limited to that. Similarly, highway safety management should not be seen as limited to projects funded from safety specific funding sources such as the Highway Safety Improvement Program (HSIP). Any project, regardless of why it is initiated and how it is funded, can include features intended specifically to reduce crash frequency and severity. Thus, all types of projects, including 3R projects, can play an important role in reducing crash frequency and severity.

Rational management of safety considerations in 3R projects requires an understanding of the crash reduction effectiveness of specific design features that may be considered as safety improvements in 3R projects. The crash reduction effectiveness of design features is typically presented in the form of crash modification factors, as explained in Section 4.2.

4.2 Quantifying Crash Reduction Effectiveness of 3R Improvements: Crash Modification Factors (CMFs)

Management of a 3R program to effectively reduce crashes requires an understanding of the crash reduction effectiveness of design improvements that can potentially be made as part of 3R projects. The following discussion introduces the concept of crash modification factors to represent the crash reduction effectiveness of design improvements, presents their definition, and describes their use. The values of crash modification factors for specific 3R improvement types are presented in Section 4.3.

4.2.1 Introduction to the Concept of Crash Modification Factors

Crash modification factors (CMFs) represent the relative change in crash frequency due to a change in a roadway design feature or any other specific condition. A CMF represents the ratio of the crash frequency of a site under two different conditions, such as after a project in comparison to before a project. Therefore, a CMF serves as an estimate of the effect of a particular geometric design or traffic control feature or the effectiveness of a particular treatment or condition. Some CMFs apply to specific crash severities, crash types, roadway types and/or may only be applicable to specific ranges of traffic volumes.

As an example, if a change in a specific design feature were expected to reduce the crash frequency at a site from 10 to 8 crashes per year, the corresponding CMF value would be 8/10 = 0.80. A CMF value less than 1.0 indicates that the design feature or treatment is expected to reduce crashes. A CMF value greater than 1.0 indicates that the design feature or treatment would be expected to increase crashes. A CMF value equal to 1.0 indicates that the design feature or treatment would not be expected to have any effect on crashes. CMFs are a useful form for expressing the expected crash reduction effectiveness of design features or treatments because the expected crash frequency for a site after a project can be estimated as the expected crash frequency before the project multiplied by the CMF.

The crash reduction effectiveness of design features or treatments can also be expressed as a crash reduction factor, which represents the expected percentage reduction in crashes resulting from a design feature or treatment. The CMF value of 0.80 presented above corresponds to a crash reduction factor of 20 percent, determined as follows:

$$\text{Crash Reduction Factor} = (1.00 - 0.80) \times 100 = 20 \text{ percent} \quad \textbf{(1)}$$

Similarly, a CMF value of 1.20 corresponds to a crash reduction factor of -20 percent (in other words, an increase in crash frequency of 20 percent), determined as follows:

$$\text{Crash Reduction Factor} = (1.00 - 1.20) \times 100 = -20 \text{ percent} \quad \textbf{(2)}$$

4.2.2 Quality and Uncertainty Issues Related to Crash Modification Factors

CMFs represent the expected or average effects of geometric design features on crash frequency and severity. CMFs are developed from data for individual sites at which the crash counts and the change in crash counts from before to after a project may vary substantially. CMFs represent the average effect of future infrastructure improvements on crash counts, but as in the data used to develop CMFs, such effects are likely to vary substantially from site to site.

Some CMFs are more precise and reliable than others. Each CMF presented in Part D of the *Highway Safety Manual* (*2*) is accompanied by a standard error that represents the degree of uncertainty associated with predictions made with that CMF. For example, the CMF applicable to all types and all severities of crashes for installing centerline rumble strips on rural two-lane highways is presented in HSM Part D as:

Crash Modification Factor	Standard Error
0.86	0.05

The CMF value of 0.86 indicates that installation of centerline rumble strips would be expected to reduce crashes by 14 percent. This can be demonstrated by replacing the value of 0.80 in Equation (1) with 0.86. The standard error represents the precision of the CMF value. The confidence range around the CMF value permits assessment of the accuracy of the CMF value. Confidence limits at the 95-percent confidence level typically range from the CMF value minus twice the standard error to the CMF value plus twice the standard error. This CMF value of 0.86 is considered reliable because a CMF value of 1.0 (no effect on crashes) is not included within the range 0.86 ± 2*(0.05), or 0.76 to 0.96. This range indicates that the effectiveness of centerline rumble strips can range from a CMF of 0.76 to a CMF of 0.96, or a reduction of crashes in the range from 4 to 24 percent. Such uncertainties are typical of even the most reliable CMFs, given the variations inherent in crash data. While the crash reduction effectiveness of centerline rumble strips at individual sites may vary over the range shown (4 to 24 percent), the overall effectiveness of applying centerline rumble strips to a broad range of rural two-lane highway sites is likely to be about 14 percent. Highway agencies can proceed with planning of 3R programs with the expectation that the available CMFs will represent the average results to be expected.

The HSM uses a formal inclusion rule (*2*, *12*) to determine whether CMFs are of sufficient quality to be applied reliably. With limited exceptions, only CMFs that meet the inclusion rule are presented in HSM Part D. Thus, CMFs from the HSM can be relied upon in planning 3R programs.

CMFs are also available from the FHWA Crash Modification Factors Clearinghouse (*13*). The FHWA Clearinghouse assigns star ratings to CMFs to represent their quality and identifies the facility type(s) to which each CMF applies. Star ratings for CMFs range from one star (lowest quality) to five stars (highest quality). The ratings are based on an assessment of the research approach and the data used in developing the CMFs. The philosophy of the FHWA Clearinghouse is to include all CMFs reported in the literature, regardless of quality, and to let the star ratings indicate the quality of individual CMFs. Thus, CMFs rated as one or two stars in the FHWA Clearinghouse are derived from research or data of low quality and should not be relied upon unless no better information is available. CMFs rated one or two stars, and some rated three stars, in the FHWA Clearinghouse would likely not pass the inclusion rule for incorporation in HSM Part D. The FHWA Clearinghouse also indicates which CMFs presented in the Clearinghouse also meet the HSM inclusion rule. Application of CMFs from the FHWA Clearinghouse should focus on those CMFs rated three stars, or preferably four or five stars, or those identified in the FHWA Clearinghouse as meeting the HSM inclusion rule.

4.2.3 Development of Crash Modification Factors

CMFs are developed primarily through analysis of crash data. The two most common types of crash analyses to develop CMFs are:

- observational before-after studies
- cross-sectional studies

Observational before-after studies are conducted by identifying projects where a design improvement has been implemented at multiple sites. Crash history and traffic volume data are then obtained for time periods before and after implementation of each project (typically at least three years of data for the period before project implementation and three years of data for the period after project implementation. Observational before-after evaluations are typically conducted with a technique known as the Empirical Bayes (EB) method, which compensates for potential biases in crash data. An observational before-after evaluation compares the observed crash count in the period after implementation of each project to an estimate of the crash count that would have been expected if the project had not been implemented. The crash count that would have been expected if the project had not been implemented is estimated with a crash prediction model known as a safety performance function (SPF). SPFs are developed with a modeling technique known as Negative Binomial regression analysis, which is well suited to modeling crash data. HSM Chapter 9 presents a computational procedure for observational before-after evaluations using the Empirical Bayes method. The analysis results provide a CMF that represents the crash reduction effectiveness of the project.

Figure 2 illustrates a typical SPF for a roadway segment developed with negative Binomial regression that could be used in developing CMFs with the EB method. This particular SPF is from HSM Figure 11-3 and applies to roadway segments on rural multilane undivided highways (nonfreeways). SPFs can have either linear or curvilinear functional forms. The horizontal axis for the SPF represents the annual average daily traffic volume (AADT) for the roadway segment. The vertical axis represents the predicted number of crashes per mile per year on the roadway segment.

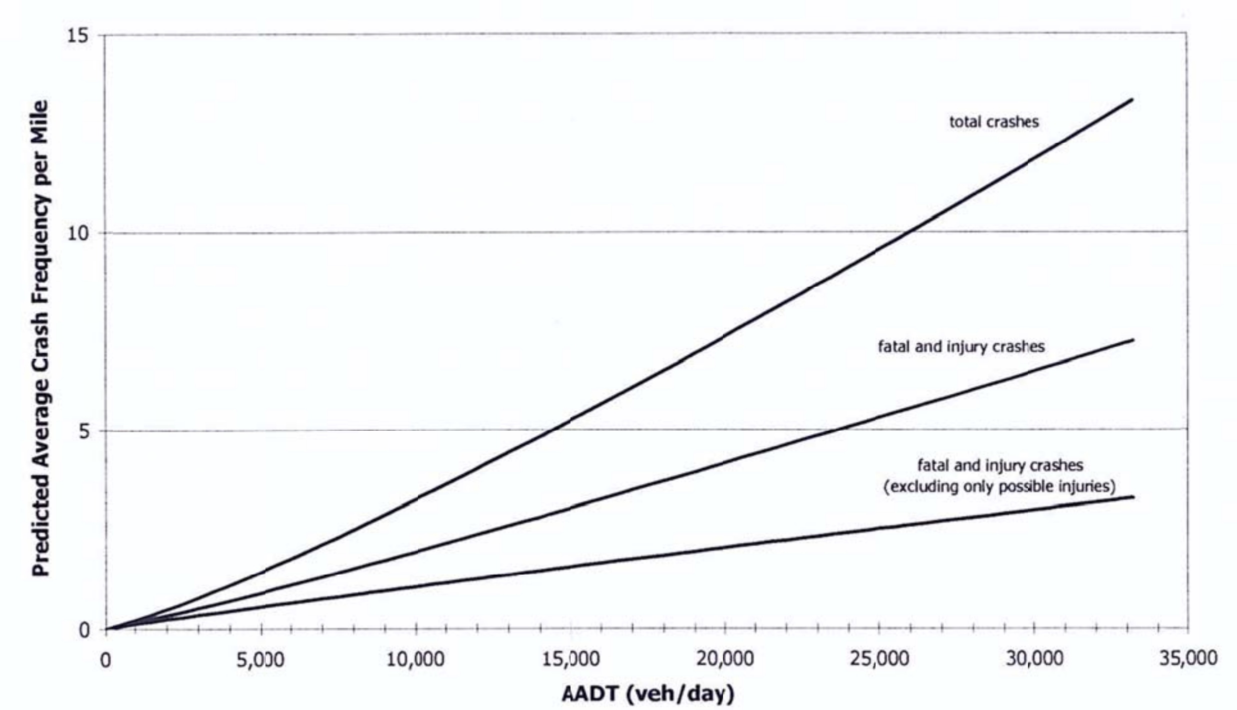


Figure 2. Example of Safety Performance Function for Undivided Roadway Segments on Rural Multilane Highways (2)

Cross-sectional studies are conducted when observational before-after evaluations are not feasible. Cross-sectional modeling uses Negative Binomial regression modeling to quantify the effect of a specific geometric design feature on crash counts by considering sites with and without that feature or where that feature is present in varying dimensions. Cross-sectional analyses must be carefully designed and conducted because, where specific design features or other factors are correlated with one another, the effect of other factors can potentially be mistaken for an effect of the geometric design feature of interest. HSM Chapter 9 also presents a computational procedure for developing CMFs with cross-sectional modeling.

Further guidance on CMF development is found, in HSM Chapter 9 (*2*) and in the FHWA report, *A Guide to Developing Crash Modification Factors* (*14*).

4.2.4 Sources for Obtaining Crash Modification Factor Values

As indicated above, the two most extensively used catalogs of CMF values for design and traffic control improvements are the HSM (*2*) and the FHWA Crash Modification Factors Clearinghouse (www.cmfclearinghouse.org). All of the CMFs in the HSM and the FHWA Clearinghouse were developed in research projects and then reviewed and assessed for inclusion. CMFs can also be obtained from review of individual research reports, although this should generally be done only for new sources that have not yet been assessed for inclusion in the HSM or the FHWA Clearinghouse.

4.3 Crash Modification Factors for Specific 3R Improvement Types

This section presents the CMF values most commonly used to represent the crash reduction effectiveness of specific 3R improvement types. The following discussion is organized by roadway type, and then, within roadway type, by design feature.

The CMFs presented here are, whenever possible, those used in the HSM (*2*), which is the most widely utilized source for such information. Where no CMF is available in the HSM, high-quality CMFs from other sources are utilized. While these other CMFs were identified in the FHWA Crash Modification Factors Clearinghouse (*13*), the original sources have also been reviewed.

4.3.1 Rural Two-Lane Highways

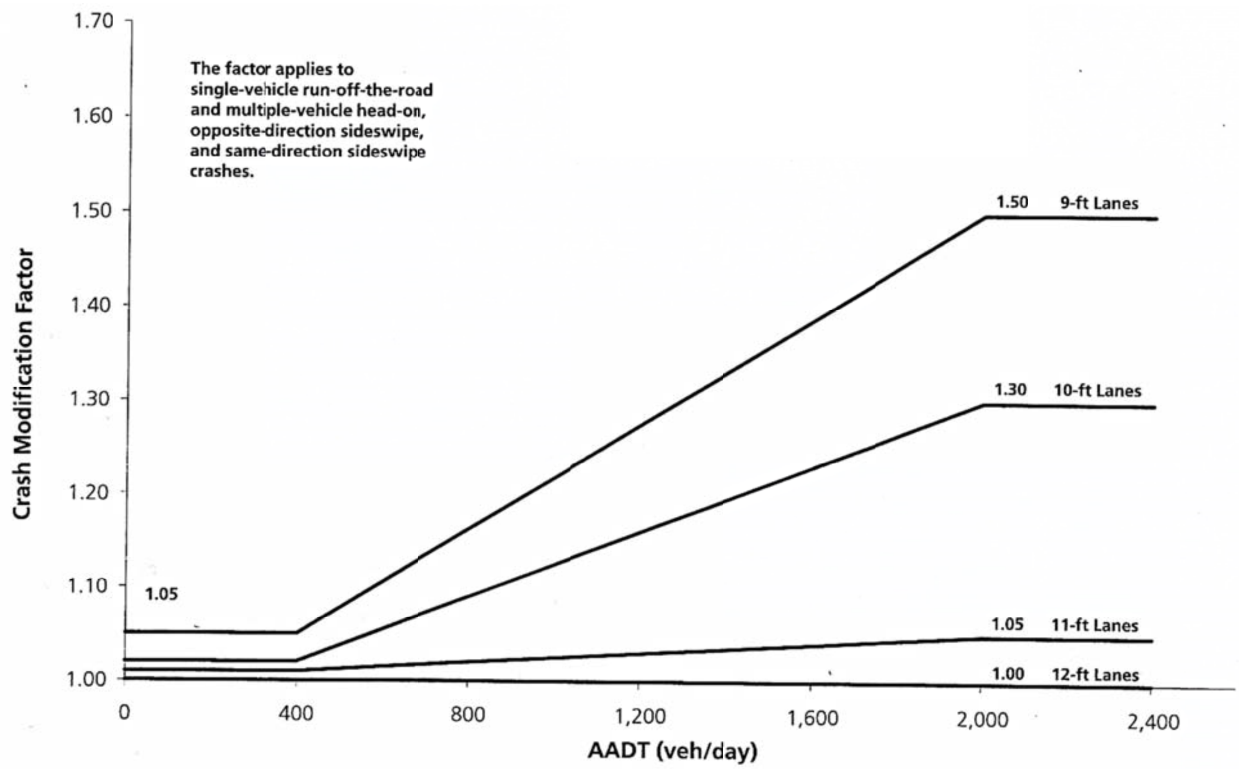
4.3.1.1 Lane Width

HSM Chapter 10 (Rural Two-Lane Highways) presents CMFs for lane widths on rural two-lane highways (*2*). The CMF is calculated using the equations shown in Table 3 based on the lane width and the average annual daily traffic (AADT) for the roadway in question. A 12-ft lane is considered to be the base condition (CMF = 1.0). The lane width CMF is illustrated graphically in Figure 3.

Table 3. CMF for Lane Width on Rural Two-Lane Roadway Segments (*2, 15, 16, 17*)

Lane width	Average annual daily traffic (AADT) (veh/day)		
	< 400	400 to 2000	> 2000
9 ft or less	1.05	$1.05 + 2.81 \times 10^{-4}$(AADT-400)	1.50
10 ft	1.02	$1.02 + 1.75 \times 10^{-4}$(AADT-400)	1.30
11 ft	1.01	$1.01 + 2.5 \times 10^{-5}$(AADT-400)	1.05
12 ft or more	1.00	1.00	1.00

NOTE: The collision types related to lane width to which these CMFs apply are single-vehicle run-off-the-road and multiple-vehicle head-on, opposite-direction sideswipe, and same-direction sideswipe crashes.
Standard error of the CMF is unknown.
To determine the CMF for changing lane width and/or AADT, divide the "new" condition CMF by the "existing" condition CMF.
NOTE: Based on HSM Table 10-8.



NOTE: Based on HSM Figure 10-7.

Figure 3. CMFra for Lane Width on Undivided Roadway Segments on Rural Two-Lane Roadway Segments (2, 15)

The lane-width CMF illustrated in Table 3 and Figure 3 applies only to single-vehicle run-off-the-road, and multiple-vehicle head-on, opposite-direction sideswipe, and same-direction sideswipe crashes. Equation (3) is used to adjust the lane-width CMF for these target or "related" crash types to a lane-width CMF applicable to total crashes:

$$CMF = (CMF_{ra} - 1.0) \times p_{ra} + 1.0 \quad \textbf{(3)}$$

where: CMF_{ra} = crash modification factor for the effect of lane width on target or "related" crashes (i.e., single-vehicle run-off-the-road and multiple-vehicle head-on, opposite-direction sideswipe, and same-direction sideswipe crashes), such as the crash modification factor for lane width shown in Table 3

P_{ra} = proportion of total crashes constituted by crash types related to lane and shoulder width

The proportion of related crashes, p_{ra}, (i.e., single-vehicle run-off-the-road, and multiple-vehicle head-on, opposite-direction sideswipe, and same-direction sideswipes crashes) is estimated as 0.574 (i.e., 57.4 percent) based on the default distribution of crash types presented in HSM Table 10-4. This default crash type distribution, and therefore, the value of p_{ra}, may be updated from local data as part of the calibration process.

4.3.1.2 Shoulder Width and Shoulder Type

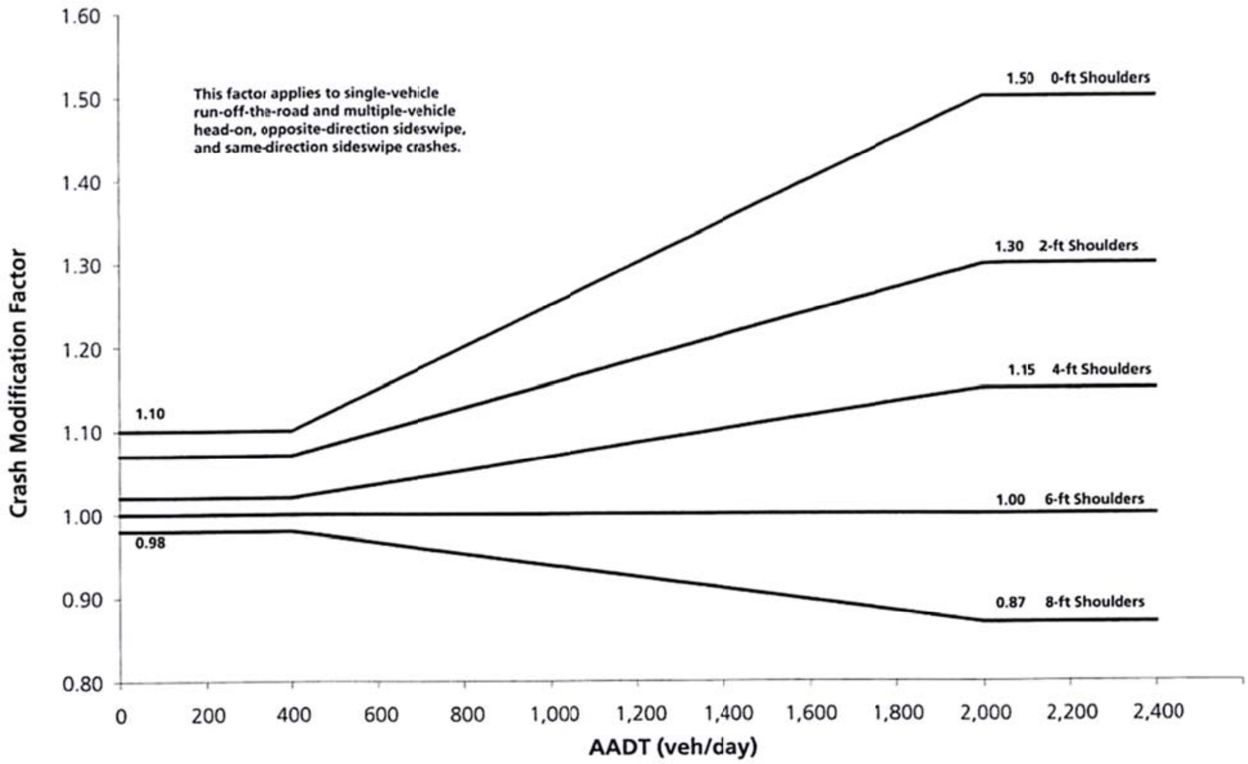
HSM Chapter 10 (Rural Two-Lane Highways) presents CMFs for shoulder width and shoulder type on rural two-lane roadways (*2*). The shoulder width effect, represented by CMF_{wra}, is calculated using the equations shown in Table 4. A 6-ft shoulder represents the base condition (CMF = 1.0). Shoulders wider than 6-ft (e.g., 8-ft shoulders) have CMFs less than 1.0, and shoulders narrower than 6 ft have CMFs greater than 1.0. The shoulder width CMF for rural two-lane highways (CMF_{wra}) is illustrated in Figure 4.

The base condition for shoulder type is a paved shoulder (CMF = 1.0). Table 5 presents values for CMF_{tra} which adjusts for the safety effects of shoulder types (paved, gravel, turf, and composite shoulders).

Table 4. CMF for Shoulder Width on Rural Two-Lane Roadway Segments (2, 15, 16, 18)

Shoulder width	Average annual daily traffic (AADT) (vehicles/day)		
	< 400	400 to 2000	> 2000
0 ft	1.10	$1.10 + 2.5 \times 10^{-4}$(AADT-400)	1.50
2 ft	1.07	$1.07 + 1.43 \times 10^{-4}$(AADT-400)	1.30
4 ft	1.02	$1.02 + 8.125 \times 10^{-5}$(AADT-400)	1.15
6 ft	1.00	1.00	1.00
8 ft or more	0.98	$0.98 - 6.875 \times 10^{-5}$(AADT-400)	0.87

NOTE: The collision types related to lane width to which this CMFs applies include single-vehicle run-off-the-road and multiple-vehicle head-on, opposite-direction sideswipe, and same-direction sideswipe crashes.
Standard error of the CMF is unknown.
To determine the CMF for changing paved shoulder width and/or AADT, divide the "new" condition CMF by the "existing" condition CMF.
NOTE: Based on HSM Table 10-9. The values from this table are used as CMF_{wra} in Equation (4).



NOTE: Based on HSM Figure 10-8.

Figure 4. Crash Modification Factor for Shoulder Width on Roadway Segments for Two-lane Highway (*2, 15, 16, 18*)

A combined CMF for shoulder width and type is computed as:

$$CMF = (CMF_{wra} \times CMF_{tra} - 1.0) \times p_{ra} + 1.0 \quad \textbf{(4)}$$

where: CMF_{wra} = crash modification factor for shoulder width from the equations in Table 4.

CMF_{tra} = crash modification factor for shoulder type from Table 5.

If the shoulder types and/or widths for the two directions of a roadway segment differ, the CMFs are determined separately for the shoulder type and width in each direction of travel and the resulting CMFs are then averaged.

The CMFs for shoulder width and type shown above apply only to the collision types that are most likely to be affected by shoulder width and type: single-vehicle run-off-the-road and multiple-vehicle head-on, opposite-direction sideswipe, and same-direction sideswipe crashes. The CMFs expressed on this basis are, therefore, adjusted to total crashes using Equation (4). The HSM default value for p_{ra} for two-lane highways in Equation (4) is 0.574.

Table 5. CMFs for Shoulder Types and Shoulder Width on Roadway Segments (CMF_{tra}) (*2, 15, 16, 18*)

Shoulder type	Shoulder width (ft)						
	0	1	2	3	4	6	8
Paved	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Gravel	1.00	1.00	1.01	1.01	1.01	1.02	1.02
Composite	1.00	1.01	1.02	1.02	1.03	1.04	1.06
Turf	1.00	1.01	1.03	1.04	1.05	1.08	1.11

NOTE: The values for composite shoulders in this table represent a shoulder for which 50 percent of the shoulder width is paved and 50 percent of the shoulder width is turf.
NOTE: Based on HSM Exhibit 10-10.

4.3.1.3 Realignment of Horizontal Curves

HSM Chapter 10 (Rural Two-Lane Highways) presents the following CMF for radius and length of horizontal curves on rural two-lane roads (*2*):

$$CMF = \frac{(1.55 \times L_c)\left(\frac{80.2}{R}\right) - (0.012 \times S)}{(1.55 \times L_c)} \quad \textbf{(5)}$$

where: L_c = Length of horizontal curve including length of spiral transitions, if present (mi);
R = Radius of curvature (ft); and
S = 1 if spiral transition curve is present: 0 if spiral transition curve is not present.

The base condition (CMF = 1.0) is a tangent alignment with no curvature. This CMF applies to total crashes and is based on research by Zegeer et al. (*19*).

4.3.1.4 Superelevation Restoration/Improvement on Horizontal Curves

HSM Chapter 10 presents a CMF for superelevation variance on rural two-lane highways (*2*), as follows:

$$CMF = 1.00 \; for \; SV < 0.01 \quad \textbf{(6)}$$

$$CMF = 1.00 + 6 \times (SV - 0.01) \; for \; 0.01 \leq SV < 0.02 \quad \textbf{(7)}$$

$$CMF = 1.06 + 3 \times (SV - 0.02) \; for \; SV \geq 0.02 \quad \textbf{(8)}$$

where: SV = superelevation variance (ft/ft), which represents the superelevation rate presented in the AASHTO *Green Book* minus the actual superelevation rate of the curve.

This CMF applies to total roadway segment crashes located on horizontal curves.

4.3.1.5 Centerline Rumble Strips

HSM Chapter 10 includes a CMF for the effects of a centerline rumble strip on a rural two-lane highway (*2*). The value of the CMF is 0.94 for crashes of all types.

4.3.1.6 Shoulder Rumble Strips

NCHRP Report 641 (*20*) found that shoulder rumble strips on rural two-lane highways reduce the target crash type, single vehicle run-off-road crashes by 15 percent, corresponding to a CMF of 0.85. Based on the estimates of crash-type proportions from HSM Chapter 10, the estimated CMF for the effect of shoulder rumble strips on total crashes is 0.92.

4.3.1.7 Striping and Delineation

3R projects often include improving the striping and delineation of the roadway. Replacement of pavement markings is an inherent part of most 3R projects, since pavement markings must be renewed when a roadway is resurfaced. No long-term safety benefit is likely if the existing pavement markings are simply replaced with equivalent pavement markings. Research for the Missouri Department of Transportation (MoDOT) in the report, *Benefit-Cost Evaluation of MoDOT's Total Striping and Delineation Program* (*21*) presents CMFs for striping and delineation improvement packages that include replacement of conventional painted markings with more durable markings that often have higher retroreflectivity. These striping and delineation packages packages often included placement of shoulder rumble strips as well, so the CMFs presented in this section should not be combined with the CMFs for shoulder rumble strips.

The MoDOT evaluation (*21*) found a 24.5 percent crash reduction in fatal-and-injury crashes on rural two-lane highways that were improved with striping and delineation packages, equivalent to a CMF of 0.76. A CMF of 0.76 also represents the best available estimate of the effectiveness of striping and delineation packages for property-damage-only crashes and for total crashes.

4.3.1.8 Roadside Slope Flattening

Flattening the roadside slope refers to lessening the steepness of the slope, such as adjusting a 1V:3H slope to a 1V:4H or 1V:6H slope. Roadside slope flattening may be considered as a crash countermeasure in 3R projects. Flatter roadside slopes provide the driver with a higher probability of a safe recovery maneuver in a vehicle that has departed the roadway, thus lessening the chance of a rollover or a collision with a roadside object. Roadside slope flattening appears to be primarily applicable to roadside foreslopes in fill sections, but flattening of cut slopes may be considered as well.

Research by Fitzpatrick et al. (*22*) quantified the effect of roadside slope flattening on total crash reduction based on the CMFs shown in Table 6. A roadside slope of 1V:3H represents the baseline condition in Table 6.

Table 6. Roadside Slope CMFs for Rural Two-Lane Highways (*22*)

Roadside slope	CMF
1V:2H	1.01
1V:3H	1.00
1V:4H	0.95
1V:6H	0.89

4.3.1.9 Guardrail Installation/Restoration

3R projects frequently install new guardrail where it is found to be needed or restore existing guardrail by providing needed maintenance or replacing older guardrail with current designs. There are no formal CMFs for guardrail installation or restoration. The cost-effectiveness of guardrail improvements is typically assessed with the Roadside Safety Analysis Program (RSAP) (*23, 24, 25*) which incorporates methods for quantifying the effectiveness of guardrail improvements.

4.3.1.10 Intersection Left- and Right-Turn Lanes

HSM Chapter 10 presents CMFs for the installation of left- and right-turn lanes at an intersection on rural two-lane highways (*2*). Table 7 presents CMFs for installing left-turn lanes and Table 8 presents CMFs for installing right-turn lanes. These CMFs apply to crashes of all crash severity levels.

Table 7. CMFs for Installation of Left-Turn Lanes on Intersection Approaches (*2*)

Intersection Type	Intersection Traffic Control	Number of Approaches with Left-Turn Lanes[a]			
		One Approach	Two Approaches	Three Approaches	Four Approaches
Three-leg Intersection	Minor road stop control[b]	0.56	0.31	—	—
Four-leg Intersection	Minor road stop control[b]	0.72	0.52	—	—
	Traffic signal	0.82	0.67	0.55	0.45

[a] Stop-controlled approaches are not considered in determining the number of approaches with left-turn lanes
[b] Stop signs present on minor road approaches only
NOTE: Based on HSM Table 10-13.

Table 8. CMFs for Installation of Right-Turn Lanes on Intersection Approaches (*2*)

Intersection Type	Intersection Traffic Control	Number of Approaches with Right-Turn Lanes[a]			
		One Approach	Two Approaches	Three Approaches	Four Approaches
Three-leg Intersection	Minor road stop control[b]	0.86	0.74	—	—
Four-leg Intersection	Minor road stop control[b]	0.86	0.74	—	—
	Traffic signal	0.96	0.92	0.88	0.85

[a] Stop-controlled approaches are not considered in determining the number of approaches with right-turn lanes
[b] Stop signs present on minor road approaches only
NOTE: Based on HSM Table 10-14.

These CMFs apply to left- or right-turn lanes installed on signalized intersection approaches or uncontrolled major-road approaches to stop-controlled intersections, but do not apply to stop-controlled approaches to stop-controlled intersections.

4.3.2 Rural Multilane Undivided Highways

4.3.2.1 Lane Width

The CMF for lane widths on multilane undivided roadways is determined using the equations in Table 9 (*2*). The base condition for lane width on multilane undivided highways is 12 ft. Figure 5 illustrates graphically the CMFs for lane widths on rural multilane undivided highways shown in Table 9.

Table 9. CMF for Lane Width on Undivided Rural Multilane Roadway Segments (*2, 26*)

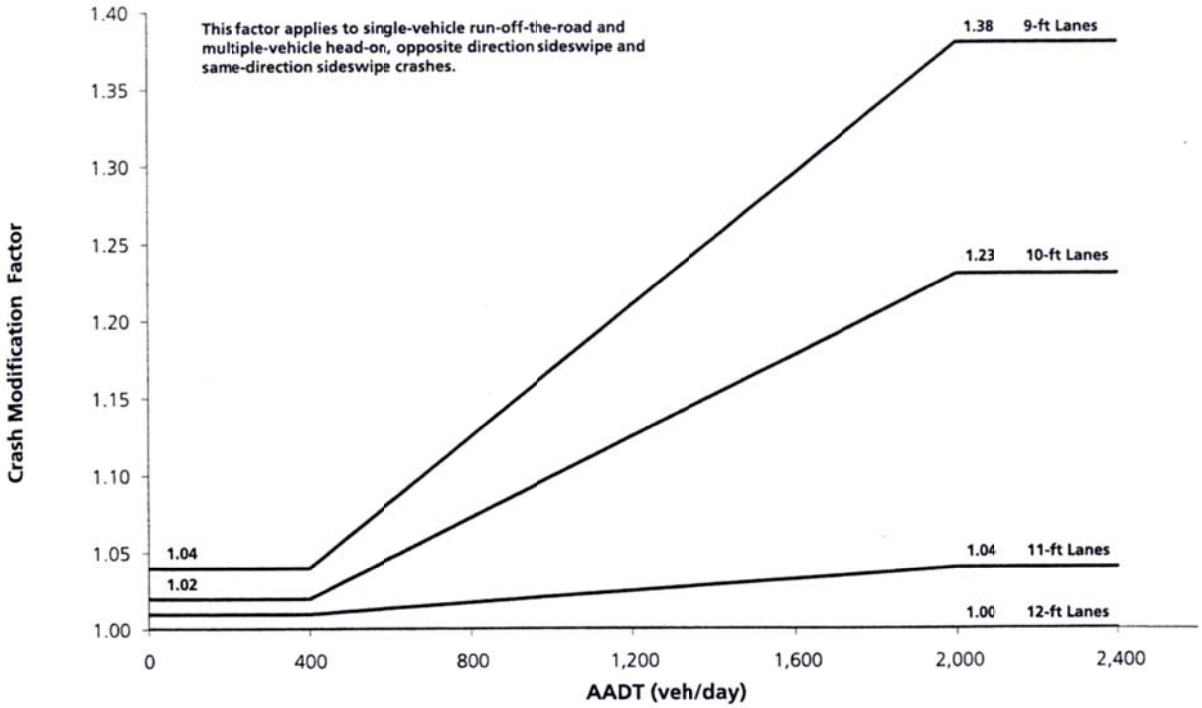
Lane width	Average annual daily traffic (AADT) (veh/day)		
	< 400	400 to 2000	> 2000
9 ft or less	1.04	$1.04 + 2.13 \times 10^{-4}$(AADT-400)	1.38
10 ft	1.02	$1.02 + 1.31 \times 10^{-4}$(AADT-400)	1.23
11 ft	1.01	$1.01 + 1.88 \times 10^{-5}$(AADT-400)	1.04
12 ft or more	1.00	1.00	1.00

NOTE: The collision types related to lane width to which these CMFs apply are single-vehicle run-off-the-road and multiple-vehicle head-on, opposite-direction sideswipe, and same-direction sideswipe crashes.
Standard error of the CMF is unknown.
To determine the CMF for changing lane width and/or AADT, divide the "new" condition CMF by the "existing" condition CMF.
NOTE: Based on HSM Table 11-11.

The CMFs shown in Table 9 and Figure 5 are applicable to single-vehicle run-off-the-road, multiple-vehicle head-on, opposite-direction sideswipe, and same-direction sideswipe crashes. Equation (3) can be used to convert these crash-type-specific CMFs to a CMF for total crashes. The default value of p_{ra} in Equation (3) is 0.27 for rural multilane undivided highways.

4.3.2.2 Shoulder Width and Shoulder Type

HSM Chapter 11 (Rural Multilane Highways) presents CMFs for shoulder type and width on rural multilane undivided highways (*2*). CMFs for undivided sections of multilane highways are calculated using the same equations as two-lane highways, using the shoulder width effect shown in Table 4 (see also Figure 4) and the shoulder type effect shown in Table 5. As in the case of rural two-lane highways, the base condition for the shoulder width CMF on a rural multilane highway is 6-ft and the base condition for shoulder type is a paved shoulder. Also, as is the case for rural two-lane highways, the shoulder width and type CMF for rural multilane highways is adjusted from related crashes to total crashes using Equation (4). The HSM default value for p_{ra} for rural multilane undivided highways used in Equation (4) is 0.27.



NOTE: Based on HSM Figure 11-8.

Figure 5. CMF$_{ra}$ for Lane Width on Undivided Roadway Segments on Rural Multilane Highways (*2, 26*)

4.3.2.3 Superelevation Restoration/Improvement on Horizontal Curves

No CMFs are available for superelevation variance or superelevation restoration for horizontal curves on rural multilane undivided highways. The CMFs shown in Equations (6) through (8) represent the best available estimate of the effect of superelevation variance on crash frequency for curves on rural multilane undivided highways.

4.3.2.4 Centerline Rumble Strips

No CMFs are available for the effect of centerline rumble strips on rural multilane highways. For purposes of these guidelines, the safety effect of centerline rumble strips on rural multilane undivided highways has been estimated as a CMF of 0.94, the same value used in the HSM for rural two-lane highway segments.

4.3.2.5 Shoulder Rumble Strips

No CMF for the effect of shoulder rumble strips on rural multilane undivided highways has been found, but for purposes of these guidelines the CMF has been estimated as 0.92, the same as the CMF for rural two-lane undivided highways.

4.3.2.6 Striping and Delineation

The MoDOT evaluation (*21*) presents striping and delineation evaluation results for rural multilane undivided highways. The MoDOT evaluation found that fatal-and-injury crashes were reduced by 29.8 percent on rural multilane undivided highways that were improved with striping and delineation packages. This is equivalent to a CMF of 0.70. For purposes of these guidelines, we have assumed that the CMFs for PDO crashes are the same as the CMF for fatal-and-injury crashes. Thus, the total crash CMF for striping and delineation packages on rural multilane undivided highways is 0.70.

4.3.2.7 Roadside Slope Flattening

HSM Chapter 11 presents CMFs for roadside slope flattening on rural multilane undivided highways (*2*), shown in Table 10. These CMFs apply to total crashes. The base condition for these crashes is a roadside slope of 1V:7H.

Table 10. Roadside Slope CMFs for Rural Multilane Highways (*2*)

Roadside slope	CMF
1V:2H	1.18
1V:3H	1.15
1V:4H	1.12
1V:5H	1.09
1V:6H	1.05
1V:7H	1.00

NOTE: Based on HSM Table 11-14.

4.3.2.8 Guardrail Installation/ Restoration

3R projects frequently install new guardrail where it is found to be needed or restore existing guardrail by providing needed maintenance or replacing older guardrail with current designs. There are no formal CMFs for guardrail installation or restoration. The cost-effectiveness of guardrail improvements is typically assessed with the Roadside Safety Analysis Program (RSAP) (*23*, *24*, *25*) which incorporates methods for quantifying the effectiveness of guardrail improvements.

4.3.2.9 Intersection Left- and Right-Turn Lanes

HSM Chapter 11 presents CMFs for the installation of left- and right-turn lanes at intersections on rural multilane highways (*2*). CMF values for installation of left- and right-turn lanes are presented in Table 11 and Table 12, respectively. Separate CMFs apply to total and fatal-and-injury crashes.

Table 11. CMFs for Installation of Left-Turn Lanes on Intersection Approaches (*2*)

Intersection Type	Crash Severity Level	Number of Approaches with Left-Turn Lanes[a]	
		One Approach	Two Approaches
Three-leg minor-road stop control[b]	Total	0.56	—
	Fatal and Injury	0.45	—
Four-leg minor-road stop control[b]	Total	0.72	0.52
	Fatal and Injury	0.65	0.42

[a] Stop-controlled approaches are not considered in determining the number of approaches with left-turn lanes.
[b] Stop signs present on minor road approaches only.
NOTE: Based on HSM Table 11-22.

Table 12. CMFs for Installation of Right-Turn Lanes on Intersection Approaches (*2*)

Intersection Type	Crash Severity Level	Number of Approaches with Left-Turn Lanes[a]	
		One Approach	Two Approaches
Three-leg minor-road stop control[b]	Total	0.86	—
	Fatal and Injury	0.77	—
Four-leg minor-road stop control[b]	Total	0.86	0.74
	Fatal and Injury	0.77	0.59

[a] Stop-controlled approaches are not considered in determining the number of approaches with right-turn lanes.
[b] Stop signs present on minor road approaches only.
NOTE: Based on HSM Table 11-23.

4.3.3 Rural Multilane Divided Highways (Nonfreeways)

4.3.3.1 Lane Width

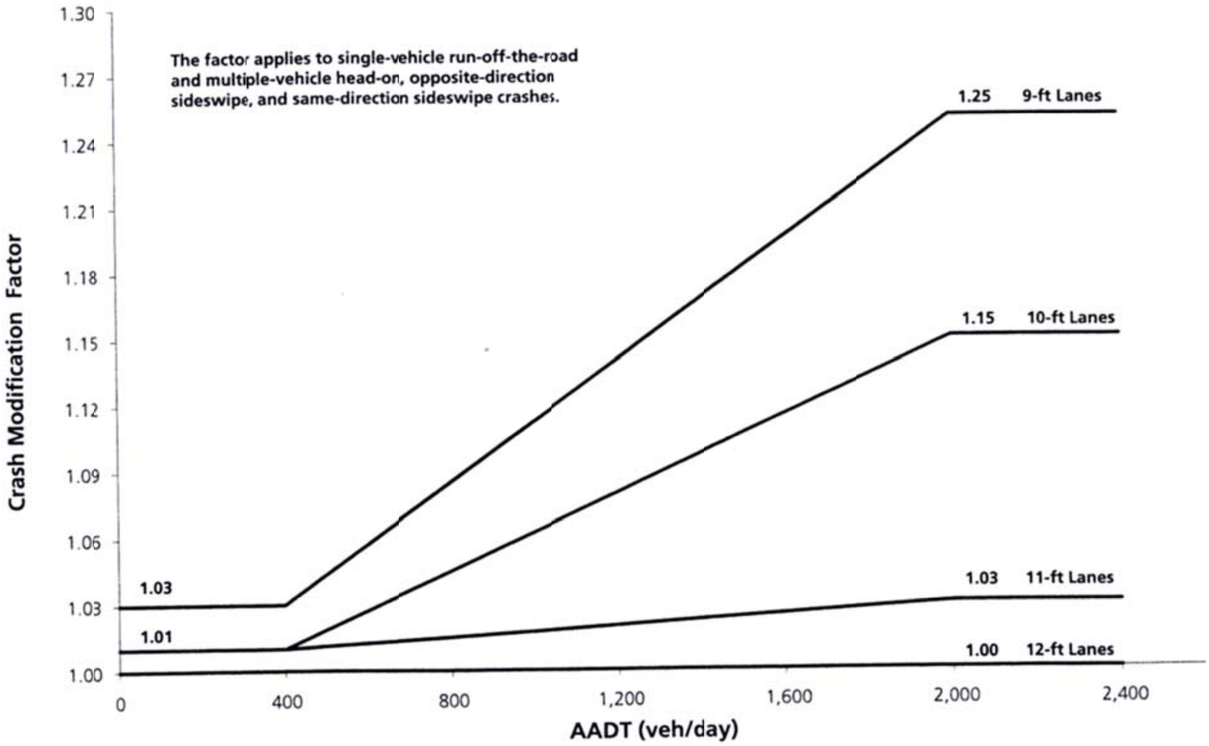
The CMF for multilane divided roadways is determined using the equations in Table 13 (*2*). The base condition for lane width on multilane undivided highways is 12 ft. Figure 6 illustrates graphically the CMFs for lane widths on rural multilane divided highways.

Table 13. CMF for Lane Width on Divided Rural Multilane Roadway Segment (*2, 26*)

Lane width	Average annual daily traffic (AADT) (vehicles/day)		
	< 400	400 to 2000	> 2000
9 ft or less	1.03	$1.03 + 1.381 \times 10^{-4}(\text{AADT}-400)$	1.25
10 ft	1.01	$1.01 + 8.75 \times 10^{-4}(\text{AADT}-400)$	1.15
11 ft	1.01	$1.01 + 1.25 \times 10^{-5}(\text{AADT}-400)$	1.03
12 ft or more	1.00	1.00	1.00

NOTE: The collision types related to lane width to which these CMFs apply are single-vehicle run-off-the-road and multiple-vehicle head-on, opposite-direction sideswipe, and same-direction sideswipe crashes.
Standard error of the CMF is unknown.
To determine the CMF for changing lane width and/or AADT, divide the “new” condition CMF by the “existing” condition CMF.
NOTE: Based on HSM Table 11-16.

The CMFs shown in Table 13 and Figure 6 are applicable to single-vehicle run-off-the-road, multiple-vehicle head-on, opposite-direction sideswipe, and same-direction sideswipe crashes. Equation (3) can be used to convert these crash-type-specific CMFs to a CMF for total crashes. The default value of p_{ra} in Equation (3) is 0.50 for rural multilane divided highways.



NOTE: Based on HSM Figure 11-10.

Figure 6. CMF$_{ra}$ for Lane Width on Divided Roadway Segments on Rural Multilane Highways (*2, 26*)

4.3.3.2 Shoulder Width

HSM Chapter 11 (Rural Multilane Highways) presents CMFs for shoulder width on rural multilane divided highways (*2*). CMFs for the width of the right (outside) shoulder of a rural multilane divided highway are given by the values presented in Table 14. The base condition (CMF = 1.0) for the divided highway shoulder width is represented by an 8-ft shoulder. This CMF applies to total crashes and does not need to be adjusted using a p_{ra} value. There is no CMF for shoulder type.

Table 14. CMFs for Paved Right (Outside) Shoulder Width on Rural Multilane Divided Highway Segments (*2, 27*)

Average paved shoulder width (ft)				
0	2	4	6	8 or more
1.18	1.13	1.09	1.04	1.00

NOTE: Based on HSM Table 11-17.

There is no CMF available for the width or type of the left (inside) shoulder of a rural multilane divided highway (nonfreeway).

4.3.3.3 Realignment of Horizontal Curves

No CMFs for horizontal curve length, radius, or superelevation on rural multilane divided highways (nonfreeways) are presented in HSM Chapter 11.

4.3.3.4 Superelevation Restoration/Improvement on Horizontal Curves

No CMFs were found for superelevation variance or superelevation restoration for horizontal curves on rural multilane divided highways. The CMFs shown in Equations (6) through (8) represent the best available estimate of the effect of superelevation variance on crash frequency for curves on rural multilane divided highways.

4.3.3.5 Shoulder Rumble Strips

A CMF for the effect of shoulder rumble strips on total crashes on multilane divided highways presented in HSM Chapter 13 is 0.84 (*2*).

4.3.3.6 Striping and Delineation

The MoDOT evaluation (*21*) also presents results for rural multilane divided highways. On rural multilane divided highways that were improved with striping and delineation packages, fatal-and-injury crashes were reduced by 13.8 percent, equivalent to a CMF of 0.86. For the purpose of this research, we have assumed that the CMFs for PDO crashes are the same as the CMF for fatal-and-injury crashes. Thus, the total crash CMF for striping and delineation packages on rural multilane divided highways is 0.86.

4.3.3.7 Roadside Slope Flattening

No CMFs are available for rural multilane divided highways, but the CMFs presented in Table 10 likely represent the best available estimate.

4.3.3.8 Guardrail Installation/Restoration

3R projects frequently install new guardrail where it is found to be needed or restore existing guardrail by providing needed maintenance or replacing older guardrail with current designs. There are no formal CMFs for guardrail installation or restoration. The cost-effectiveness of guardrail improvements is typically assessed with the Roadside Safety Analysis Program (RSAP) (*23, 24, 25*) which incorporates methods for quantifying the effectiveness of guardrail improvements.

4.3.3.9 Intersection Left- and Right-Turn Lanes

HSM Chapter 11 presents CMFs for the installation of left- and right-turn lanes at intersections on rural multilane highways. CMF values for installation of left- and right-turn lanes are presented in Table 15 and Table 16, respectively. Separate CMFs apply to total and fatal-and-injury crashes.

Table 15. CMFs for Installation of Left-Turn Lanes on Intersection Approaches (*2*)

Intersection Type	Crash Severity Level	Number of Approaches with Left-Turn Lanes[a]	
		One Approach	Two Approaches
Three-leg minor-road stop control[b]	Total	0.56	—
	Fatal and Injury	0.45	—
Four-leg minor-road stop control[b]	Total	0.72	0.52
	Fatal and Injury	0.65	0.42

[a] Stop-controlled approaches are not considered in determining the number of approaches with left-turn lanes.
[b] Stop signs present on minor road approaches only.
NOTE: Based on HSM Table 11-22.

Table 16. CMFs for Installation of Right-Turn Lanes on Intersection Approaches (*2*)

Intersection Type	Crash Severity Level	Number of Approaches with Left-Turn Lanes[a]	
		One Approach	Two Approaches
Three-leg minor-road stop control[b]	Total	0.86	—
	Fatal and Injury	0.77	—
Four-leg minor-road stop control[b]	Total	0.86	0.74
	Fatal and Injury	0.77	0.59

[a] Stop-controlled approaches are not considered in determining the number of approaches with right-turn lanes.
[b] Stop signs present on minor road approaches only.
NOTE: Based on HSM Table 11-23.

4.3.4 Urban and Suburban Arterials

4.3.4.1 Lane Width

There are no CMFs for lane width on urban and suburban arterials in HSM Chapter 12. The AASHTO *Green Book* (*2*) provides broad flexibility for the use of 10-, 11-, and 12-ft lanes on urban and suburban arterials. Recent research (*28*) found no substantial differences in safety performance between 10-, 11-, and 12-ft lanes, except in limited cases. Research is currently underway in NCHRP Project 3-112 to document the safety performance of lane widths on urban and suburban arterials and provide design guidance.

4.3.4.2 Shoulder Type and Width

There are no CMFs for shoulder width on urban and suburban arterials in HSM Chapter 12. The AASHTO *Green Book* (*2*) provides broad flexibility in choosing shoulder widths on urban and suburban arterials, including use of curb-and-gutter sections with no shoulder on low- and intermediate-speed arterials. Research is underway as part of the FHWA Highway Safety

Information System (HSIS) program to assess the safety performance of shoulder widths and curb-and-gutter sections on urban and suburban arterials.

4.3.4.3 Realignment of Horizontal Curves

There are no CMFs for horizontal curve length or radius on urban and suburban arterials in HSM Chapter 12 and there is no definitive research on this topic. Research is underway as part of the FHWA HSIS program to assess the effects of horizontal curve design elements on urban and suburban arterials.

4.3.4.4 Superelevation

There are no CMFs for superelevation of horizontal curves on urban and suburban arterials in HSM Chapter 12 and there is no definitive research on this topic.

4.3.4.5 Centerline Rumble Strips

NCHRP Report 641, *Guidance for the Design and Application of Shoulder and Centerline Rumble Strips* (*20*), found that centerline rumble strips on urban two-lane arterials reduce total target crashes by 40 percent, corresponding to a CMF of 0.60. Target crashes for centerline rumble strips are those involving a lane departure to the left. Based on the estimates of crash-type proportions from HSM Chapter 10 and the assumption that 50 percent of lane departures on rural two-lane highways are to the left, the estimated CMF for the effect of centerline rumble strips on total crashes on urban and suburban two-lane roads is 0.96.

No CMFs are available for the safety effects of centerline rumble strips on multilane urban and suburban arterials.

4.3.4.6 Shoulder Rumble Strips

No research was found on CMFs for shoulder rumble strips on urban and suburban arterials. For the purposes of these guidelines, it is estimated that the CMF for shoulder rumble strips is 0.92 for undivided arterials and 0.84 for divided arterials, consistent with the values found in research for rural highways. It is assumed that shoulder rumble strips would only be installed on urban and suburban arterials with open cross sections (i.e., with shoulder present) and not on urban and suburban arterials with curb-and-gutter sections.

4.3.4.7 Striping and Delineation

There are no accepted CMFs for striping and delineation packages on urban and suburban arterials.

4.3.4.8 Intersection Left- and Right-Turn Lanes

HSM Chapter 12 presents CMFs for the installation of left- and right-turn lanes at intersections on urban and suburban arterials (*2*). CMF values for installation of left- and right-turn lanes are shown in Table 17 and Table 18, respectively. These CMFs apply to crashes of all severity levels.

Table 17. CMFs for Installation of Left-Turn Lanes on Intersection Approaches (*2*)

Intersection Type	Intersection Traffic Control	Number of Approaches with Left-Turn Lanes[a]			
		One Approach	Two Approaches	Three Approaches	Four Approaches
Three-leg intersection	Minor-road stop control[b]	0.67	0.45	—	—
	Traffic signal	0.93	0.86	0.80	—
Four-leg intersection	Minor-road stop control[b]	0.73	0.53	—	—
	Traffic signal	0.90	0.81	0.73	0.66

[a] Stop-controlled approaches are not considered in determining the number of approaches with left-turn lanes.
[b] Stop signs present on minor road approaches only.
NOTE: Based on HSM Table 11-24.

Table 18. CMFs for Installation of Right-Turn Lanes on Intersection Approaches (*2*)

Intersection Type	Intersection Traffic Control	Number of Approaches with Right-Turn Lanes[a]			
		One Approach	Two Approaches	Three Approaches	Four Approaches
Three-leg intersection	Minor-road stop control[b]	0.86	0.74	—	—
	Traffic signal	0.96	0.92	—	
Four-leg intersection	Minor-road stop control[b]	0.86	0.74	—	—
	Traffic signal	0.96	0.92	0.88	0.85

[a] Stop-controlled approaches are not considered in determining the number of approaches with right-turn lanes.
[b] Stop signs present on minor road approaches only.
NOTE: Based on HSM Table 11-26.

4.3.5 Rural and Urban Freeways

4.3.5.1 Lane Width

HSM Chapter 18 (*3*) presents CMFs for lane width on through traffic lanes on freeways (*2*). The CMFs are the same for fatal-and-injury multiple-vehicle crashes and fatal-and-injury single-vehicle crashes and are determined using the following equations. The CMF is applicable to lane widths in the range of 10.5 to 14 ft.

$$CMF = e^{a(W_l - 12)}, If\ W_l < 13\ ft \quad \textbf{(9)}$$

$$CMF = b, If\ W_l \geq 13\ ft \quad \textbf{(10)}$$

where: a = -0.0376
b = 0.963
W_l = lane width (ft)

The HSM shows no quantifiable effect of lane width on property-damage-only crashes.

4.3.5.2 Inside Shoulder Width

HSM Chapter 18 (*3*) presents a CMF for paved shoulder width on the inside or median side of freeways. The CMF is calculated using the following equation.

$$CMF = e^{a(W_{is}-6)} \quad \textbf{(11)}$$

where: a = CMF coefficient (see Table 19)
W_{is} = paved inside shoulder width (ft)

This CMF is applicable to paved shoulder widths in the range of 2 to 12 ft. The CMF is computed separately for fatal-and-injury crashes and property-damage-only crashes. Table 19 shows the coefficient values that are used in Equation (11). Note that for a given crash severity level, the coefficient values are the same for multiple- and single-vehicle crashes.

Table 19. Coefficients for Inside Shoulder Width CMF on Freeways (*3*)

Crash Type	Crash Severity Level	CMF Coefficient (*a*)
Multiple vehicle	Fatal and injury	-0.0172
	Property damage only	-0.0153
Single vehicle	Fatal and injury	-0.0172
	Property damage only	-0.0153

4.3.5.3 Outside Shoulder Width

HSM Chapter 18 (*3*) presents a CMF for paved shoulder width on the outside or right side of freeway roadways (2). The CMF is calculated using the following equation:

$$CMF = \left(1.0 - \sum_{i=1}^{m} \frac{L_{c,i}}{2L}\right) e^{a(W_s-10)} + \left(\sum_{i=1}^{m} \frac{L_{c,i}}{2L}\right) e^{b(W_s-10)} \quad \textbf{(12)}$$

where: a,b = CMF coefficients (see Table 20)
W_s = paved inside shoulder width (ft)
$L_{c,i}$ = length of curve i on freeway segment (mi)
L = length of freeway segment (mi)
m = total number of curves on freeway section for both directions of travel combined

The curve lengths need to be summed for both directions of the freeway. The coefficient values used in Equation (12) are shown in Table 20. This CMF is only applicable to paved outside shoulder widths in the range of 4 to 14 ft. Also, this CMF is only applicable to single-vehicle crashes of all severity levels. Equation (12) is presented here in a slightly different form than it appears in the HSM so that the effect of all curves for both direction so travel combined can be estimated in a single calculation.

Table 20. Coefficients for Outside Paved Shoulder Width CMF on Freeways (*3*)

Crash Type	Crash Severity Level	CMF Coefficients	
		a	*b*
Single-vehicle	Fatal and injury	-0.0647	-0.0897
	Property damage only	0.00	-0.0840

4.3.5.4 Shoulder Rumble Strips

HSM Chapter 18 (*3*) presents a CMF for the presence of shoulder rumble strips on the inside and outside shoulders of freeway roadways (*2*). The CMF is presented in the following equations:

$$CMF = \left(1.0 - \sum_{i=1}^{m} \frac{L_{c,i}}{2L}\right) f_{tan} + \left(\sum_{i=1}^{m} \frac{L_{c,i}}{2L}\right) \quad \textbf{(13)}$$

$$f_{tan} = 0.5[(1.0 - P_{ir}) + 0.811 P_{ir}] + 0.5[(1.0 - P_{or}) + 0.811 P_{or}] \quad \textbf{(14)}$$

where: P_{ir} = proportion of segment with rumble strips present on the inside shoulders
P_{or} = proportion of segment with rumble strips present on the outside shoulders

Equation (13) is presented here in a slightly different form than it appears in the HSM so that the effect of all curves for both directions of travel combined can be estimated in a single calculation.

4.3.5.5 Median Barrier

HSM Chapter 18 (*3*) presents a CMF for the presence of a median barrier on a freeway (*2*). The CMF is computed using the following equations. This CMF is applicable to both for single- and multiple-vehicle collisions of all crash severity levels.

$$CMF = (1.0 - P_{ib}) + P_{ib} e^{\frac{a}{W_{icb}}} \quad \textbf{(15)}$$

where: a = CMF coefficient (see Table 21)
P_{ib} = proportion of segment length with a barrier present in the median (see discussion below for calculation of P_{ib})
W_{icb} = distance from edge of inside shoulder to barrier face (see discussion below for calculation of W_{icb})

If a continuous median barrier is centered in the median, use Equations (16) and (17) to calculate P_{ib} and W_{icb}.

$$W_{icb} = \frac{2L}{\sum \frac{L_{ib,i}}{W_{off,in,i} - W_{is}} + \frac{2L - \sum L_{ib,i}}{0.5(W_m - 2W_{is} - W_{ib})}} \quad \textbf{(16)}$$

$$P_{ib} = 1.0 \quad \textbf{(17)}$$

where:

L = length of segment (mi)
$L_{ib,i}$ = length of lane paralleled by inside barrier *i* (mi)
$W_{off,in,i}$ = horizontal clearance from the edge of the traveled way to the face of inside barrier *i* (ft)
W_{is} = paved inside shoulder width (ft)
W_m = median width (measured from near edges of traveled way in both directions) (ft)
W_{ib} = inside barrier width (measured from barrier face to barrier face) (ft)

If a continuous median barrier is adjacent to one of the directions of travel, but not centered in the median, use Equation (18) and (19) to calculate P_{ib} and W_{icb}.

$$W_{icb} = \frac{2L}{\frac{L}{W_{near} - W_{is}} + \sum \frac{L_{ib,i}}{W_{off,in,i} - W_{is}} + \frac{L - \sum L_{ib,i}}{W_m - 2W_{is} - W_{ib} - W_{near}}} \quad \textbf{(18)}$$

$$P_{ib} = 1.0 \quad \textbf{(19)}$$

where: W_{near} = near horizontal clearance from the edge of the traveled way to the continuous median barrier (measure for both travel directions and use the smaller distance) (ft)

For segments with some short sections of barrier in the median, use Equation (20) and (21) to determine P_{ib} and W_{icb}.

$$W_{icb} = \frac{\sum L_{ib,i}}{\sum W_{off,in,i} - W_{is}} \quad \textbf{(20)}$$

$$P_{ib} = \frac{\sum L_{ib,i}}{2L} \quad \textbf{(21)}$$

Values for the median barrier CMF coefficient, *a*, are presented in Table 21. This coefficient is used in Equation (15).

Table 21. Coefficients for Presence of Median Barrier CMF on Freeways (*3*)

Crash Type	Crash Severity Level	CMF Coefficient (*a*)
Multiple vehicle	Fatal and injury	0.131
	Property damage only	0.169
Single vehicle	Fatal and injury	0.131
	Property damage only	0.169

4.3.5.6 Traffic Barrier on the Outside or Right Side of a Freeway

HSM Chapter 18 (*3*) presents a CMF for the presence of a traffic barrier on the outside or right roadside of a freeway. The CMF is calculated using the following equations. This CMF is only applicable to single-vehicle collisions. The HSM shows no quantifiable effect the presence of a of median barrier on multiple-vehicle collisions.

$$CMF = (1.0 - P_{ob}) + P_{ob} e^{\frac{a}{W_{ocb}}} \quad \textbf{(22)}$$

where: a = CMF coefficient (see Table 22)
P_{ob} = proportion of segment length with a barrier present on the roadside
W_{ocb} = distance from edge of outside shoulder to barrier face (ft)

Use Equations (23) and (24) to calculate P_{ob} and W_{ocb}.

$$W_{ocb} = \frac{\sum L_{ob,i}}{\sum \frac{L_{ob,i}}{W_{off,o,i} - W_s}} \quad \textbf{(23)}$$

$$P_{ob} = \frac{\sum L_{ob,i}}{2L} \quad \textbf{(24)}$$

where: L = length of segment (mi)
$L_{ob,i}$ = length of lane paralleled by outside barrier i (mi)
$W_{off,o,i}$ = horizontal clearance from the edge of the traveled way to the face of outside barrier i (ft)
W_s = paved outside shoulder width (ft)

Values for the outside barrier CMF coefficient, a, are presented in Table 22. This coefficient is used in Equation (22).

Table 22. Coefficients for Presence of Outside Barrier CMF on Freeways (*3*)

Crash Type	Crash Severity Level	CMF Coefficient (*a*)
Single vehicle	Fatal and injury	0.131
	Property damage only	0.169

4.3.5.7 Median Width

HSM Chapter 18 (*3*) presents a CMF for median width on a freeway (*2*). Median width is not likely to be changed in a 3R project. However, this CMF is presented here because the median width CMF is influenced by the paved inside shoulder width (W_{is}), which may be changed in a 3R project.

The median width CMF is calculated using the following equation. This CMF is applicable to both single- and multiple-vehicle collisions of all crash severity levels.

$$CMF = (1.0 - P_{ib})e^{a(W_m - 2W_{is} - 48)} + P_{ib}e^{a(2W_{icb} - 48)} \qquad \textbf{(25)}$$

where: a = CMF coefficient (see Table 25)
W_{is} = paved inside shoulder width (ft)
W_m = median width (measured from near edges of traveled way in both directions) (ft)
P_{ib} = proportion of segment length with a barrier present in the median (see Equations (16) through (21) for calculation of this variable)
W_{icb} = distance from edge of inside shoulder to barrier face (ft) (see Equations (16) through (21) for calculation of this variable)

Values for the median width CMF coefficient, a, are presented in Table 23. This coefficient is used in Equation (25).

Table 23. Coefficients for Median Width on Freeways (*3*)

Crash Type	Crash Severity Level	CMF Coefficient (*a*)
Multiple vehicle	Fatal and injury	-0.00302
	Property damage only	-0.00291
Single vehicle	Fatal and injury	0.00102
	Property damage only	-0.00289

4.4 Investing Available 3R Funds for Maximum Reduction of Crash Frequency and Severity

Since funds available for highway infrastructure improvements are limited, it is important that those funds, including funds for 3R projects, be invested to accomplish the project objectives, including preserving the pavement and extending the pavement service life, improving traffic operations, and, to the extent practical, maximizing the potential reduction in crash frequency and severity. Maximizing the reduction in crash frequency and severity requires that the available funds be invested in a logical priority fashion, focusing on those projects where the maximum crash reduction benefit can be obtained for the least cost.

Recent research (*6*) has shown that investing available funds in safety improvement without careful planning can lead to suboptimal results. This is illustrated by the following example.

4.4.1 Example of Optimal and Suboptimal Strategies for Investing Available Funds in Design Improvements to Reduce Crash Frequency and Severity

Highway agency users who apply the 3R design guidelines will apply them to one site at a time, but their appropriateness can be tested by applying them systemwide to rural highway systems and reviewing the results. As an example, four potential strategies for lane widening to the rural two-lane highway system of an actual state using data from the FHWA Highway Safety Information System (HSIS) were tested in recent research (*7*). This rural two-lane highway system consists of 4,630.71 mi of road with AADTs up to 25,000 veh/day. The current lane width distribution for this road system is:

Lane Width (ft)	Total Length (mi)
9	18.29
10	251.74
11	2,087.38
12	2,273.30
TOTAL	4,630.71

The following improvement strategies were considered and were applied as if the entire road system were a candidate for resurfacing in a single year:

- Widen all lanes with widths less than 12 ft to 12 ft
- Widen lanes where a need is indicated by the TRB Special Report 214 (*1*) lane width criteria presented in Table 24
- Widen lanes on roadways where the AADT exceeds the minimum AADT criteria presented in Table 24
- Widen lanes where the net present benefits of the project exceeds zero (i.e., where the benefits exceed the costs) based on the benefit-cost analysis procedure presented in Chapter 5

The benefits and cost of lane widening in this example are based on assumptions concerning crash costs, unit construction costs, project service life, and minimum attractive rate of return presented in Section 5.1. These values vary widely in current practice, but the assumptions used here are typical of the middle range of values currently used by highway agencies.

Table 24. Minimum Lane and Shoulder Widths for Rural Two-Lane Highways from TRB Special Report 214 (*1*)

Design year volume (ADT)[a]	10 percent or more trucks[c]			Less than 10 percent trucks	
	Running speed[b] (mph)	Lane width (ft)	Combined lane and shoulder width (ft)[d]	Lane width (ft)	Combined lane and shoulder width (ft)[d]
1-750	Under 50	10	12	9	11
	50 and over	10	12	10	12
751-2,000	Under 50	11	13	10	12
	50 and over	12	15	11	14
Over 2,500	All	12	18	11	17

[a] Design volume for a given highway feature should match average traffic anticipated over the expected performance of that feature.
[b] Highway segments should be classified as “under 50” only if most vehicles have an average speed of less than 50 mph over the length of the segment.
[c] For this comparison, trucks are defined as heavy vehicles with six or more tires.
[d] One foot less for highways in mountainous terrain.
NOTE: This table is presented as an example of historical practice but, as shown below, its use is no longer recommended.

4.4.1.1 Lane Widening Strategy—Widen All Lanes to 12 ft

This strategy would select for widening the 2,357.41 mi of roadway with existing lane widths less than 12 ft. This would change the lane-width distribution on the roadway system as shown below:

	Total Length (mi)	
Lane Width (ft)	**Before**	**After**
9	18.29	0.00
10	251.74	0.00
11	2,087.38	0.00
12	2,273.30	4,630.71
TOTAL	4,630.71	4,630.71

This improvement program would provide benefits of $68,911,192 at a cost of $516,336,773, equivalent to a benefit-cost ratio of 0.13. Of the 2,357.41 mi of roadway improved, 97 percent consisted of projects with benefit-cost ratios less than 1.0. This high proportion of projects that were not cost-effective occurred because most of the extensive mileage of two-lane roadways consisted of 11-ft lanes, where lane widening provides only a limited benefit (see Section 4.3.1.1)

4.4.1.2 Lane Widening Strategy—Widen Lanes Based on TRB Special Report 214 Criteria

This strategy would select for widening the 832.28 mi of roadway that do not meet the TRB Special Report 214 lane width criteria shown in Table 24. This would change the lane-width distribution on the roadway system as shown below:

	Total Length (mi)	
Lane Width (ft)	**Before**	**After**
9	18.29	0.00
10	251.74	175.20
11	2,087.38	1,432.58
12	2,273.30	3,022.93
TOTAL	4,630.71	4,630.71

This improvement program would provide benefits of $57,180,686 at a cost of $200,107,835, equivalent to a benefit-cost ratio of 0.29. Of the 832.28 mi of roadway improved, 96 percent consisted of projects with benefit-cost ratios less than 1.0. This strategy does a better job at focusing on the best projects and avoided many of the projects included in the 12-ft lane strategy that were not cost-effective, but not all of them.

4.4.1.3 Lane Widening Strategy—Minimum AADT Levels

This strategy would select for widening the 54.88 mi of roadway that meet the minimum AADT criteria presented in Section 5.4. This would change the lane-width distribution on the roadway system as shown below:

	Total Length (mi)	
Lane Width (ft)	**Before**	**After**
9	18.29	18.29
10	251.74	231.25
11	2,087.38	2,052.99
12	2,273.30	2,328.18
TOTAL	4,630.71	4,630.71

This improvement program would provide benefits of $12,391,936 at a cost of $14,824,774, equivalent to a benefit-cost ratio of 0.84. Of the 54.88 mi of roadway improved, 60 percent consisted of projects with benefit-cost ratios less than 1.0. This strategy does a better job at focusing on the best projects and avoided many of the projects that are not cost-effective.

4.4.1.4 Lane Widening Strategy—Benefit-Cost Analysis for Individual Projects

This strategy would select for widening 35.34 mi of roadway for which a need for lane widening was identified by a benefit-cost analysis using the benefit-cost analysis procedure presented in

Section 5.2.2. This would change the lane-width distribution on the roadway system as shown below:

	Total Length (mi)	
Lane Width (ft)	**Before**	**After**
9	18.29	18.29
10	251.74	219.36
11	2,087.38	2,076.96
12	2,273.30	2,301.32
TOTAL	4,630.71	4,630.71

This improvement program would provide benefits of $7,817,183 at a cost of $5,603,567, equivalent to a benefit-cost ratio of 1.40. Every portion of the 35.34 mi of roadway improved in this program, was a cost-effective project, and the benefits for the program as a whole exceed the costs. This strategy does the best job at focusing on the best projects and avoids many of the projects that are not cost-effective.

4.4.1.5 Summary of Findings from the Example of Lane Widening Strategies

The example of lane widening strategies for a statewide system of rural two-lane highways shows that an improvement program based on benefit-cost analysis for individual projects would provide the greatest net present benefits and the greatest return per dollar spent and would avoid improvements that are not cost-effective. However, benefit-cost analysis results are not necessarily exact, and not every highway agency will have the data available and in a suitable form for a benefit-cost analysis. Minimum AADT criteria developed through a benefit-cost analysis come the closest of the other alternatives to providing optimal results. Both blanket lane widening to a minimum 12-ft lane width and lane widening based on the design criteria from TRB Special Report 214 (*1*) result in many lane widening investments that would not be cost-effective. The primary drawback of strategies developed before publication of the HSM is likely to be a focus on widening 11 ft lanes to 12 ft, which is unlikely to be cost-effective except at very high volumes. Finally, it should be noted that in actual practice some roadways might be found to have experienced patterns of single-vehicle run-off-road, head-on, opposite-direction sideswipe, or same-direction sideswipe crashes that could indicate a need for lane widening regardless of the results of the benefit-cost analysis.

Chapter 5.
Application of Benefit-Cost Analysis for 3R Projects

Benefit-cost analysis enables highway agencies to assess design alternatives for 3R projects and decide (a) whether geometric design improvements should be made as part of the project and, if so, (b) which geometric design improvements are appropriate for particular projects.

5.1 Elements of Benefit-Cost Analysis

The elements of a benefit-cost analysis for a particular design alternative are presented here. Examples of the use of these elements in benefit-cost analysis are presented below. While the computations needed for a benefit-cost analysis may appear complex, they can be performed automatically by the benefit-cost analysis spreadsheet tools presented in Section 5.6.

5.1.1 Implementation Cost for Geometric Design Improvements

A key element of benefit-cost analysis for a particular geometric design alternative is the cost of implementing that alternative. This cost is referred to as the implementation cost, rather than the construction cost, because it includes not only construction costs, but also the cost of acquiring any right-of-way needed to implement the design alternative. Highway agencies differ in their policies concerning right-of-way acquisition as part of 3R projects. Some agencies almost never consider design alternatives that involve right-of-way acquisition as part of 3R projects; other agencies routinely consider 3R project alternatives that involve right-of-way acquisition. The benefit-cost procedures presented here will support either approach.

Utility relocation costs may be incurred in some 3R projects. Such costs are site-specific and difficult to generalize. Therefore, they have not been included in the automated cost estimation procedures incorporated in the spreadsheet tools used with these guidelines. However, users of the procedures may include utility relocation costs in site-specific project implementation costs for benefit-cost analysis, where appropriate.

The cost of pavement resurfacing should not be included as part of the implementation cost for benefit-cost analysis of potential geometric design improvements considered in conjunction with 3R projects. For most 3R projects, the pavement will be resurfaced regardless of whether geometric design improvements are made, so the pavement resurfacing cost is not relevant to decisions concerning geometric design improvements and should not be included in the project implementation cost.

Every highway agency has established procedures for estimating the cost of geometric design alternatives, both for cost estimates that are sufficiently accurate for planning-level analyses and for detailed cost estimates prepared in final design. It is assumed that, in most cases, highway agencies will prefer to use their own project cost estimation procedures as the basis for 3R project benefit-cost analyses. Cost estimates with planning-level accuracy are appropriate for deciding whether to incorporate geometric design improvements in a 3R project and what geometric design improvements to implement.

A default procedure for estimating the implementation costs of 3R improvements at specific sites is presented in Appendix A. This default cost estimation procedure is intended for application by highway agencies that want to make a quick assessment of the need for geometric improvements in a specific 3R project without the effort needed to apply their own cost estimation procedures. The unit cost values used in the default cost estimation procedure may be easily modified to reflect local conditions. The project implementation cost estimates made with the default procedure can be refined later, if appropriate, using the agency's own project cost estimation procedures.

The implementation cost for geometric design improvements may represent the cost of a single geometric design change or the combined cost of multiple geometric design changes that may potentially be made as part of the same project. The default cost estimation procedure presented in Appendix A can address either single or multiple geometric design improvements.

The value of the default cost estimation procedure to highway agencies is that they can quickly determine whether geometric design alternatives should be considered at all and what the general scope of design improvement should be without going to the effort of making detailed cost estimates with their own cost estimation procedures. For example, if a benefit cost-analysis based on the default cost estimation procedure showed that the costs of design alternatives for a particular project far exceed the benefits, the effort required to make more accurate estimates of project implementation cost using the agencies own project cost estimation procedures can be avoided.

The decision as to whether to use the default project cost estimation procedure or the agency's own project cost estimation procedures can be made by each highway agency that uses these guidelines.

5.1.2 3R Project Crash Frequency and Severity Reduction Benefits

The benefits of 3R projects are being estimated with a combination of the following elements:

- Expected crash frequency by crash severity level for the existing highway if no geometric design improvements are made based on the HSM Part C predictive methods. The agency may choose to base the benefit-cost analysis on the predicted crash frequency from the HSM Part C predictive method or, when site-specific crash history data are available, to combine the predicted and observed crash frequencies using the empirical Bayes (EB) procedure presented in the Appendix to HSM Part C.
- Expected reduction in crash frequency due to project implementation based on CMFs for specific countermeasures from the HSM and other sources.
- Crash cost savings per crash reduced by severity level.

- Improvement service life, which is typically assumed to be 20 years (see below), except that a shorter service life should be used for striping and delineation and rumble strips.

Each of these issues is addressed in more detail below.

5.1.3 Expected Crash Frequency by Crash Severity Level If No Geometric Design Improvements are Made

This section summarizes the crash prediction methodology from HSM Part C (*2*), as applied to rural two-lane highways (see HSM Chapter 10), rural multilane highways (see HSM Chapter 11), and urban and suburban arterials (see HSM Chapter 12). Full details of these procedures are provided in the HSM.

5.1.3.1 Roadway Segments on Rural Two-Lane Highways

The HSM Chapter 10 crash prediction model for roadway segments on rural two-lane highways has the following functional form (*2*):

$$N_{predicted\ ravg} = \sum_{y=1}^{n} [\left(\mathrm{AADT}_y \times \mathrm{L} \times 365 \times 10^{-6} \times \mathrm{e}^{-0.312}\right) \times \mathrm{C}_r \times (\mathrm{CMF}_{1r} \times \mathrm{CMF}_{2r} \times \ldots \times \mathrm{CMF}_{nr})]/n \qquad \textbf{(26)}$$

where:

$N_{predicted\ ravg}$	=	predicted annual average crash frequency for a particular road segment averaged over the improvement service life
$AADT_y$	=	annual average daily traffic volume for year *y* of the improvement service life (veh/day)
n	=	improvement service life (years)
L	=	length of roadway segment (mi)
C_r	=	calibration factor for roadway segments of a particular type developed for a particular jurisdiction or geographical area
CMF_{1r} … CMF_{nr}	=	applicable crash modification factors (see HSM Part C)

Equation (26) provides the predicted frequency for total crashes. Values presented in HSM Table 10-3 are used to break this total down for specific severity levels.

5.1.3.2 Roadway Segments on Rural Multilane Highways

The HSM Chapter 11 crash prediction model for roadway segments on rural multilane highways has the following functional form (*2*):

$$N_{predicted\ ravg} = \sum_{y=1}^{n} [\left(e^{(a+b\ \times \ln(AADT)\ \times \ln(\mathrm{L}))}\right) \times \mathrm{C}_r \times (\mathrm{CMF}_{1r} \times \mathrm{CMF}_{2r} \times \ldots \times \mathrm{CMF}_{nr})]/n \qquad \textbf{(27)}$$

where: a,b = coefficients presented in HSM Chapter 11

In the HSM Chapter 11 procedure, Equation (27) is applied separately for crashes by severity level. The values of coefficients *a* and *b* in Equation (27) are presented in HSM Table 11-3 for rural multilane undivided roadway segments and in HSM Table 11-5 for rural multilane divided roadway segments. The CMFs used in Equation (27) also differ between rural multilane undivided and divided roadway segments.

5.1.3.3 Roadway Segments on Urban and Suburban Arterial Roadway Segments

The HSM Chapter 12 crash prediction model for roadway segments on urban and suburban arterials is a combination of three terms (*2*):

$$N_{predicted\ ravg} = \sum_{y=1}^{n} [\left(N_{br} + N_{pedr} + N_{biker}\right) \times \mathrm{C}_r]/n \qquad \textbf{(28)}$$

where: N_{br} = predicted average crash frequency for an individual roadway segment averaged over the improvement service life (including multiple-vehicle nondriveway crashes, single-vehicle crashes, and multiple-vehicle driveway crashes)
N_{pedr} = predicted average crash frequency of vehicle-pedestrian crashes for an individual roadway segment averaged over the improvement service life
N_{biker} = predicted average crash frequency of vehicle-bicycle crashes for an individual roadway segment averaged over the improvement service life

Equation (28) provides the predicted frequency for crashes separately by severity level. N_{br} is a combination of separate models for multiple-vehicle nondriveway crashes, single-vehicle crashes, and multiple-vehicle driveway crashes. The models for multiple-vehicle nondriveway crashes and single-vehicle crashes each incorporate applicable CMFs. The details of the models used for each term in Equation (28) are presented in HSM Chapter 12.

5.1.3.4 At-Grade Intersections

The predictive models for at-grade intersections on all facility types have the following general form (*2*):

$$N_{predicted\ iavg} = \sum_{i=1}^{y} [\left(e^{(a+b\ \times \ln\left(AADT_{y,maj}\right) + \mathrm{c}\ \times \ln\left(AADT_{y,min}\right))}\right) \times C_i \times (CMF_{1i} \times CMF_{2i} \times \ldots \times CMF_{ni})]/n \qquad \textbf{(29)}$$

where: $N_{predicted\ iavg}$ = predicted average crash frequency for a particular intersection for a particular year
a,b,c = coefficients presented in HSM Chapter 10, 11, and 12
$AADT_{y,maj}$ = annual average daily traffic volume on the major road (veh/day)
$AADT_{y,min}$ = annual average daily traffic volume on the minor road (veh/day)
C_i = calibration factor for intersections of a particular type developed for a particular jurisdiction or geographical area
$CMF_{1i} \ldots CMF_{ni}$ = applicable crash modification factors (see HSM Part C)

The values for coefficients *a*, *b*, and *c* are presented in the HSM as follows:

- in HSM Equations (10-8) through (10-10) for intersections on rural two-lane highways
- in HSM Tables 11-7 and 11-8 for intersections on rural multilane highways
- in HSM Tables 12-10 and 12-12 for intersections on urban and suburban arterials

For intersections on urban and suburban arterials, Equation (29) is applied separately for multiple- and single-vehicle collisions.

5.1.3.5 Combining Predicted and Observed Crash Frequencies

Many highway agencies may prefer to take a systemic approach and make risk-based decisions on the need for geometric design improvements in 3R projects based on predicted crash frequencies from the HSM alone. However, observed crash history data can also be considered in analyses for individual sites using the EB procedure presented in the Appendix to HSM Part C (*2*). This procedure determines a weighted-average crash frequency using the following procedure:

$$N_{expected} = w \times N_{predicted} + (1 - w) \times N_{observed} \tag{30}$$

$$w = \frac{1}{1 + k \sum_{\substack{\text{all study} \\ \text{years}}} N_{predicted}} \tag{31}$$

where: $N_{expected}$ = estimate of expected average crash frequency for the crash data period
$N_{predicted}$ = predictive model estimate of average crash frequency predicted for the crash data period under the given conditions ($N_{predicted\ ravg}$ or $N_{predicted\ iavg}$)
$N_{observed}$ = observed crash frequency at the site over the study period
w = weighted adjustment to be placed on the predictive model estimate
k = overdispersion parameter of the associated SPF used to estimate $N_{predicted}$

Values for the overdispersion parameter, *k*, can be determined from:

- HSM Equation (10-7) for roadway segments on rural two-lane highways
- Text accompanying HSM Equations (10-8) through (10-10) for intersections on rural two-lane highways
- HSM Equation (11-8) and Tables 11-3 and 11-5 for rural multilane highways
- HSM Tables 11-7 and 11-8 for intersections on rural multilane highways
- HSM Tables 12-3 and 12-5 for roadway segments on urban and suburban arterials
- HSM Tables 12-10 and 12-12 for intersections on urban and suburban arterials

The EB procedure is implemented by applying the applicable predictive model [i.e. Equation (26), (27), (28), or (29)] to the past period for which observed crash data are available rather than to the future period over which the improvement will be in service. Equations (30) and (31) are then applied to combine the predicted and observed crash frequencies for the crash data period. Finally, the expected crash frequency determined with Equations (30) and (31) is updated to future years as follows:

$$N_{expected,y} = N_{expected} \times \frac{N_{predicted,y}}{N_{predicted}} \quad \textbf{(32)}$$

where: $N_{expected,y}$ = expected average crash frequency for year y
$N_{predicted,y}$ = predicted average crash frequency for year y

5.1.4 Expected Reduction in Crash Frequency for Specific Design Alternatives

The expected reduction in crash frequency for specific candidate design alternatives can be determined by applying the CMFs presented in Section 4.3 of these guidelines. The expected reduction in crash frequency for a specific crash severity level resulting from implementation of a a particular design alternative at a particular site can be determined as:

$$CR_{mjk} = \left(1 - CMF_{jk}\right) N_{mk} \quad \textbf{(33)}$$

where: CR_{mjk} = expected reduction in crash frequency for crash severity level *k* resulting from implementation of improvement *j* at site *m*
CMF_{jk} = crash modification factor for crash severity level *k* from implementing improvement *j*
N_{mk} = expected annual crash frequency for crash severity level *k* at site *m* prior to improvement

N_{mk} represents the value of $N_{predicted}$ or $N_{expected}$ derived in Section 5.1.3.

The CMF representing the effectiveness of a single geometric design improvement is determined as:

$$CMF_{jk} = \frac{CMF_{j,after}}{CMF_{j,before}} \tag{34}$$

where: $CMF_{j,after}$ = crash modification factor for improvement *j* in the condition after improvement
$CMF_{j,before}$ = crash modification factor for improvement *j* in the condition before improvement

The CMF representing the combined effectiveness for a design alternative that incorporates several geometric design improvements is determined as:

$$CMF_{jk} = \frac{CMF_{1,after}}{CMF_{1,before}} \times \frac{CMF_{2,after}}{CMF_{2,before}} \times \ldots \times \frac{CMF_{n,after}}{CMF_{n,before}} \tag{35}$$

5.1.5 Crash Costs by Crash Severity Level

Each highway agency has its own policy concerning the estimated cost savings of reducing crashes of specific severity levels used in benefit-cost analyses. These estimates vary widely based on the assumptions made in developing those estimates. Some agencies rely on estimates of the societal costs of crashes, while others are based on an approach that assesses an individual's willingness to pay for injury avoidance. Until a national consensus is reached on the appropriate method for estimating crash costs, each highway agency should follow its own policy concerning the appropriate crash cost values for use in benefit-cost analyses.

If a highway agency has no specific policy on crash costs for use in benefit-cost analyses, the values in Table 25, which have been updated from those presented in the HSM and represent comprehensive societal costs of crashes, are recommended as default values:

Table 25. Comprehensive Societal Costs of Crashes Updated from the Values Recommended in the HSM

Crash Severity Level	Comprehensive Societal Crash Costs
Fatal (K)	$5,722,300
Disabling Injury (A)	302,900
Evident Injury (B)	110,700
Possible Injury (C)	62,400
Property Damage Only (O)	10,100

NOTE: Updated from HSM Table 7-1 as shown in Appendix C.

The methodology used to update the crash cost values presented in Table 25 is documented in Appendix C.

5.1.6 Improvement Service Life

Pavement resurfacing typically has a service life of 7 to 12 years, depending upon construction and material quality and traffic volume, until resurfacing is needed again. However, the service life for the pavement surface does not typically enter directly into benefit-cost analyses concerning geometric design improvements, because the pavement will require resurfacing at the same interval whether geometric design improvements are incorporated in a 3R project or not. Thus, the interval between pavement resurfacing projects should not typically be a factor in determining the service life for potential geometric design improvements.

Geometric design improvements such as widening of the roadway cross section, changing the road alignment, improving the roadside, or improving an intersection are essentially permanent in nature (i.e., they remain in place through future pavement resurfacing). However, they may have a functional life shorter than their physical life because future development or traffic growth may create a need for further improvements. The recommended improvement service life for improvements that involve physical changes to the roadway cross section, the roadway alignment, the roadside, or intersections is 20 years. The recommended improvement service life for rumble strips and striping and delineation improvements (particularly those that use durable pavement markings) is 5 years. However, highway agencies may use other values of improvement service life based on their own policies and experience.

5.1.7 Discount Rate or Minimum Attractive Rate of Return

A discount rate or minimum attractive rate of return of 7 percent has been used in the benefit-cost analysis, in accordance with the higher value of the discount rates recommended in current Federal guidelines (*29*). The discount rate or minimum attractive rate of return is used in computing the present value of implementation costs and safety benefits (see below).

5.1.8 Present Value of Implementation Costs and Safety Benefits

The present value of the implementation costs and safety benefits must be calculated to obtain a benefit-cost ratio. For implementation costs, the present value must be found only if the improvement is to be repeated in the future (such as striping and delineation which may be repeated several times during the service life of a geometric design improvement). In this case, the present value is computed by multiplying the future implementation cost by the single payment present worth factor:

$$(\mathrm{P/F}, i\%, n) = \left(1 + \frac{i}{100}\right)^{-n} \qquad \textbf{(36)}$$

where: (P/F, *i*%, *n*) = single payment present worth factor
i = discount rate or minimum attractive rate of return (in decimal form); i.e., 7 percent is expressed as 0.07
n = number of years into the future when the improvement will be performed

The present values for each future improvement are then summed to determine the total present value.

Safety benefits are annual crash cost savings. To calculate the present value of safety benefits, the annual crash cost savings are multiplied by the uniform series present worth factor:

$$(\mathrm{P/A}, i\%, n) = \frac{\left(1 + \frac{i}{100}\right)^{n} - 1}{i/100\left(1 + \frac{i}{100}\right)^{n}} \qquad \textbf{(37)}$$

where: (P/A, *i*%, *n*) = uniform series present worth factor
i = discount rate or minimum attractive rate of return (in decimal form); i.e., 7 percent is expressed as 0.07
n = improvement service life (years)

5.1.9 Benefit-Cost Ratio

The benefit-cost ratio for a geometric design alternative in a 3R project is computed as:

$$\mathrm{B/C} = \left[\sum_{k} CR_{mjk} C_k (P/A\,, i\%, n)\right] / \left[IC_{ij} (P/F\,, i\%, n)\right] \qquad \textbf{(38)}$$

where: B/C = benefit-cost ratio
C_k = benefit ($) per crash reduced for crash severity level *k*
IC_{ij} = implementation cost ($) for improvement *j* at site *i*

Only design alternatives with benefit-cost ratios that exceed 1.0 are considered cost-effective. Highway agencies seeking to enhance the effectiveness of the safety improvement investments may choose to seek benefit-cost ratios of 2.0 or higher.

5.1.10 Net Benefit

The benefit-cost ratio by itself does not provide a complete picture of the magnitude of difference between the safety benefits and implementation costs for a design alternative in a 3R project. The net benefit (also referred to as net present value) is the difference between the present value of safety benefits and present value of implementation costs.

$$\mathrm{NB} = \left[\sum_{k} CR_{mjk} C_k (P/A\,, i\%, n)\right] - IC_{ij}(P/F\,, i\%, n) \tag{39}$$

where: NB = net benefit

The net benefit is often the most useful form of benefit-cost analysis results for identifying the design alternative that will maximize the safety benefits for any given level of expenditure on geometric design improvements in 3R projects.

5.2 Computational Examples of Benefit-Cost Analysis

This section and Section 5.3 present examples to illustrate the interpretation of benefit-cost analysis results. These examples suggest how benefit-cost analysis can be used in the design guidelines presented in Chapter 6. If improvement costs and crash costs were consistent throughout the U.S., these examples might serve as a basis for 3R design policy. However, since the values used for improvement costs and crash costs vary widely from agency to agency, these examples in their current form should not be used as a basis for policy. Rather, benefit-cost analyses analogous to these examples, but based on site-specific or agency-specific data, should serve as a decision-making tool for choosing among 3R project design alternatives.

5.2.1 Estimating 3R Project Implementation Costs

The cost estimation procedure shown in Appendix A is used to calculate the cost of a hypothetical 3R project in which the lane width on a section of roadway is widened from 10 to 12 ft. Table 26 in the following section presents roadway geometric information needed to estimate the implementation cost in this example. Unit costs for all elements of the cost estimation are presented in Appendix A. The total cost of the 3R project is determined to be $850,551. This cost however should be modified to exclude costs associated with milling and resurfacing of the existing traveled way. The benefit-cost analysis is only concerned with the costs resulting from the geometric improvement, which is lane widening in this example. The modified total implementation cost is $475,889.

5.2.2 Computational Example of Quantifying Safety Benefits for a 3R Design Alternative

Section 5.1 presents the methodology for quantifying safety benefits with and without using observed crash data. In the following example, the annual safety benefit will be calculated for a roadway segment undergoing lane widening as part of a 3R project. Table 26 shows segment characteristics, which will be used in this example.

Table 26. Input Data for Safety Benefits Calculation Example

Geometric Improvement	Lane Widening from 10 to 12 ft
Lane Widening Service Life	20 yrs
Discount Rate	7%
Roadway Type	Rural Two-lane Highway
Shoulder Width	2 ft
Shoulder Type	Paved
Roadside Slope	1V:3H
Centerline Rumble Strip	No
Shoulder Rumble Strip	No
Section Length	3 mi
AADT (does not change)	1,000 veh/day
Terrain	Level
Percent of Section Length on Curves	20%
Typical Curve Radius	2,000 ft
Number of Curves on Section	5
Presence of Spiral Transitions	Yes
Crash History Period	5 yrs
Total Fatal-and-Injury Crashes	2
Total Property-Damage-Only Crashes	5

First, the predicted annual average crash frequency, $N_{predicted\ ravg}$, is calculated using Equation (26) for the existing roadway prior to the 3R project. Since the AADT does not change over time in this example, the equation simplifies to not having a summation. Using the HSM and data from Table 26, CMFs are calculated for use in determining $N_{predicted\ ravg}$.

To determine the CMF for a rural two-lane highway with 10-ft lane width, use Table 3. Since the AADT of the roadway section is between 400 and 2,000 veh/day, an equation is used to calculate the CMF_{ra}:

$$CMF_{ra,Lane\ Width,10\ ft} = 1.05 + 2.81 \times 10^{-4}(AADT - 400) \quad \textbf{(40)}$$

$$CMF_{ra,Lane\ Width,10\ ft} = 1.05 + 2.81 \times 10^{-4}(1000 - 400) = 1.13 \quad \textbf{(41)}$$

CMF_{ra} applies only to single-vehicle run-off-the-road and multiple-vehicle head-on, opposite-direction sideswipe, and same-direction sideswipe crashes. Equation (3) is used to convert CMF_{ra} to a CMF for total crashes. For this example p_{ra} is 0.574, the default value given in the HSM.

$$CMF_{lr,Lane\ Width,10\ ft} = (1.13 - 1.0) \times 0.574 + 1.0 = 1.07 \quad \textbf{(42)}$$

Other CMFs that are calculated for this example are shown in Table 27.

Table 27. CMFs for Example Roadway Section

Roadway Feature	CMF
Shoulder Width	1.09
Horizontal Curve	1.01
Roadside Slope	1.00
Centerline Rumble Strip	1.00
Shoulder Rumble Strip	1.00

$$N_{predicted\ ravg} = \sum_{y=1}^{n} [\left(\mathrm{AADT}_y \times \mathrm{L} \times 365 \times 10^{-6} \times \mathrm{e}^{-0.312}\right) \times \mathrm{C}_r \times (\mathrm{CMF}_{1r} \times \mathrm{CMF}_{2r} \times \ldots \times \mathrm{CMF}_{nr})]/n \quad \textbf{(43)}$$

$$N_{predicted\ ravg} = (\mathrm{AADT} \times \mathrm{L} \times 365 \times 10^{-6} \times \mathrm{e}^{-0.312}) \times \mathrm{C}_r \times (\mathrm{CMF}_{1r} \times \mathrm{CMF}_{2r} \times \ldots \times \mathrm{CMF}_{nr}) \quad \textbf{(44)}$$

$$N_{predicted\ ravg} = (1000 \times 3 \times 365 \times 10^{-6} \times \mathrm{e}^{-0.312}) \times 1.00 \times (1.07 \times 1.09 \times 1.01 \times 1.00 \times 1.00 \times 1.00) = 0.942\ crashes/yr \quad \textbf{(45)}$$

The predicted annual average crash frequency for the roadway prior to the 3R project is 0.942 crashes per year, as shown in Equations (43) through (45).

Since the lane width is being modified as part of the 3R project, the CMF for the change in lane widths must be calculated using Equation (34). To do this, the CMF for a lane width of 12 ft must first be calculated using the same procedure shown above for determining the CMF of a 10-ft lane. Table 3 shows that the CMF for 12-ft lanes is 1.00 regardless of AADT.

$$CMF_{lane\ width,10\rightarrow 12ft} = \frac{CMF_{lane\ width,12\ ft}}{CMF_{lane\ width,10\ ft}} \quad \textbf{(46)}$$

$$CMF_{lane\ width,10\rightarrow 12ft} = \frac{1.00}{1.07} = 0.934 \quad \textbf{(47)}$$

The CMF for increasing lane width from 10 to 12 ft is 0.93, which is calculated in Equations (46) and (47).

At this point in the process of calculating the annual safety benefits, it must be decided whether to use observed crash data in the calculation of CR_{mjk}, the expected reduction in crash frequency. For the purpose of this example, both methods will be used.

5.2.2.1 Observed Crash Data Unavailable

If observed crash data are unavailable, or not to be used in the analysis, the expected annual crash reduction is computed, as shown in Equation (48) through (50).

$$CR_{mjk} = \left(1 - CMF_{jk}\right) N_{mk} \quad \textbf{(48)}$$

$$CR_{total\ per\ year} = \left(1 - CMF_{lane\ width,10\rightarrow 12ft}\right) N_{predicted\ ravg} \quad \textbf{(49)}$$

$$CR_{total\ per\ year} = (1 - 0.934) \times 0.942 = 0.062\ crashes\ reduced\ per\ year \quad \textbf{(50)}$$

5.2.2.2 Using Observed Crash Data

The EB methodology, described in Section 5.1.3.5 is used to incorporate observed crash data into the calculation of the expected reduction in crash frequency. The overdispersion factor, k, is 0.236 divided by the section length, which correlates with the safety performance function for predicting crash frequency on rural two-lane roadways. Using the equations shown in Section 5.1.3.5 the expected crash frequency is calculated in Equations (51) through (54). The total crash reduction per year is calculated in Equations (55) through (57).

$$w = \frac{1}{1 + k \sum_{all\ study\ years} N_{predicted\ ravg}} \quad \textbf{(51)}$$

$$w = \frac{1}{1 + \frac{0.236}{3} \times \frac{0.942 crashes}{yr} \times 5yrs} = 0.730 \quad \textbf{(52)}$$

$$N_{expected} = w \times N_{predicted} + (1 - w) \times N_{observed} \quad \textbf{(53)}$$

$$N_{expected} = 0.730 \times 0.942 \times 5yrs + (1 - 0.730) \times (5 + 2) \quad \textbf{(54)}$$

$$= 5.33\ crashes\ per\ 5\ yr\ or\ 1.065\ crashes/yr$$

$$CR_{mjk} = \left(1 - CMF_{jk}\right) N_{mk} \quad \textbf{(55)}$$

$$CR_{total\ per\ year} = \left(1 - CMF_{lane\ width, 10 \rightarrow 12ft}\right) N_{expected\ per\ year} \quad \textbf{(56)}$$

$$CR_{total\ per\ year} = (1 - 0.934) \times 1.065 \quad \textbf{(57)}$$

$$= 0.071\ crashes\ reduced\ per\ year$$

5.2.2.3 Calculate Present Value of Safety Benefit

To this point in the example, the total crash reduction per year has been calculated with and without the use of observed crash history. The present value of the safety benefit in this example is calculated using Equation (58). Equation (58) is the numerator of Equation (38).

$$\mathrm{B} = \sum_{k} CR_{mjk} C_k (P/A, i\%, n) \quad \textbf{(58)}$$

Equation (58) can be broken into three components: (a) CR_{mjk}, crash reduction by severity level; (b) C_k, crash cost by severity level; and (c) the uniform series present worth factor. Default crash severity distributions from HSM Chapter 10 are used to transform total annual crash reduction into annual crash reduction by severity level in Table 28.

Table 28. Annual Crash Reduction by Severity Level Calculation

Crash Severity Level	Proportion of Total Crashes	CRtotal per year, Observed Crash History Known	CRtotal per year, Observed Crash History Unknown	CRk, Observed Crash History Known	CRk, Observed Crash History Unknown
K	0.013	0.071	0.062	0.000923	0.000806
A	0.054	0.071	0.062	0.00383	0.00335
B	0.109	0.071	0.062	0.00774	0.00676
C	0.145	0.071	0.062	0.0103	0.00899
O	0.679	0.071	0.062	0.0482	0.0421

The crash cost by severity level is shown in Table 25.

The uniform series present worth factor is needed to transform the annual crash reduction benefit into present crash reduction benefit over the entire service life of the improvement. This is calculated in Equations (59) and (60).

$$(\mathrm{P/A}, i\%, n) = \frac{\left(1+\frac{i}{100}\right)^{n} - 1}{i/100\left(1+\frac{i}{100}\right)^{n}} \tag{59}$$

$$(\mathrm{P/A}, i\%, n) = \frac{\left(1+\frac{7}{100}\right)^{20} - 1}{7/100\left(1+\frac{7}{100}\right)^{20}} = 10.5940 \tag{60}$$

Equations (61) and (62) shows the computation of the present value of the safety benefit. For the purposes of this example, only the expected crash reduction by severity level where the observed crash history is unknown is used in the calculation of the present value of the safety benefit.

$$\mathrm{B} = \sum_{k} CR_{mjk} C_k (P/A\,, i\%, n) \tag{61}$$

$$\begin{aligned} \mathrm{B} = (&0.000806 * 4008900 + 0.00335 * 216000 + 0.00676 * 79000 \\ &+0.00899 * 44900 + 0.0421 * 7400) \times 10.5940 = \$56{,}041 \end{aligned} \tag{62}$$

5.2.3 Computational Example of Benefit-Cost Analysis

The implementation cost of widening the roadway section in this example is $475,889, which was discussed in Section 5.2.1. There is no need to convert this implementation cost to a present value, because the cost of the 3R project occurs in the present. No future improvements will be made during the 20-yr service life. The present value of the safety benefit is $56,041, which was calculated in Section 5.2.2. The benefit-cost ratio of widening the example roadway section can now be computed, which is shown in Equation (63).

$$B/C_{lane\ widening,10\rightarrow 12\ ft} = \frac{\$56{,}041}{\$475{,}889} = 0.12 \quad \textbf{(63)}$$

5.3 Interpreting Benefit-Cost Analysis Results

Further examples of benefit-cost analysis results are presented here to illustrate how analyses to assess design alternatives can be conducted and how the results of such analyses should be interpreted.

5.3.1 Example of Benefit-Cost Analysis for a Specific Project Alternative

This example of a benefit-cost analysis uses the results derived in Section 5.2 to address the cost-effectiveness of widening lanes from 10 to 12 ft for a rural two-lane highway in level terrain with 2-ft paved shoulders, 1V:3H roadside foreslopes, and flexible pavement. The section of roadway considered in this example is 3 mi in length with an AADT of 1,000 veh/day. The roadway section contains modest horizontal curvature (20 percent of section length consists of horizontal curves with a typical curve radius of 2,000 ft). The safety performance of the roadway before and after widening is estimated using the HSM Chapter 10 procedures and the implementation cost for widening is based on the cost estimation procedures contained in Spreadsheet Tool 1 which is presented in detail in Appendix A.

The present value of the net implementation cost for this example is \$475,889 (see Section 5.2.1). The net implementation cost does not include the milling and resurfacing costs for the existing traveled way with 10-ft lanes, since these costs would be incurred by the highway agency regardless of whether the lanes are widened. The annual safety benefit of widening the lanes from 10 to 12 ft for a rural two-lane highway in this example is \$5,290 (see Section 5.2.2). Assuming a discount rate of 7 percent and a service life of 20 years, the present value of the safety benefit is calculated using Equations (61) and (62), as \$56,041. The benefit-cost ratio is then calculated as follows:

$$B/C_{10\rightarrow 12\ for\ AADT=1{,}000} = \frac{\$56{,}041}{\$475{,}889} = 0.12 \quad \textbf{(64)}$$

The benefit-cost ratio is 0.12, meaning that the lane widening is not economically justifiable for this roadway section. Widening the lanes from 10 to 12 ft in this 3R project would not be a desirable investment of scarce resources, unless the roadway had an existing crash pattern that is potentially correctable by widening or the level of service (LOS) was less than the highway agency’s target LOS for this roadway and widening the lanes would help to meet that target. Absent these concerns, the funds that would be needed to widen the lanes on this roadway (\$475,889) would be better invested on another roadway where the safety benefits would be higher.

Consider, for example, a similar site, identical in most respects to the previous example, but with an AADT of 4,000 veh/day. In this case, the net implementation cost remains the same at

$475,889. However, the annual safety benefit would increase to $54,641, resulting in a present value of safety benefits equal to $578,871. The benefit-cost ratio for widening lanes from 10 to 12 ft would be:

$$B/C_{10\rightarrow 12\ for\ AADT=4{,}000} = \frac{\$578{,}871}{\$475{,}889} = 1.22 \tag{65}$$

This example illustrates that the difference in AADT between 1,000 to 4,000 veh/day results in lane widening being economically justifiable. Lane widening for the roadway with the AADT of 4,000 veh/day would be a much better investment in safety improvement than lane widening for the roadway with an AADT of 1,000 veh/day.

5.3.2 Example of Benefit-Cost Analysis to Establish Minimum Traffic Volume Levels for Improvement Alternatives

As the examples in Section 5.3.1 demonstrate, benefit-cost analysis can serve as a tool for assessing the cost-effectiveness of geometric design improvements for specific projects. These examples also suggest that benefit-cost analysis can serve as a tool to establish minimum AADT threshold for specific improvement types. Site-specific benefit-cost analyses are the more desirable approach, because they can consider both site-specific cost and benefit estimates. However, where site-specific benefit-cost analyses are not feasible, development of minimum AADT thresholds for specific improvement types may provide useful guidance to highway agencies in making 3R project design decisions. Such minimum AADT thresholds are most applicable to sites that represent average implementation costs for a particular highway agency and terrain type. Because unit construction costs, typical right-of-way costs, and crash cost values vary from agency to agency, the following tables should be considered as examples and not as a basis for design policy.

Table 29 presents the results of benefit-cost calculations for widening lanes from 10 to 12 ft in level terrain on a rural two-lane highway. This example is based on the same assumptions as the examples presented in Section 5.3.1 Indeed, the lines in the table for AADTs of 1,000 and 4,000 veh/day are the results of the two computational examples shown in the previous section.
Table 29 shows that the minimum AADT levels that would provide benefit-cost ratios of at least 1.0 and 2.0 for widening lanes from 10 to 12 ft are 4,000 and 7,000 veh/day respectively.

Table 29. Example of Benefit-Cost Calculations for Lane Widening from 10 to 12 ft in Level Terrain on a Rural Two-Lane Highway

Lane Width (ft)		AADT (veh/day)	Net Implementation Cost ($)	Present Value of Safety Benefits ($)	Benefit-Cost Ratio
Before	After				
10	12	1,000	475,889	56,041	0.17
10	12	2,000	475,889	289,265	0.61
10	12	3,000	475,889	434,153	0.91
10	12	4,000	475,889	578,871	1.22
10	12	5,000	475,889	723,589	1.52
10	12	6,000	475,889	868,306	1.82
10	12	7,000	475,889	1,013,024	2.13
10	12	8,000	475,889	1,157,742	2.43
10	12	9,000	475,889	1,302,459	2.74
10	12	10,000	475,889	1,447,177	3.04

NOTE: Assumed conditions – 2-ft paved shoulders; 1V:3H roadside foreslopes; flexible pavement.

This analysis can be repeated for determining minimum traffic volume levels in which lane widening of other intervals becomes economically feasible. Using the same roadway section characteristics of the previous examples, benefit-cost ratios for widening lanes of different widths can be calculated at several AADT levels using the same procedures. Tables 30 through 34 show the results.

Table 30. Example of Benefit-Cost Calculations for Lane Widening from 9 to 10 ft in Level Terrain on a Rural Two-Lane Highway

Lane Width (ft)		AADT (veh/day)	Net Implementation Cost ($)	Present Value of Safety Benefits ($)	Benefit-Cost Ratio
Before	After				
9	10	1,000	380,941	41,964	0.11
9	10	2,000	380,941	192,458	0.50
9	10	3,000	380,941	289,435	0.76
9	10	4,000	380,941	385,914	1.01
9	10	5,000	380,941	482,392	1.27
9	10	6,000	380,941	578,871	1.52
9	10	7,000	380,941	675,349	1.77
9	10	8,000	380,941	771,828	2.03
9	10	9,000	380,941	868,306	2.28
9	10	10,000	380,941	964,785	2.53

NOTE: Assumed conditions – 2-ft paved shoulder; 1V:3H roadside foreslopes; flexible pavement.

Table 31. Example of Benefit-Cost Calculations for Lane Widening from 9 to 11 ft in Level Terrain on a Rural Two-Lane Highway

Lane Width (ft)		AADT (veh/day)	Net Implementation Cost ($)	Present Value of Safety Benefits ($)	Benefit-Cost Ratio
Before	After				
9	11	1,000	475,889	86,797	0.18
9	11	2,000	475,889	433,512	0.91
9	11	3,000	475,889	651,230	1.37
9	11	4,000	475,889	868,306	1.82
9	11	5,000	475,889	1,085,383	2.28
9	11	6,000	475,889	1,302,459	2.74
9	11	7,000	475,889	1,519,536	3.19
9	11	8,000	475,889	1,736,613	3.65
9	11	9,000	475,889	1,953,689	4.10
9	11	10,000	475,889	2,170,766	4.56

NOTE: Assumed conditions – 2-ft paved shoulders; 1V:3H roadside foreslopes; flexible pavement.

Table 32. Example of Benefit-Cost Calculations for Lane Widening from 9 to 12 ft in Level Terrain on a Rural Two-Lane Highway

Lane Width (ft)		AADT (veh/day)	Net Implementation Cost ($)	Present Value of Safety Benefits ($)	Benefit-Cost Ratio
Before	After				
9	12	1,000	570,837	98,005	0.17
9	12	2,000	570,837	481,723	0.84
9	12	3,000	570,837	723,589	1.27
9	12	4,000	570,837	964,785	1.69
9	12	5,000	570,837	1,205,981	2.11
9	12	6,000	570,837	1,447,177	2.54
9	12	7,000	570,837	1,688,373	2.96
9	12	8,000	570,837	1,929,570	3.38
9	12	9,000	570,837	2,170,766	3.80
9	12	10,000	570,837	2,411,962	4.22

NOTE: Assumed conditions – 2-ft paved shoulders; 1V:3H roadside foreslopes; flexible pavement.

Table 33. Example of Benefit-Cost Calculations for Lane Widening from 10 to 11 ft in Level Terrain on a Rural Two-Lane Highway

Lane Width (ft)		AADT (veh/day)	Net Implementation Cost ($)	Present Value of Safety Benefits ($)	Benefit-Cost Ratio
Before	After				
10	11	1,000	380,941	44,833	0.12
10	11	2,000	380,941	241,054	0.63
10	11	3,000	380,941	361,794	0.95
10	11	4,000	380,941	482,392	1.27
10	11	5,000	380,941	602,990	1.58
10	11	6,000	380,941	723,589	1.90
10	11	7,000	380,941	844,187	2.22
10	11	8,000	380,941	964,785	2.53
10	11	9,000	380,941	1,085,682	2.85
10	11	10,000	380,941	1,205,981	3.17

NOTE: Assumed conditions – 2-ft paved shoulders; 1V:3H roadside foreslopes; flexible pavement.

Table 34. Example of Benefit-Cost Calculations for Lane Widening from 11 to 12 ft in Level Terrain on a Rural Two-Lane Highway

Lane Width (ft)		AADT (veh/day)	Net Implementation Cost ($)	Present Value of Safety Benefits ($)	Benefit-Cost Ratio
Before	After				
11	12	1,000	380,941	11,208	0.03
11	12	2,000	380,941	48,211	0.13
11	12	3,000	380,941	72,359	0.19
11	12	4,000	380,941	96,478	0.25
11	12	5,000	380,941	120,598	0.32
11	12	6,000	380,941	144,718	0.38
11	12	7,000	380,941	168,837	0.44
11	12	8,000	380,941	192,957	0.51
11	12	9,000	380,941	217,077	0.57
11	12	10,000	380,941	241,196	0.63
11	12	11,000	380,941	265,316	0.70
11	12	12,000	380,941	289,435	0.76
11	12	13,000	380,941	313,555	0.82
11	12	14,000	380,941	337,675	0.89
11	12	15,000	380,941	361,794	0.95
11	12	16,000	380,941	385,914	1.01
11	12	17,000	380,941	410,034	1.08
11	12	18,000	380,941	434,153	1.14
11	12	19,000	380,941	458,273	1.20
11	12	20,000	380,941	482,392	1.27

NOTE: Assumed conditions – 2-ft paved shoulders; 1V:3H roadside foreslopes; flexible pavement.

5.4 Using Benefit-Cost Analysis to Establish Minimum AADT Guidelines for 3R Improvements

The cost-effectiveness of any specific design alternative for a 3R project can be assessed in a benefit-cost analysis analogous to that shown in any line of Tables 29 through 34. However, benefit-cost analysis has a further advantage in that it can be used to identify which of multiple design alternatives for a 3R project would be most cost-effective. This type of analysis is referred to as incremental benefit-cost analysis.

Incremental benefit-cost analysis assesses whether each additional expenditure in implementation cost provides an added net benefit. The simplest method for performing an incremental benefit-cost analysis is to determine the net benefit (present value of safety benefits minus implementation cost) for each design alternative and select the design alternative with the highest net benefit, as long as that highest net benefit is also greater than zero.

The example in Table 35 shows an incremental benefit-cost analysis for lane widening for an existing rural two-lane highway with 9-ft lanes in level terrain. The implementation cost, safety benefit, and benefit-cost ratio shown in Table 35 for lane widening from 9 to 10 ft, 9 to 11 ft, and 9 to 12 ft are those shown in Tables 30, 31, and 32, respectively. In each case, the net benefit has also been added. Table 35 shows the following results for roadways with existing 9-ft lanes:

- for a roadway with an AADT of 1,000 veh/day, none of the lane widening alternatives are cost-effective
- for a roadway with an AADT of 2,000 or 3,000 veh/day, lane widening from 9 to 11 ft has the maximum net benefit. While lane widening from 9 to 12 ft is cost-effective, its net benefit is less than the net benefit of widening from 9 to 11 ft, and therefore the additional increment of investment to widen to 12-ft lanes is not cost-effective
- for a roadway with an AADT of 4,000 veh/day or more, widening from 9 to 12 ft has the highest net benefit in all cases

Table 36 shows a similar analysis for lane widening for an existing two-lane highway with 10-ft lanes in level terrain which indicates that:

- for a roadway with an AADT of 3,000 veh/day or less, none of the lane widening alternatives are cost-effective
- for a roadway with an AADT of 4,000 veh/day, the alternatives of lane widening from 10 to 11 ft and from 10 to 12 ft are nearly equal in net benefits, although widening from 10 to 12 ft is slightly higher
- for a roadway with an AADT of 5,000 veh/day or more, widening from 10 to 12 ft has the highest net benefit in all cases

For an existing two-lane highway with 11-ft lanes in level terrain, there is only one alternative to be considered (lane widening from 11 to 12 ft), so no incremental analysis is needed. Table 34 addresses this situation, indicating that lane widening from 11 to 12 ft only becomes cost-effective for roadways with AADT of 16,000 veh/day or more. Thus, lane widening in 3R projects on most existing rural two-lane highways with 11-ft lanes is not a desirable safety investment. The reason for this result is that the HSM Chapter 10 procedures show very little difference in crash frequency between 11- and 12-ft lanes on rural two-lane highways (see Figure 2).

The results of the incremental benefit-cost analyses presented above show that benefit-cost analyses can be used to create guidelines on the minimum AADT levels for which lane widening or other geometric design improvements may be cost-effective in 3R projects. Further examples of using benefit-cost analysis to establish 3R design guidelines using minimum AADT levels are presented in the next section.

Tables 29 to 34 show that the minimum AADT levels that would provide benefit-cost ratios of at least 1.0 and 2.0 for each widening scenarios are as follows:

Lane Widening Scenario	Minimum AADT (veh/day) for	
	B/C=1.0	B/C=2.0
Widen from 9 to 10 ft	4,000	8,000
Widen from 9 to 11 ft	3,000	5,000
Widen from 9 to 12 ft	3,000	5,000
Widen from 10 to 11 ft	4,000	7,000
Widen from 10 to 12 ft	4,000	7,000
Widen from 11 to 12 ft	16,000	32,000

Table 35. Example of Incremental Analysis to Determine Net Benefits of Lane Widening for Existing Rural Two-Lane Highways with 9-ft Lanes in Level Terrain

AADT (veh/day)	Lane Widening from 9 to 10 ft				Lane Widening from 9 to 11 ft				Lane Widening from 9 to 12 ft			
	Implementation Cost ($)	Crash Reduction Benefit ($)	B-C Ratio	Net Benefit ($)	Implementation Cost ($)	Crash Reduction Benefit ($)	B-C Ratio	Net Benefit ($)	Implementation Cost ($)	Crash Reduction Benefit ($)	B-C Ratio	Net Benefit ($)
1,000	380,941	41,964	0.11	-338,977	475,889	86,797	0.18	-389,092	570,837	98,005	0.17	-472,832
2,000	380,941	192,458	0.5	-188,483	475,889	433,512	0.91	-42,377	570,837	481,723	0.84	-89,114
3,000	380,941	289,435	0.76	-91,506	475,889	651,230	1.37	175,341	570,837	723,589	1.27	152,752
4,000	380,941	385,914	1.01	4,973	475,889	868,306	1.82	392,417	570,837	964,785	1.69	393,948
5,000	380,941	482,392	1.27	101,451	475,889	1,085,383	2.28	609,494	570,837	1,205,981	2.11	635,144
6,000	380,941	578,871	1.52	197,930	475,889	1,302,459	2.74	826,570	570,837	1,447,177	2.54	876,340
7,000	380,941	675,349	1.77	294,408	475,889	1,519,536	3.19	1,043,647	570,837	1,688,373	2.96	1,117,536
8,000	380,941	771,828	2.03	390,887	475,889	1,736,613	3.65	1,260,724	570,837	1,929,570	3.38	1,358,733
9,000	380,941	868,306	2.28	487,365	475,889	1,953,689	4.1	1,477,800	570,837	2,170,766	3.8	1,599,929
10,000	380,941	964,785	2.53	583,844	475,889	2,170,766	4.56	1,694,877	570,837	2,411,962	4.22	1,841,125

NOTE: Based on conditions evaluated in Tables 29 through 34.

Table 36. Examples of Incremental Analysis to Determine Net Benefits of Lane Widening for Existing Rural Two-Lane Highways with 10-ft Lanes in Level Terrain

AADT (veh/day)	Lane Widening from 10 to 11 ft				Lane Widening from 10 to 12 ft			
	Implementation Cost ($)	Crash Reduction Benefit ($)	B-C Ratio	Net Benefit ($)	Implementation Cost ($)	Crash Reduction Benefit ($)	B-C Ratio	Net Benefit ($)
1,000	380,941	44,833	0.12	-336,108	475,889	56,041	0.17	-419,848
2,000	380,941	241,054	0.63	-139,887	475,889	289,265	0.61	-186,624
3,000	380,941	361,794	0.95	-19,147	475,889	434,153	0.91	-41,736
4,000	380,941	482,392	1.27	101,451	475,889	578,871	1.22	102,982
5,000	380,941	602,990	1.58	222,049	475,889	723,589	1.52	247,700
6,000	380,941	723,589	1.9	342,648	475,889	868,306	1.82	392,417
7,000	380,941	844,187	2.22	463,246	475,889	1,013,024	2.13	537,135
8,000	380,941	964,785	2.53	583,844	475,889	1,157,742	2.43	681,853
9,000	380,941	102,452	2.85	-278,489	475,889	1,302,459	2.74	826,570
10,000	380,941	1,205,981	3.17	825,040	475,889	1,447,177	3.04	971,288

NOTE: Based on conditions evaluated in Tables 29 through 34.

The high values for minimum AADT level for widening from 11 to 12 ft occur because there is relatively little safety benefit in widening lanes from 11 to 12 ft on a rural two-lane highway (see Figure 3). The minimum AADT levels for lane widening can be expanded to include rolling and mountainous terrain types, as shown in Table 37. Minimum AADT levels can be established for shoulder widening using the same procedure described above, as shown in Table 38.

Table 37. Example of AADT Levels at which Lane Widening Becomes Cost-Effective Rural Two-Lane Highway Segments Assuming 2-ft Paved Shoulders, 1V:3H Roadside Foreslopes, and Moderate Horizontal Curvature

Proposed Improvement	Minimum AADT level (veh/day) for benefit-cost ratio = 1.0			Minimum AADT level (veh/day) for benefit-cost ratio = 2.0		
	Level	Rolling	Mountainous	Level	Rolling	Mountainous
Widen from 9 to 10 ft	4,000	5,000	7,000	8,000	10,000	14,000
Widen from 9 to 11 ft	3,000	3,000	4,000	5,000	5,000	8,000
Widen from 9 to 12 ft	3,000	3,000	4,000	5,000	6,000	8,000
Widen from 10 to 11 ft	4,000	4,000	6,000	7,000	8,000	11,000
Widen from 10 to 12 ft	4,000	4,000	6,000	7,000	8,000	11,000
Widen from 11 to 12 ft	16,000	19,000	28,000	32,000	37,000	55,000

Table 38. Example of AADT Levels at which Shoulder Widening Becomes Cost-Effective Rural Two-Lane Highway Segments Assuming 10-ft Lanes, Paved Shoulders, 1V:3H Roadside Foreslopes, and Moderate Horizontal Curvature

Proposed Improvement	Minimum AADT level (veh/day) for benefit-cost ratio = 1.0			Minimum AADT level (veh/day) for benefit-cost ratio = 2.0		
	Level	Rolling	Mountainous	Level	Rolling	Mountainous
Widen from 0 to 2 ft	3,000	4,000	6,000	6,000	8,000	12,000
Widen from 0 to 4 ft	3,000	4,000	5,000	6,000	7,000	10,000
Widen from 0 to 6 ft	3,000	4,000	5,000	6,000	7,000	9,000
Widen from 0 to 8 ft	3,000	4,000	5,000	6,000	7,000	9,000
Widen from 2 to 4 ft	5,000	6,000	9,000	10,000	12,000	17,000
Widen from 2 to 6 ft	4,000	5,000	6,000	8,000	9,000	12,000
Widen from 2 to 8 ft	4,000	4,000	6,000	8,000	8,000	11,000
Widen from 4 to 6 ft	6,000	7,000	10,000	12,000	13,000	19,000
Widen from 4 to 8 ft	5,000	5,000	7,000	9,000	10,000	14,000
Widen from 6 to 8 ft	8,000	9,000	12,000	16,000	17,000	24,000

5.5 Specific Benefit-Cost Analysis Applications for 3R Project Design Descriptions

Three specific benefit cost-analysis applications have a role in 3R project design decisions. These are:

- benefit-cost analysis for a single design alternative for a specific site
- benefit-cost analysis to choose among several design alternatives for a specific site
- benefit-cost analysis to develop agency-specific minimum AADT guidelines for application in design decisions

Each of these benefit-cost applications is discussed below.

5.5.1 Benefit-Cost Analysis for a Single Design Alternative for a Specific Site

A single design alternative for a specific site can be evaluated by determining the benefit-cost ratio for the alternative using Equation (38). If the computed benefit-cost ratio equals or exceeds 1.0, the design alternative is cost-effective and implementation of the geometric design improvement deserves consideration as part of the 3R project. If the benefit-cost ratio is less than 1.0, the design alternative is not cost-effective and should not typically be considered as part of the 3R project unless the crash history shows a specific crash pattern that is potentially correctable by the geometric design improvement in question or the geometric design improvement is essential to achieving the traffic operational LOS for the project. An equivalent analysis can be performed by determining whether the net benefits determined with Equation (39) exceed zero. Highway agencies may prefer to seek minimum benefit-cost ratios greater than 1.0 to assure that limited funds available for safety improvements are invested productively.

Benefit-cost analysis for a single design alternative can be performed with Spreadsheet Tool 1 presented below in Section 5.6.1.

5.5.2 Benefit-Cost Analysis to Choose Among Several Design Alternatives for a Specific Site

Multiple design alternatives for a specific site can be evaluated by comparing their net benefits determined with Equation (39) and selecting for consideration the alternative that has the largest positive value of net benefits. If all of the design alternatives considered have net benefits less than zero, none of the alternatives are cost-effective and none deserve consideration as part of the 3R project unless the crash history shows a specific crash pattern that is potentially correctable by one or more of the design alternatives or that one or more of the design alternatives is essential to achieving the traffic operational LOS for the project. Highway agencies should consider budget constraints in choosing among multiple alternatives, and may also consider the magnitude of the benefit-cost ratio for the selected design alternative, computed with Equation (38), as focusing the expenditure of limited funds on design alternatives with benefit-cost ratios substantially greater than 1.0 helps assure that the funds available for safety improvements are invested productively.

Benefit-cost analysis for multiple design alternatives can be performed with Spreadsheet Tool 2 presented below in Section 5.6.2.

5.5.3 Benefit-Cost Analysis to Develop Agency-Specific Minimum AADT Guidelines for Application in Design Decisions

Highway agencies can develop minimum AADT guidelines for application in 3R project design decisions, analogous to those shown in Tables 37 and 38. Such guidelines can be developed through repeated application of Spreadsheet Tool 1, presented below in Section 5.6.1. Each entry in Tables 29 through 34 is obtained from a single application of Spreadsheet Tool 1. The results are then summarized in a form like Tables 35 and 36. The results like those in Tables 35 and 36 can then be expressed as minimum AADT guidelines like those presented in Tables 37 and 38. Benefit-cost analyses to establish minimum AADT guidelines should be based on generic site characteristics representative of a specific agency's facilities. Separate minimum AADT guidelines are needed for each facility type and terrain category. All assumptions in the benefit-cost analysis, including implementation costs and crash costs, should be based on the policies and experience of an individual highway agency.

Policies based on agency-specific minimum AADT guidelines are an acceptable method for making 3R project design decisions, but will not provide results as reliable as the site-specific benefit-cost analyses discussed in Sections 5.5.1 and 5.5.2.

5.6 Benefit-Cost Analysis Tools

Two spreadsheet tools for benefit-cost analysis in support of 3R project design decisions are discussed in this section. These include a tool for analysis of a single design alternative (Spreadsheet Tool 1) and a tool for comparison of several design alternatives (Spreadsheet Tool 2). Each of these tools is discussed below.

5.6.1 Spreadsheet Tool 1—Benefit-Cost Analysis for a Single Design Alternative

Spreadsheet Tool 1 is a spreadsheet-based benefit-cost analysis tool that can be used to assess the cost-effectiveness of specific improvement alternatives for implementation in conjunction with a 3R project. The tool helps users in making the decision as to whether the 3R project should consist of pavement resurfacing only or should also include geometric design improvements. Tool 1 is used to assess one improvement alternative (or combination of alternatives) at a time. Tool 2 (see Section 5.6.2 and Appendix B) can assess multiple alternatives (and combinations of alternatives) in a single analysis.

Tool 1 can be applied as part of the planning process for 3R projects. If a specific project site has no observed crash patterns or no traffic operational needs that would justify a design improvement, then geometric design improvements are recommended for implementation as part of a 3R project only if it is anticipated that such improvements would be cost-effective. Tool 1 provides a capability to assess any particular improvement alternative (or combination of alternatives) to determine if it is anticipated to be cost-effective. Tool 1 addresses candidate 3R projects on rural two-lane highways, rural four-lane undivided and divided highways (nonfreeways), and rural and urban freeways. The tool does not address 3R projects on urban and suburban arterials (nonfreeways).

Examples of the application of Tool 1 are presented below in Sections 5.7.1 through 5.7.3 of this guide. A detailed users guide for Tool 1 is presented in Appendix A of this guide.

The input data to Tool 1 include a description of the existing roadway conditions and selection by the user of the improvement(s) to be assessed. The tool considers a single set of AADT, terrain, and cross-section geometrics for the roadway between intersections within the candidate project being assessed. Variations in cross-section geometrics at intersections or on intersection approaches do not need to be considered in using the tool. Where there are minor variations in AADT on the project or in cross-section geometrics on the roadway between intersections within the project, the average AADT and the most common cross-section geometrics should be used as input to the tool. Thus, the tool can be applied even where the cross section throughout the project is not entirely homogeneous. Where there are major changes in cross-section geometrics on the roadway between intersections (e.g., half the project has 6-ft paved shoulders and half has 2-ft unpaved shoulders), the user can break the project into separate sections and analyze each section separately. Breaking the project into separate sections for analysis is only appropriate where the differences in cross-section geometrics are substantial.

Tool 1 includes logic to estimate the implementation cost of the improvement alternatives evaluated. The project costs are estimated from default values of unit construction costs that are built into the tool. The user has the option to change these default unit costs to match their agency's experience or to replace the project cost estimated by the tool with the agency's own site-specific estimate. The user also has the option, for any given analysis, to include the cost of right-of-way acquisition in the project implementation cost estimate. Right-of-way costs can also be based on default values built into the tool, user-specific unit costs for right-of-way, or site-specific cost estimates made by the agency.

The safety performance of the roadway being analyzed and the safety benefits of improvement alternatives estimated in Tool 1 are based on the crash prediction procedures presented in Part C of the AASHTO *Highway Safety Manual* (HSM) including HSM Chapters 10, 11, and 18 (*1*). The tool analyzes roadway segment (i.e., nonintersection) crashes only. The HSM crash prediction procedures are applied first to predict the crash frequencies by severity level for the existing roadway based on safety performance functions (SPFs), crash modification factors (CMFs), and local calibration factors (if available). The crash reduction effectiveness of improvements is based on the CMFs presented in Section 4.3 of this guide. The user has the option to replace the default SPFs from the HSM with their own agency-specific SPFs for all roadway types other than freeways. The local calibration factor is set equal to 1.0 by default, but may be replaced by the user with an agency-specific value. The user has the option to provide site-specific crash history data and apply the Empirical Bayes (EB) method for converting predicted crash frequencies to expected crash frequencies, using the procedures presented in the Appendix to HSM Part C. Crash costs by severity level are set by default to values built into the tool, but may be replaced by the user with agency-specific values.

The user of Tool 1 has the option to select which improvement alternative (or combination of alternatives) will be considered in the benefit-cost analysis. The improvement alternatives that may be considered include:

- Lane widening
- Shoulder widening (outside shoulder only on two-lane and four-lane nonfreeways; both outside and inside shoulders on freeways)
- Shoulder paving (nonfreeways only)
- Roadside slope flattening (two-lane and four-lane nonfreeways only)
- Centerline rumble strips (undivided highways only)
- Shoulder rumble strips (outside shoulder only on undivided roads; both outside and inside shoulders on divided nonfreeways and freeways)
- Enhanced striping/delineation (nonfreeways only)
- Add or modify median barrier (freeways only)
- Add or modify roadside barrier (freeways only)
- Add passing lane(s) (rural two-lane highways only)
- Improve/restore curve superelevation (nonfreeways only)

The results provided by Tool 1 for the analysis of any improvement alternative (or combination of alternatives) include:

- Project implementation cost ($)
- Annual safety benefit ($)
- Present value of safety benefit ($)
- Benefit-cost ratio (benefit divided by cost)
- Net benefit (benefit minus cost) ($)
- Fatal-and injury (FI) crashes per year in before period
- Property-damage-only (PDO) crashes per year in before period
- FI crashes per year in after period
- PDO crashes per year after period
- FI crashes per year reduced by project
- PDO crashes per year reduced by project

Tool 1 has been developed entirely in Microsoft Excel worksheets without any supplementary Visual Basic programming. This should make Tool 1 easily implementable on computers with nearly any operating system and nearly any version of Microsoft Excel. By contrast, Tool 2, presented in Appendix B, incorporates supplementary programming in Visual Basic; therefore, macros must be enabled on the user's computer for Tool 2 to function.

5.6.2 Spreadsheet Tool 2—Benefit-Cost Analysis for Comparison of Several Design Alternatives

Spreadsheet Tool 2 is a spreadsheet-based benefit-cost analysis tool that can be used to assess the cost-effectiveness of specific improvement alternatives for implementation in conjunction with a 3R project. The tool helps users in making the decision as to whether the 3R project should consist of pavement resurfacing only or should also include geometric design improvements. Tool 2 has the capability to assess multiple improvement alternatives as a part of a single analysis and identify the most cost-effective alternative (or combination of alternatives). By contrast, Tool 1 considers only one alternative (or combination of alternatives) at a time.

Tool 2 can be applied as part of the planning process for 3R projects. If a specific project site has no observed crash patterns or no traffic operational needs that would justify a design improvement, then geometric design improvements are recommended for implementation as part of a 3R project only if it is anticipated that such improvements would be cost-effective. Tool 2 provides a capability to assess all feasible improvement alternatives (or combinations of alternatives) for a given set of improvement types (see below). Like Tool 1, Tool 2 addresses candidate 3R projects on rural two-lane highways, rural four-lane undivided and divided highways (nonfreeways), and rural and urban freeways. The tool does not address 3R projects on urban and suburban arterials (nonfreeways).

An example of the application of Tool 2 is presented below in Section 5.7.4 of this guide. A detailed users guide for Tool 2 is presented in Appendix B of this guide.

The input data for Tool 2 include a description of the existing roadway conditions and selection by the user of the improvement(s) to be assessed. The roadway characteristics input data for Tool 2 are essentially identical to the roadway characteristics input data for Tool 1. The tool considers a single set of AADT, terrain, and cross-section geometrics for the roadway between intersections within the candidate project being assessed. Variations in cross-section geometrics at intersections or on intersection approaches do not need to be considered in using the tool. Where there are minor variations in AADT on the project or in cross-section geometrics on the roadway between intersections within the project, the average AADT and the most common cross-section geometric features should be used as inputs to the tool. Thus, the tool can be applied even where the cross section throughout the project is not entirely homogeneous. Where there are major changes in cross-section geometrics on the roadway between intersections (e.g., half the project has 6-ft paved shoulders and half has 2-ft unpaved shoulders), the user can break the project into separate sections and analyze each section separately. Breaking the project into separate sections for analysis is only appropriate where the differences in cross-section geometrics are substantial.

Tool 2 includes logic to estimate the implementation cost of the improvement alternatives evaluated; the cost estimation logic in Tool 2 is essentially equivalent to the cost estimation logic in Tool 1. The project costs are estimated from default values of unit construction costs that are built into the tool. The user has the option to change these default unit costs to match their agency’s experience. The user also has the option, for any given analysis, to include the cost of right-of-way acquisition in the project implementation cost estimate. Right-of-way costs can also be based on default values built into the tool, user-specific unit costs for right-of-way.

The safety performance of the roadway being analyzed and the safety benefits of improvement alternatives estimated in Tool 2 are based on the crash prediction procedures presented in Part C of the AASHTO *Highway Safety Manual* (HSM) including HSM Chapters 10, 11, and 18 (*2*,*3*). The tool analyzes roadway segment (i.e., nonintersection) crashes only. The HSM crash prediction procedures are applied first to predict the crash frequencies by severity level for the existing roadway based on safety performance functions (SPFs), crash modification factors (CMFs), and local calibration factors (if available). The crash reduction effectiveness of improvements is based on the CMFs presented in Section 4.3 of this guide. The user has the option to replace the default SPFs from the HSM with their own agency-specific SPFs for all roadway types except freeways. The local calibration factor is set equal to 1.0 by default, but may be replaced by the user with an agency-specific value. The user has the option to provide site-specific crash history data and apply the Empirical Bayes (EB) method for converted predicted crash frequencies to expected crash frequencies, using the procedures presented in the Appendix to HSM Part C (*2*). Crash costs by severity level are set by default to values built into the tool, but may be replaced by the user with agency-specific values.

The user of Tool 2 has the option to select which improvement alternatives (or combinations of alternatives) will be considered in the benefit-cost analysis. The improvement alternatives that may be considered include:

- Lane widening
- Shoulder widening (outside shoulder only on two-lane and four-lane nonfreeways; both outside and inside shoulders on freeways)
- Shoulder paving
- Roadside slope flattening (two-lane and four-lane nonfreeways only)
- Centerline rumble strips (undivided highways only)
- Shoulder rumble strips (outside shoulder only on undivided roads; both outside and inside shoulders on divided nonfreeways and freeways)
- Enhanced striping/delineation (nonfreeways only)
- Add or modify median barrier (freeways only)
- Improve/restore curve superelevation (nonfreeways only)

The results provided by Tool 2 for the analysis of any improvement alternative (or combination of alternatives) include:

- Project implementation cost ($)
- Present value of safety benefit ($)
- Benefit-cost ratio (benefit divided by cost)
- Net benefit (benefit minus cost) ($)

The most cost-effective improvement alternative (or combination of alternatives) identified by Tool 2 is the alternative (or combination of alternatives) with the highest net benefit whose implementation cost is within the highway agency's available budget.

Because of its greater complexity, Tool 2 has most, but not all, of the capabilities of Tool 1 for allowing the user to change default values. For example, in Tool 2, the SPF coefficients from the HSM cannot be changed.

Tool 2 has been developed in Microsoft Excel worksheets with supplementary Visual Basic programming. Therefore, macros must be enabled on the user's computer for Tool 2 to function.

5.7 Application Examples Using the Benefit-Cost Spreadsheet Tools

This section presents several examples of the analysis of 3R project alternatives using the benefit-cost analysis spreadsheet tools. These examples serve to illustrate how the tools are used to analyze 3R project alternatives on specific roadway types and how the tools can be applied for a sequence of analyses to address specific design decision scenarios.

The examples presented are as follows:

- Example 1—Assessment of specific improvement alternatives for a typical rural two-lane highway at two different AADT levels
    - Example 1A—Assessment of separate lane widening, shoulder paving, and superelevation improvement alternatives for a rural two-lane highway at two different AADT levels using Spreadsheet Tool 1
    - Example 1B—Assessment of combined lane widening and superelevation improvement alternatives for the same rural two-lane highway at a higher AADT level (8,600 veh/day) using Spreadsheet Tool 1
    - Example 1C—Assessment of separate lane widening, shoulder paving, and superelevation improvement alternatives for a rural two-lane highway considering site-specific crash history data using Spreadsheet Tool 1
    - Example 1D—Achieving the same result as Examples 1A and 1B in one step using Spreadsheet Tool 2
- Example 2—Quantifying minimum AADT levels for cost-effective application to two specific improvements on a rural two-lane highway
- Example 3—Assessment of specific improvement alternatives for a typical rural four-lane highway
- Example 4—Assessment of specific improvement alternatives for a typical freeway

Examples 1 and 2 illustrate the full range of recommended applications of Spreadsheet Tools 1 and 2 for rural two-lane highways. Examples 3 and 4 are not intended to be as comprehensive as Example 1; rather, Examples 3 and 4 are presented to illustrate the variations in data entry and tool application for rural four-lane highways and freeways.

The examples shown here illustrate the application of the spreadsheet-based tools in benefit-cost analysis. Detailed instructions for the application of Tools 1 and 2 are presented in Appendices A and B, respectively.

5.7.1 Example 1—Rural Two-Lane Highway Assessment

A highway agency plans to resurface a section of rural two-lane highway and wants to assess if it would be cost-effective to include lane widening, shoulder widening, and/or superelevation improvements as part of the 3R project.

Tables 39 and 40 describe the existing geometric design and other existing conditions for the roadway segment. Table 39 presents the section length, AADT, terrain, pavement type, and existing cross-section geometrics. Table 40 presents the geometrics of the four horizontal curves located within the project limits.

Table 39. Existing Cross-Section Design and Other Existing Conditions for the Rural Two-Lane Highway in Example 1

Section Length	5 mi
AADT	2,000 veh/day
Terrain	Rolling
Pavement type	Flexible
Lane width	10.5 ft
Unpaved shoulder width	4 ft
Roadside slope	1V:4H
Rumble strips present	Centerline and Shoulder
Maximum curve superelevation (e_{max})	8%
Design speed	55 mph

Table 40. Existing Horizontal Curve Geometrics for the Rural Two-Lane Highway in Example 1

Curve #	Curve Length (mi)	Transition Length (mi)	Radius (ft)	Spiral Present	Existing Superelevation (%)
1	0.156	0.089	1,300	Yes	2.4
2	0.237	0.122	940	Yes	3.8
3	0.155	0.098	2,000	Yes	6.0
4	0.222	0.095	1,500	Yes	3.0

Example 1A—Assessment of Separate Lane Widening, Shoulder Paving, and Superelevation Alternatives for the Rural Two-Lane Highway in Example 1 at Two Different AADT Levels Using Spreadsheet Tool 1

First, Spreadsheet Tool 1 will be applied to determine if lane widening from the existing lane width of 10.5 ft to 12 ft would be cost-effective for this roadway segment. All default values provided in the R2U_Setup worksheet of Spreadsheet Tool 1 are used. In this analysis, potential right-of-way acquisition costs are not considered and existing crash history is either not available or is not considered. Construction costs are computed using the default unit costs in the R2U_Setup worksheet and the cost estimation procedures built into Tool 1.

Figures 7 through 12 show screenshots from Spreadsheet Tool 1 illustrating how input data for Example 1A are entered. Each figure is a screenshot of one particular table from the R2U_Project worksheet in Tool 1. Figure 7 illustrates the roadway data entered for Example 1A.

ROADWAY DATA	
Section Length (mi)	5.000
AADT (veh/day)	2,000
Terrain	Rolling
Pavement Type	Flexible

Figure 7. Roadway data input for rural two-lane highway in Example 1A

Figure 8 illustrates the options for entry of alignment data; in this case, the option to enter specific curve data is chosen. This option indicates that the characteristics of individual horizontal curves will be entered on a subsequent screen.

ALIGNMENT DATA	
Enter average curve data	○
*Enter specific curve data	◉

Figure 8. Alignment data option for rural two-lane highway in Example 1A

Figure 9 shows the existing cross section data from Table 39 that are entered.

EXISTING CROSS SECTION	
Lane Width (ft)	10.5 ft
Shoulder Width (ft)	4 ft
Shoulder Type	Unpaved
Roadside Slope	1V:4H
Centerline Rumble Strip	Yes
Shoulder Rumble Strip	Yes

Figure 9. Existing cross section data for rural two-lane highway in Example 1A

Figure 10 shows the selected option not to enter existing crash history data for this site. Selecting this option means that the Empirical Bayes method in the AASHTO *Highway Safety Manual* will not be used.

CRASH HISTORY	
Consider existing crash history?	
Yes ○	No ◉

Figure 10. Crash history option for rural two-lane highway in Example 1A

Figure 11 illustrates the specific curve data from Table 40 that are entered into Tool 1. The table illustrated in Figure 11 only appears when the option to enter specific curve data is selected on the Alignment Data screen shown in Figure 8.

SPECIFIC CURVE DATA							
Number of Curves in Roadway Section				4			
Maximum Superelevation Rate (e_{max})				8%			
Design Speed (mph)				55 mph			
Curve #	Curve Length (mi)	Transition Length (mi)	Radius (ft)	Spiral	Existing e (%)	Consider for Improvement	Improved e (%)
1	0.156 mi	0.089 mi	1300.00 ft	Yes	2.4%	No	[illegible]
2	0.237 mi	0.122 mi	940.00 ft	Yes	3.8%	No	[illegible]
3	0.155 mi	0.098 mi	2000.00 ft	Yes	6.0%	No	[illegible]
4	0.222 mi	0.095 mi	1500.00 ft	Yes	3.0%	No	[illegible]

Figure 11. Specific curve data for rural two-lane highway in Example 1A

Assessment of Lane Widening Alternative

Figure 12 shows that, in the Alternatives to Consider table in Tool 1, the user has specified consideration of one potential improvement alternative, widening the existing 10.5-ft lanes to 12 ft. This assessment considers lane widening only, with no other improvements considered.

Alternatives to Consider	Consider for Improvement	User Selection	Value Selected
Lane Width (ft)	☑	12.0 ft	12.0 ft
Shoulder Width (ft)	☐		Retain Shoulder Width
Shoulder Type	☐		Unpaved Shoulder
Roadside Slope	☐		Retain Roadside Slope
Centerline Rumble Strip	☐		Retain Centerline Rumble Strip
Shoulder Rumble Strip	☐		Retain Shoulder Rumble Strip
Enhanced Striping/Delineation	☐		Not Selected
Add New Passing Lane(s)	☐		Not Selected

Figure 12. User selection of lane widening as an alternative to be assessed for rural two-lane highway in Example 1A

Figure 13 shows how the results of the lane widening assessment specified in Figure 12, for the two-lane highway specified in Figures 7 through 11, will appear in the Results section of Tool 1. Figure 13 indicates that the lane widening is expected to cost $620,794 and have safety benefits of $223,531. The figure also indicates that the benefit-cost ratio (benefits divided by costs) would be 0.360 and the net benefits (benefits minus costs) would be -$397,263. The value of the benefit-cost ratio less than 1.0 and the negative value of net benefits indicate that the lane widening alternative is not cost-effective.

Table 41 shows the annual FI crash count for the period before project implementation, the annual predicted FI crash count for the period after project implementation, and the predicted number of annual FI crashes reduced. The values shown in Table 41 are displayed in Tool 1 next to the Results table.

RESULTS	Calculated	User Supplied	Value Used
PV MODIFIED TOTAL COST ($)*	$620,794		$620,794

*total cost minus milling and resurfacing cost for existing traveled way

ANNUAL SAFETY BENEFIT ($)	$21,100	BENEFIT-COST RATIO	0.360
PRESENT VALUE OF SAFETY BENEFIT ($)	$223,531	NET BENEFIT ($)	-$397,263

Figure 13. Benefit-cost analysis results for widening lanes to 12 ft for the rural two-lane highway with AADT of 2,000 veh/day in Example 1A

Table 41. Crash Frequencies Before and After Lane Widening for the Rural Two-Lane Highway with AADT of 2,000 veh/day in Example 1A

Before FI Crashes	0.884 crashes/yr
Before PDO Crashes	1.870 crashes/yr
After FI Crashes	0.803 crashes/yr
After PDO Crashes	1.699 crashes/yr
Reduced FI Crashes	0.081 crashes/yr
Reduced PDO Crashes	0.171 crashes/yr

Next, Tool 1 is applied to consider lane widening from 10.5 ft to 12 ft on a two-lane highway with the same characteristics as presented in Figures 7 through 12 but with a higher AADT equal to 8,600 veh/day. The only change needed in the input data is that the AADT of 2,000 veh/day in Figure 7 is changed to 8,600 veh/day.

The Results table from Tool 1 shown in Figure 14 indicates that widening the lanes to 12 ft on the roadway if the AADT is 8,600 veh/day has the same cost as in Figure 13, $620,794, but higher benefits of $961,182. The benefit-cost ratio is 1.548 and the net benefit is $340,388. Thus at this higher AADT level, lane widening to 12 ft would be cost-effective.

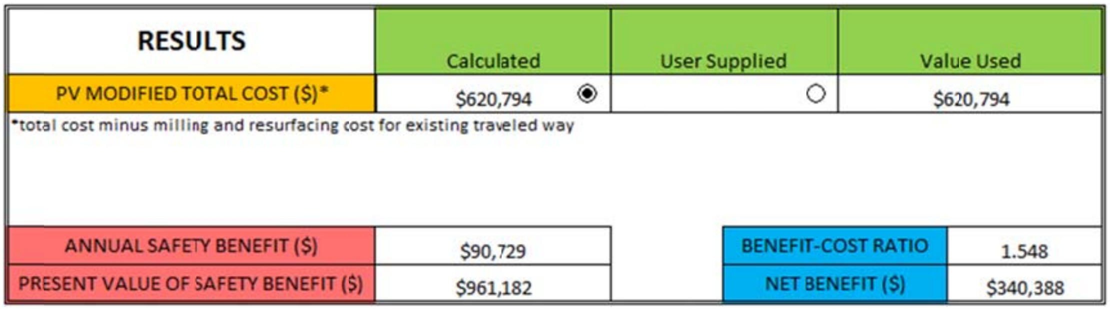


Figure 14. Benefit-cost analysis results for widening lanes to 12 ft for the rural two-lane highway with AADT of 8,600 veh/day in Example 1A

Table 42 shows the increased crash reduction resulting from lane widening on the higher AADT roadway assessed in Figure 13.

Table 42. Crash Frequencies Before and After Lane Widening for the Rural Two-Lane Highway with AADT of 8,600 veh/day in Example 1A

Before FI Crashes	3.802 crashes/yr
Before PDO Crashes	8.042 crashes/yr
After FI Crashes	3.455 crashes/yr
After PDO Crashes	7.308 crashes/yr
Reduced FI Crashes	0.347 crashes/yr
Reduced PDO Crashes	0.734 crashes/yr

Assessment of Shoulder Paving Alternative

The next set of benefit-cost assessments considers another improvement alternative, paving the existing 4-ft unpaved shoulder, with no other improvements considered. The first assessment of shoulder paving considers the two-lane highway described in Figures 7 through 12 with an AADT of 2,000 veh/day.

Figure 15 shows the selection of the shoulder type improvement to a paved shoulder in the Alternatives to Consider table in Tool 1.

Figure 16 shows that the benefits of shoulder paving are very small and that shoulder paving would not be cost-effective for the two-lane highway at an AADT level of 2,000 veh/day, since the costs exceed the benefits.

Figure 17 shows that, even when the AADT of the rural two-lane highway is increased to 8,600 veh/day, the shoulder paving improvement alternative is still not cost-effective, since the costs exceed the benefits.

Based on the results of the benefit-cost analyses in Figures 16 and 17, paving the unpaved shoulder in conjunction with the 3R project is not cost-effective at either of the AADT levels considered.

Alternatives to Consider	Consider for Improvement	User Selection	Value Selected
Lane Width (ft)	☐		Retain Lane Width
Shoulder Width (ft)	☐		Retain Shoulder Width
Shoulder Type	☑	Paved	Paved Shoulder
Roadside Slope	☐		Retain Roadside Slope
Centerline Rumble Strip	☐		Retain Centerline Rumble Strip
Shoulder Rumble Strip	☐		Retain Shoulder Rumble Strip
Enhanced Striping/Delineation	☐		Not Selected
Add New Passing Lane(s)	☐		Not Selected

Figure 15. User selection of shoulder paving as an alternative to be assessed for rural two-lane highway in Example 1A

RESULTS	Calculated	User Supplied	Value Used
PV MODIFIED TOTAL COST ($)*	$499,628 ◉	○	$499,628

*total cost minus milling and resurfacing cost for existing traveled way

ANNUAL SAFETY BENEFIT ($)	$1,396	BENEFIT-COST RATIO	0.030
PRESENT VALUE OF SAFETY BENEFIT ($)	$14,793	NET BENEFIT ($)	-$484,835

Figure 16. Benefit-cost analysis results for shoulder paving for the rural two-lane highway with AADT of 2,000 veh/day in Example 1A

RESULTS	Calculated	User Supplied	Value Used
PV MODIFIED TOTAL COST ($)*	$499,628 ◉	○	$499,628

*total cost minus milling and resurfacing cost for existing traveled way

ANNUAL SAFETY BENEFIT ($)	$6,004	BENEFIT-COST RATIO	0.127
PRESENT VALUE OF SAFETY BENEFIT ($)	$63,611	NET BENEFIT ($)	-$436,017

Figure 17. Benefit-cost analysis results for shoulder paving for the rural two-lane highway with AADT of 8,600 veh/day in Example 1A

Superelevation Improvement Alternative

The next analysis assesses the cost-effectiveness of improving the superelevation on the horizontal curves to *Green Book* criteria in conjunction with the 3R project at both AADT levels of 2,000 and 8,600 veh/day. Table 43 shows that superelevation improvements are potentially applicable to three of the four horizontal curves within the project limits. These improved superelevation rates are then inserted into the rightmost column of the Specific Curve Data table in Tool 1. Figure 11 shows the existing Specific Curve Data table used in the previous example calculations, with no superelevation specified. Figure 18 shows the updated Specific Curve Data table with superelevation improvements for three of the four horizontal curves indicated.

Table 43. Horizontal Curve Improved Superelevation Rates for Example 1A

Curve #	Improved Superelevation (%)
1	7.6
2	8.0
3	No Change
4	7.0

SPECIFIC CURVE DATA							
Number of Curves in Roadway Section				4			
Maximum Superelevation Rate (e_{max})				8%			
Design Speed (mph)				55 mph			
Curve #	Curve Length (mi)	Transition Length (mi)	Radius (ft)	Spiral	Existing e (%)	Consider for Improvement	Improved e (%)
1	0.156 mi	0.089 mi	1300.00 ft	Yes	2.4%	Yes	7.6%
2	0.237 mi	0.122 mi	940.00 ft	Yes	3.8%	Yes	8.0%
3	0.155 mi	0.098 mi	2000.00 ft	Yes	6.0%	No	[illegible]
4	0.222 mi	0.095 mi	1500.00 ft	Yes	3.0%	Yes	7.0%

Figure 18. Specific curve data for rural two-lane highway in Example 1A with potential superelevation improvements entered

Figure 19 shows the Results table from Tool 1 for assessment of the superelevation improvement for the rural two-lane highway with an AADT of 2,000 veh/day. The results show that the superelevation improvement would not be cost-effective, since the costs exceed the benefits.

Figure 20 shows the Results table from Tool 1 for assessment of the superelevation improvement for the rural two-lane highway with a higher AADT of 8,600 veh/day. The results show that, at the higher AADT level, the superelevation improvement is cost-effective, since the benefits exceed the costs.

RESULTS	Calculated	User Supplied	Value Used
PV MODIFIED TOTAL COST ($)*	$61,624 ◉	○	$61,624

*total cost minus milling and resurfacing cost for existing traveled way

ANNUAL SAFETY BENEFIT ($)	$3,678	BENEFIT-COST RATIO	0.632
PRESENT VALUE OF SAFETY BENEFIT ($)	$38,962	NET BENEFIT ($)	-$22,662

Figure 19. Benefit-cost analysis results for superelevation improvement for the rural two-lane highway with AADT of 2,000 veh/day in Example 1A

RESULTS	Calculated	User Supplied	Value Used
PV MODIFIED TOTAL COST ($)*	$61,624 ◉	○	$61,624

*total cost minus milling and resurfacing cost for existing traveled way

ANNUAL SAFETY BENEFIT ($)	$15,814	BENEFIT-COST RATIO	2.719
PRESENT VALUE OF SAFETY BENEFIT ($)	$167,535	NET BENEFIT ($)	$105,912

Figure 20. Benefit-cost analysis results for superelevation improvement for the rural two-lane highway with AADT of 8,600 veh/day in Example 1A

Results of Individual Improvement Alternative Assessments

The results presented above show that for the rural two-lane highway with an AADT level of 2,000 veh/day, none of the improvement alternatives considered is cost-effective. Therefore, a 3R project on this road should generally be limited to resurfacing only, unless there is a site-specific crash pattern or a traffic operational LOS below the highway agency's target level of service.

For a rural two-lane highway, with an AADT level of 8,600 veh/day, however, the lane widening and superelevation improvements were found to be cost-effective, while the shoulder paving improvement was not. Therefore, it is reasonable to give consideration to the lane widening and superelevation improvements as part of the 3R project.

Example 1B—Assessment of Combined Lane Widening and Superelevation Improvement Alternatives for the Same Rural Two-Lane Highway at a Higher AADT Level (8,600 veh/day) using Spreadsheet Tool 1

A benefit-cost assessment was performed with Tool 1 considering the combined effects of lane widening and superelevation improvement for the rural two-lane highway with an AADT level of 8,600 veh/day. Figure 21 presents the results of this assessment. The figure shows that the combined lane widening and superelevation improvements would cost $652,331 and provide benefits of $1,113,424. The benefit-cost ratio for the combined improvements is 1.707 and the net benefit is $461,093. Therefore, the combined lane widening and superelevation improvement should be considered for inclusion in the 3R project.

RESULTS	Calculated	User Supplied	Value Used
PV MODIFIED TOTAL COST ($)*	$652,331 ◉	○	$652,331

*total cost minus milling and resurfacing cost for existing traveled way

ANNUAL SAFETY BENEFIT ($)	$105,099	BENEFIT-COST RATIO	1.707
PRESENT VALUE OF SAFETY BENEFIT ($)	$1,113,424	NET BENEFIT ($)	$461,093

Figure 21. Benefit-cost analysis results for combined lane widening and superelevation improvements for the rural two-lane highway with AADT of 8,600 veh/day in Example 1B

Example 1C—Assessment of Separate Lane Widening, Shoulder Paving, and Superelevation Improvement Alternatives for a Rural Two-Lane Highway Considering Site-Specific Crash History Data Using Spreadsheet Tool 1

So far in Example 1, the crash reduction benefits have been solely on the crash prediction method from the AASHTO *Highway Safety Manual*. To add more confidence in the analysis, Tool 1 can also consider site-specific crash history data using the Empirical Bayes method. The site-specific crash history and the crash predictions are combined as a weighted average to provide a more accurate representation of the site's safety performance.

Two cases of analysis with site-specific crash history data are presented here, one that decreases the combined cost-effectiveness of the lane width and superelevation improvements and one that increases the combined cost-effectiveness. The results indicate that site-specific crash history data can make important contributions to the results of the benefit-cost analyses. All of the scenarios analyzed for Example 1C apply to the rural two-lane highway with an AADT level of 8,600 veh/day.

For the first case, the site-specific crash history data indicate fewer crashes than the crash prediction models. In this case, for a crash history period of three years, there was one fatal-and-injury crash and ten property-damage-only crashes on the rural two-lane highway segment.

Figure 22 shows that the question posed in the Crash History box shown previously in Figure 10 is now answered Yes. A Crash Data Table (also shown in Figure 22) opens in Tool 1 and the crash history data are entered by the user.

Figures 23 through 25 show the Results tables for the benefit-cost analyses of the individual improvement alternatives. The figures show that, with consideration of the site-specific crash history data, only the superelevation improvement for the rural two-lane highway with an AADT level of 8,600 veh/day remains cost-effective.

CRASH HISTORY	
Consider existing crash history?	
Yes ◉	No ○

CRASH DATA	
Crash History Period (yrs)	3
Total Fatal-and-Injury Crashes	1
Total Property-Damage-Only Crashes	10

Figure 22. Entering site-specific crash data for Example 1C with site-specific crash history lower than predicted

RESULTS	Calculated	User Supplied	Value Used
PV MODIFIED TOTAL COST ($)*	$620,794 ◉	○	$620,794

*total cost minus milling and resurfacing cost for existing traveled way

ANNUAL SAFETY BENEFIT ($)	$51,489	BENEFIT-COST RATIO	0.879
PRESENT VALUE OF SAFETY BENEFIT ($)	$545,472	NET BENEFIT ($)	-$75,322

Figure 23. Benefit-cost analysis results for lane widening for the rural two-lane highway with AADT of 8,600 veh/day with site-specific crash history data lower than predicted in Example 1C

RESULTS	Calculated	User Supplied	Value Used
PV MODIFIED TOTAL COST ($)*	$499,628 ◉	○	$499,628

*total cost minus milling and resurfacing cost for existing traveled way

ANNUAL SAFETY BENEFIT ($)	$3,408	BENEFIT-COST RATIO	0.072
PRESENT VALUE OF SAFETY BENEFIT ($)	$36,099	NET BENEFIT ($)	-$463,529

Figure 24. Benefit-cost analysis results for shoulder paving for the rural two-lane highway with AADT of 8,600 veh/day with site-specific crash history data lower than predicted in Example 1C

RESULTS	Calculated	User Supplied	Value Used
PV MODIFIED TOTAL COST ($)*	$61,624 ◉	○	$61,624

*total cost minus milling and resurfacing cost for existing traveled way

ANNUAL SAFETY BENEFIT ($)	$8,975	BENEFIT-COST RATIO	1.543
PRESENT VALUE OF SAFETY BENEFIT ($)	$95,076	NET BENEFIT ($)	$33,453

Figure 25. Benefit-cost analysis results for superelevation improvement for the rural two-lane highway with AADT of 8,600 veh/day with site-specific crash history data lower than predicted in Example 1C

For the second case, the site-specific crash history data indicate more crashes than the crash prediction models. In this case, for a crash history period of three years, there were 20 fatal-and-injury crashes and 43 property-damage-only crashes on the rural two-lane highway segment.

Figure 26 shows that the question posed in the Crash History box shown previously in Figure 10 is now answered Yes. A Crash Data Table (also shown in Figure 26) opens in Tool 1 and the crash history data are entered by the user.

Figures 27 through 29 show the Results tables for the benefit-cost analyses of the individual improvement alternatives. The figures show that, with consideration of the site-specific crash history data, both lane widening and superelevation improvement for the rural two-lane highway with an AADT level of 8,600 veh/day are cost-effective, but that shoulder paving is not cost-effective.

CRASH HISTORY	
Consider existing crash history?	
Yes ◉	No ○

CRASH DATA	
Crash History Period (yrs)	3
Total Fatal-and-Injury Crashes	20
Total Property-Damage-Only Crashes	43

Figure 26. Entering site-specific crash data for Example 1C with site-specific crash history higher than predicted

RESULTS	Calculated	User Supplied	Value Used
PV MODIFIED TOTAL COST ($)*	$620,794 ◉	○	$620,794

*total cost minus milling and resurfacing cost for existing traveled way

ANNUAL SAFETY BENEFIT ($)	$134,673	BENEFIT-COST RATIO	2.298
PRESENT VALUE OF SAFETY BENEFIT ($)	$1,426,728	NET BENEFIT ($)	$805,935

Figure 27. Benefit-cost analysis results for lane widening for the rural two-lane highway with AADT of 8,600 veh/day with site-specific crash history data lower than predicted in Example 1C

RESULTS	Calculated	User Supplied	Value Used
PV MODIFIED TOTAL COST ($)*	$499,628 ◉	○	$499,628

*total cost minus milling and resurfacing cost for existing traveled way

ANNUAL SAFETY BENEFIT ($)	$8,913	BENEFIT-COST RATIO	0.189
PRESENT VALUE OF SAFETY BENEFIT ($)	$94,421	NET BENEFIT ($)	-$405,207

Figure 28. Benefit-cost analysis results for shoulder paving for the rural two-lane highway with AADT of 8,600 veh/day with site-specific crash history data higher than predicted in Example 1C

RESULTS	Calculated	User Supplied	Value Used
PV MODIFIED TOTAL COST ($)*	$61,624 ◉	○	$61,624

*total cost minus milling and resurfacing cost for existing traveled way

ANNUAL SAFETY BENEFIT ($)	$23,474	BENEFIT-COST RATIO	4.035
PRESENT VALUE OF SAFETY BENEFIT ($)	$248,681	NET BENEFIT ($)	$187,057

Figure 29. Benefit-cost analysis results for superelevation improvement for the rural two-lane highway with AADT of 8,600 veh/day with site-specific crash history data higher than predicted in Example 1C

Example 1D—Achieving the Same Results as Examples 1A and 1B in One Step Using Spreadsheet Tool 2

Spreadsheet Tool 2 can be used to obtain the same results obtained in Examples 1A and 1B in a single step. When applied to the rural two-lane highway with an AADT level of 2,000 veh/day, Tool 2 will show in one step that none of the alternatives considered (or any of their combinations) are cost-effective. When applied to the rural two-lane highway with an AADT level of 8,600 veh/day, Tool 2 will show in one step that the combination of lane widening from 10.5 ft to 12 ft and the superelevation improvement is the most cost-effective of the alternatives considered (or any of their combinations).

Tool 2 has an advantage over Tool 1 in that it can consider several improvement types and all combinations of alternatives for those improvement types in a single analysis. However, since Tool 2 incorporates supplementary programming in Visual Basic, macros must be enabled on the user's computer for Tool 2 to function.

Example 1D uses all of the default values provided in Tool 2 and does not consider existing crash history. The example also does not include consideration of right-of-way acquisition cost in the analysis. Tool 2 can consider pavement marking and delineator data, but these data are not needed in this example, because adding enhanced pavement markings and roadside delineators is not considered as an improvement alternative.

Figures 30 through 34 present screenshots of the data entry userform windows showing the data for the rural two-lane highway with an AADT level of 2,000 veh/day, equivalent to the Tool 1 data entry tables shown in Figures 7 through 11.

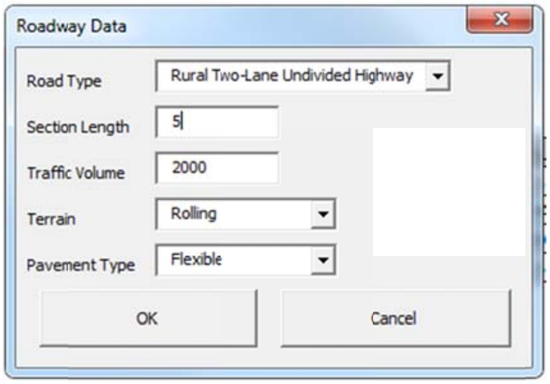


Figure 30. Roadway data input for a rural two-lane highway for Example 1D in Tool 2

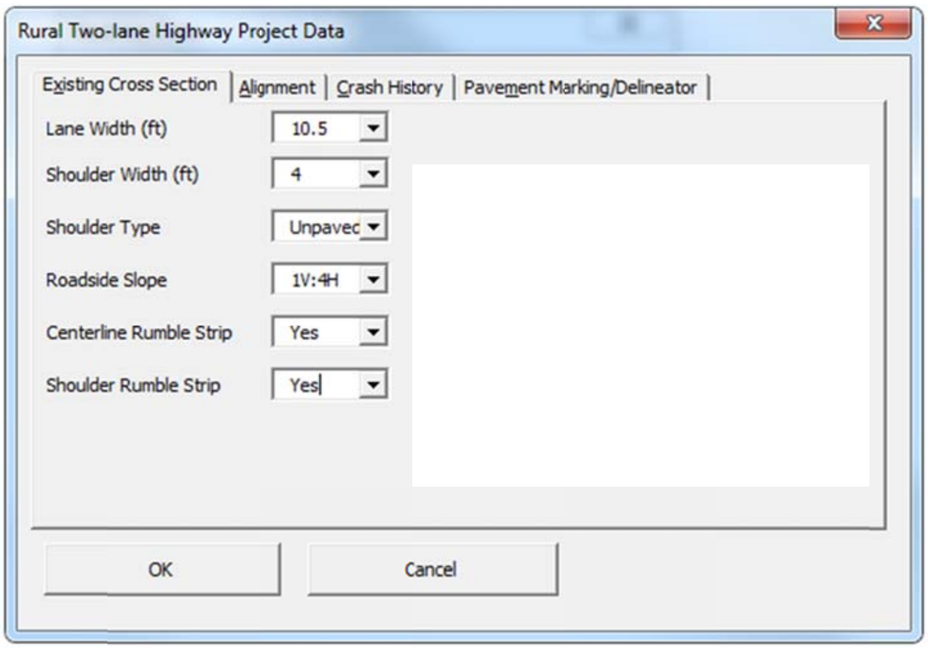


Figure 31. Existing cross section data input for rural two-lane highway for Example 1D in Tool 2

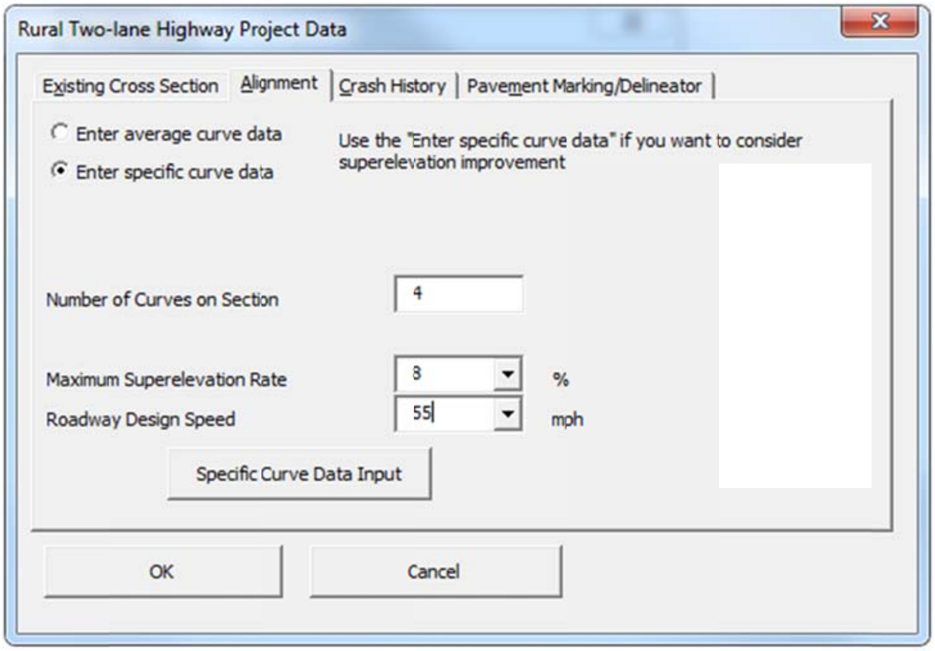


Figure 32. Alignment data input for rural two-lane highway for Example 1D in Tool 2

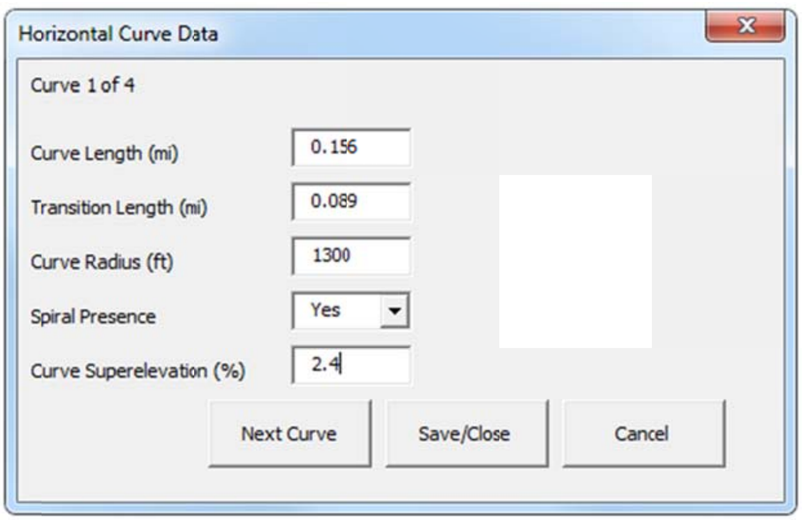


Figure 33. Specific curve data input for rural two-lane highway for Example 1D in Tool 2

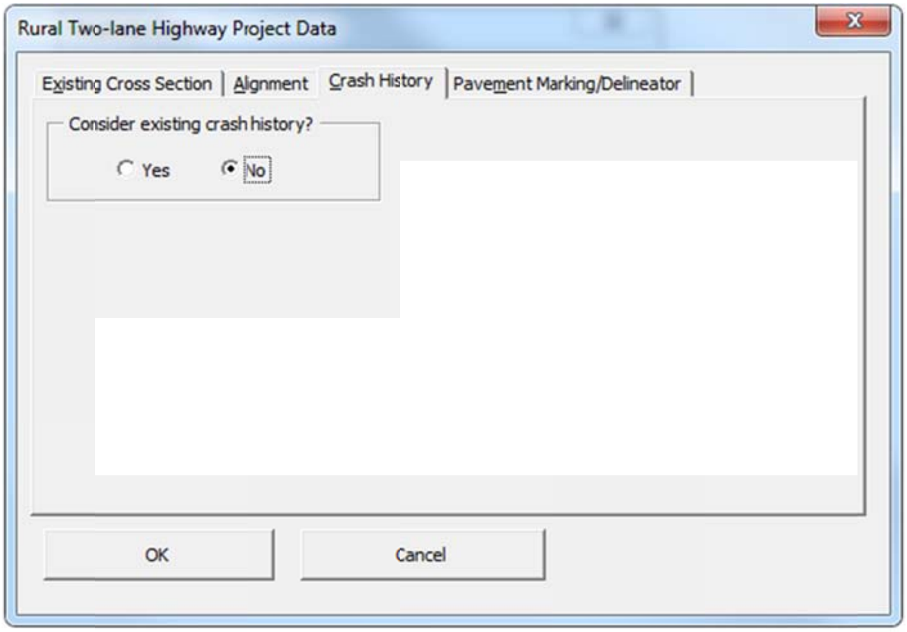


Figure 34. Crash history input for rural two-lane highway for Example 1D in Tool 2

Figure 35 shows the dialogue box used by the analyst in Tool 2 to specify the improvement alternatives to be considered. Tool 2 automatically considers all feasible alternatives and combinations of alternatives for the specified improvement types. For example, given the existing lane width of 10.5 ft, checking Widen Lane Width in Figure 35 is equivalent to specifying that lane widths of 10.5, 11.0, 11.5, and 12.0 ft will be considered. Checking Pave Existing Unpaved Shoulders specifies that both unpaved and paved shoulders of the current width will be considered. Checking Improve Curve Superelevation starts a comparison of the superelevation of each curve to the superelevation indicated in AASHTO *Green Book* criteria (*4*). Two alternatives are considered: (a) leave all curves with their existing superelevation unchanged or (b) improve all curves with superelevation below the *Green Book* superelevation value to the *Green Book* superelevation value. The improved superelevation rates identified by Tool 2 for each horizontal curve are summarized in Table 44; it should be noted that these improved superelevation rates match those shown previously in Table 43. This includes a total of four lane widening alternatives, two shoulder paving alternatives, and two superelevation improvement alternatives, representing 16 combinations of alternatives are considered.

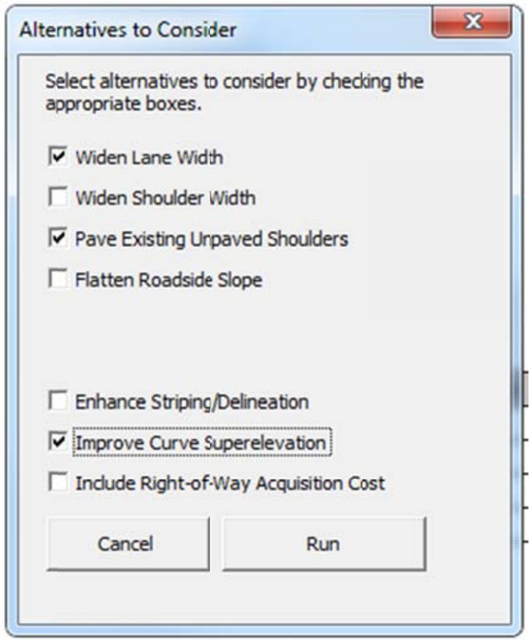


Figure 35. User selection of improvement alternatives to be considered in Tool 2 selected for rural two-lane highway in Example 1D

Table 44. Minimum *Green Book* Superelevation Rates Provided by Tool 2

Curve	Improved Superelevation (%)
1	7.6
2	8.0
3	No Change Needed
4	7.0

The results of the analysis conducted with Tool 2 for the rural two-lane highway with an AADT level of 2,000 veh/day are summarized Table 45. The improvement scenarios (combinations of alternatives) are sorted from most cost-effective to least cost-effective, with cost-effectiveness classified based on the net benefit resulting from implementation of the alternative. The table also shows the total cost for each improvement scenario so that scenarios that exceed the available budget can be eliminated from consideration. In Table 45, all of the improvement scenarios have net benefits less than zero, so none of the scenarios are considered cost-effective. This is the same conclusion reached after multiple applications of Tool 1.

Table 45. Results of Benefit-Cost Analysis Using Tool 2 for a Rural Two-Lane Highway with AADT Level of 2,000 veh/day in Example 1D

Net Benefit ($)	B/C Ratio	Improved Lane Width (ft)	Improved Shoulder Type	Improve Super-elevation	Total Benefit ($)	Total Cost ($)
-$22,662	0.632	10.5	Unpaved	Yes	$38,962	$61,624
-$284,419	0.408	11	Unpaved	Yes	$196,086	$480,505
-$294,340	0.352	11	Unpaved	No	$159,665	$454,005
-$338,853	0.402	11.5	Unpaved	Yes	$227,511	$566,364
-$345,801	0.357	11.5	Unpaved	No	$191,598	$537,399
-$393,395	0.397	12	Unpaved	Yes	$258,936	$652,331
-$397,263	0.360	12	Unpaved	No	$223,531	$620,794
-$484,835	0.030	10.5	Paved	No	$14,793	$499,628
-$492,156	0.098	10.5	Paved	Yes	$53,520	$545,676
-$717,036	0.195	11	Paved	No	$173,494	$890,530
-$730,113	0.223	11	Paved	Yes	$209,695	$939,808
-$768,690	0.211	11.5	Paved	No	$205,234	$973,924
-$785,612	0.235	11.5	Paved	Yes	$240,930	$1,026,542
-$820,345	0.224	12	Paved	No	$236,974	$1,057,318
-$841,221	0.244	12	Paved	Yes	$272,165	$1,113,386

The same assessment was then rerun with a higher AADT, changing the AADT value in the input data in Figure 30 from 2,000 to 8,600 veh/day. The results of this second analysis for Example 1D are presented in Table 46, sorted by net benefits value in order from most cost-effective to least cost-effective. In Table 46, given the higher AADT value than Table 45, several improvement scenarios have net benefits greater than zero. The highest net benefits value is for the combination of lane widening to 12 ft and superelevation improvement. This is the same conclusion reached after multiple applications of Tool 1.

Table 46. Results of Benefit-Cost Analysis Using Tool 2 for a Rural Two-Lane Highway with AADT Level of 8,600 veh/day in Example 1D

Net Benefit ($)	B/C Ratio	Improved Lane Width (ft)	Improved Shoulder Type	Improve Super-elevation	Total Benefit ($)	Total Cost ($)
$461,093	1.707	12	Unpaved	Yes	$1,113,424	$652,331
$411,934	1.727	11.5	Unpaved	Yes	$978,297	$566,364
$362,665	1.755	11	Unpaved	Yes	$843,170	$480,505
$340,388	1.548	12	Unpaved	No	$961,182	$620,794
$286,471	1.533	11.5	Unpaved	No	$823,870	$537,399
$232,554	1.512	11	Unpaved	No	$686,559	$454,005
$105,912	2.719	10.5	Unpaved	Yes	$167,535	$61,624
$56,924	1.051	12	Paved	Yes	$1,170,310	$1,113,386
$9,457	1.009	11.5	Paved	Yes	$1,035,999	$1,026,542
-$38,119	0.959	11	Paved	Yes	$901,688	$939,808
-$38,332	0.964	12	Paved	No	$1,018,987	$1,057,318
-$91,419	0.906	11.5	Paved	No	$882,505	$973,924
-$144,507	0.838	11	Paved	No	$746,022	$890,530
-$315,541	0.422	10.5	Paved	Yes	$230,134	$545,676
-$436,017	0.127	10.5	Paved	No	$63,611	$499,628

5.7.2 Example 2—Quantifying Minimum AADT Levels for Cost-Effective Application of a Selected Improvement Type on a Rural Two-Lane Highway

In Example 2, an agency wants to construct a table of minimum AADT values that can be used as a guideline for the situations under which lane widening should be considered in 3R projects on rural two-lane highways. While application of Tool 1 or Tool 2 to each individual 3R project site would produce more accurate results, Section 5.4 of this guide indicates that application of such minimum AADT tables is an acceptable method for making 3R project decisions for specific improvement types. Minimum AADT tables for specific improvement types can be created with Tool 1 using agency specific assumptions for all setup variables in Tool 1 including, if desired, agency-specific values for unit construction costs, crash costs, SPF coefficients and or calibration factors. In addition, agencies can chose whether to include or omit right-of way costs from the calculations and, if right-of-way costs are included, agency-specific values of right-of-way cost per acre for specific area types and road types can be used.

In Example 2, an agency chooses to develop minimum AADT tables for lane widening on rural two-lane highways using the assumed set of existing conditions presented in Table 47. Use Tool 1 to calculate benefit-cost ratios for every 1,000 veh/day increments of AADT. Use the road attributes given in Table 47 to input into Tool 1.

Table 47. Roadway Attributes for Rural Two-Lane Highway Considered in Example 2

Section Length	1 mi
AADT	1,000 to 20,000 veh/day
Terrain	Level
Pavement Type	Flexible
Paved Shoulder Width	2 ft
Roadside Slope	1V:3H
Rumble Strips Present	None
Horizontal Curves	None

Tool 1 is then applied to lane widening from 9 to 10 ft for AADTs beginning at 1,000 veh/day and increasing in increments of 1,000 veh/day. The results are shown in Table 48.

Table 48. Benefit-Cost Ratios for Lane Widening from 9 to 10 ft on Rural Two-Lane Highway Segment at Various AADT Levels for Example 2

Lane Width (ft)		AADT (veh/day)	Net Implementation Cost ($)	Present Value of Safety Benefits ($)	Benefit-Cost Ratio
Before	After				
9	10	1,000	109,896	13,904	0.13
9	10	2,000	109,896	63,767	0.58
9	10	3,000	109,896	95,899	0.87
9	10	4,000	109,896	127,865	1.16
9	10	5,000	109,896	159,832	1.45
9	10	6,000	109,896	191,798	1.74
9	10	7,000	109,896	223,764	2.04
9	10	8,000	109,896	255,731	2.33
9	10	9,000	109,896	287,697	2.62
9	10	10,000	109,896	319,663	2.91

NOTE: Assumed conditions – 2-ft paved shoulder; 1V:3H roadside foreslopes; flexible pavement

According to the results shown in Table 48, widening a rural two-lane highway with 9-ft lanes to 10-ft lanes will produce a benefit-cost ratio greater than 1.0 at AADTs of 4,000 veh/day and higher. Widening will also produce benefit-cost ratios greater than 2.0 at AADTs 7,000 veh/day and higher. This same analysis can then be repeated for each additional lane widening scenario: 9 to 11 ft, 9 to 12 ft, 10 to 11 ft, 10 to 12 ft, and 11 to 12 ft. Based on the results of these analyses, a table can be constructed showing minimum AADT levels that would provide benefit-cost ratios of at least 1.0 and 2.0 for each lane widening scenario (see Table 49).

Table 49. Minimum AADT Levels at which Benefit-Cost Ratios Exceed 1.0 and 2.0 for Lane Widening for Example 2

Lane Widening Scenario	Minimum AADT (veh/day) for	
	B/C=1.0	B/C=2.0
Widen from 9 to 10 ft	4,000	7,000
Widen from 9 to 11 ft	3,000	5,000
Widen from 9 to 12 ft	3,000	5,000
Widen from 10 to 11 ft	3,000	6,000
Widen from 10 to 12 ft	4,000	7,000
Widen from 11 to 12 ft	14,000	>20,000

The minimum AADT thresholds shown in Table 49 apply only to rural two-lane highways with the attributes shown previously in Table 47. Similar analyses can be conducted for rural two-lane highways in other terrains (see Table 50) as well as varying shoulder widths and roadside slopes (see Table 51) for example.

Table 50. AADT Levels at which Lane Widening Becomes Cost-Effective on Rural Two-Lane Highways Assuming 2-ft Paved Shoulders and 1V:3H Roadside Foreslopes for Example 2

Proposed Improvement	Minimum AADT level (veh/day) for benefit-cost ratio = 1.0			Minimum AADT level (veh/day) for benefit-cost ratio = 2.0		
	Level	Rolling	Mountainous	Level	Rolling	Mountainous
9-ft existing lane width						
Widen from 9 to 10 ft	4,000	4,000	6,000	7,000	8,000	12,000
Widen from 9 to 11 ft	3,000	3,000	4,000	5,000	5,000	7,000
Widen from 9 to 12 ft	3,000	3,000	4,000	5,000	5,000	7,000
10-ft existing lane width						
Widen from 10 to 11 ft	3,000	4,000	5,000	6,000	7,000	10,000
Widen from 10 to 12 ft	4,000	4,000	5,000	7,000	7,000	10,000
11-ft existing lane width						
Widen from 11 to 12 ft	14,000	16,000	>20,000	>20,000	>20,000	>20,000

Table 51. AADT Levels at which Lane Widening Becomes Cost-Effective on Rural Two-Lane Highways Assuming 4-ft Paved Shoulders and 1V:6H Roadside Foreslopes for Example 2

Proposed Improvement	Minimum AADT level (veh/day) for benefit-cost ratio = 1.0			Minimum AADT level (veh/day) for benefit-cost ratio = 2.0		
	Level	Rolling	Mountainous	Level	Rolling	Mountainous
9-ft existing lane width						
Widen from 9 to 10 ft	8,000	9,000	13,000	15,000	17,000	>20,000
Widen from 9 to 11 ft	4,000	5,000	7,000	8,000	9,000	13,000
Widen from 9 to 12 ft	4,000	5,000	7,000	8,000	9,000	13,000
10-ft existing lane width						
Widen from 10 to 11 ft	6,000	7,000	11,000	12,000	14,000	>20,000
Widen from 10 to 12 ft	6,000	7,000	10,000	12,000	13,000	20,000
11-ft existing lane width						
Widen from 11 to 12 ft	>20,000	>20,000	>20,000	>20,000	>20,000	>20,000

Based on tables like Tables 50 and 51, the agency can establish specific guidelines for the minimum AADT levels at which specific lane widening scenarios will be established.

5.7.3 Example 3—Rural Four-Lane Highway Assessment

Example 3 is presented to illustrate the application of Tools 1 and 2 to a rural four-lane highway. Example 3 is presented primarily to illustrate the data entry procedures for rural four-lane highways, and this example is not intended to be as comprehensive as Example 1.

In Example 3, a 3R project is being planned for a section of rural four-lane undivided highway. Tools 1 and 2 are used to assess whether specific proposed improvements, to supplement pavement resurfacing, are economically justifiable. The example uses default values provided for all data elements in the R4UD_Setup worksheet.

The existing roadway and cross section data are shown in Table 52.

Table 52. Roadway Characteristics for Rural Four-Lane Undivided Highway in Example 3

Road Type	Four-lane Undivided
Section Length	3.2 mi
AADT	28,000 veh/day
Terrain	Level
Pavement	Rigid
Lane Width	12 ft
Paved Shoulder Width	2 ft
Roadside Slope	1V:2H
Rumble Strips Present	Centerline Only
Roadside Delineators	Present on entire length of section
Crash History Period	5 yr
Number of Fatal-and-injury Crashes	20
Number of Property-damage-only Crashes	41
Maximum Curve Superelevation	8%
Design Speed	65 mph

There is only one horizontal curve within the project limits. Table 53 presents the available geometric data for this curve.

Table 53. Specific Horizontal Curve Data for Example 3

Curve Length	0.102 mi
Curve Radius	4000 ft
Presence of Spiral Transitions	No
Existing Superelevation Rate	3.0%

The agency planning the 3R project wants to determine the economic feasibility of flattening the roadside slope to 1V:6H, installing shoulder rumble strips, re-installing the centerline rumble strip, and adding enhanced pavement markings and delineation as part of the 3R project.

Figures 36 through 41 show how the project inputs should appear in the spreadsheet-based tool.

ROADWAY DATA	
Divided or Undivided	4-lane Undivided
Section Length (mi)	3.200
AADT (veh/day)	28,000
Terrain	Level
Pavement Type	Rigid

Figure 36. Roadway data input for rural four-lane highways in Example 3

EXISTING CROSS SECTION	
Lane Width (ft)	12.0 ft
Shoulder Width (ft)	2 ft
Shoulder Type	Paved
Roadside Slope	1V:2H
Centerline Rumble Strip	Yes
Shoulder Rumble Strip	No

Figure 37. Existing cross section data input for rural four-lane highways in Example 3

CRASH HISTORY
Consider existing crash history?
Yes ◉ No ○

CRASH DATA	
Crash History Period (yrs)	5
Total Fatal-and-Injury Crashes	20
Total Property-Damage-Only Crashes	41

Figure 38. Crash data input for rural four-lane highways in Example 3

SPECIFIC CURVE DATA							
Number of Curves in Roadway Section				1			
Maximum Superelevation Rate (e_{max})				8%			
Design Speed (mph)				65 mph			
Curve #	Curve Length (mi)	Transition Length (mi)	Radius (ft)	Spiral	Existing e (%)	Consider for Improvement	Improved e (%)
1	0.102 mi	0.000 mi	4000.00 ft	No	3.0%	No	

Figure 39. Specific curve data for Example 3

Alternatives to Consider	Consider for Improvement	User Selection	Value Selected
Lane Width (ft)	☐		Retain Lane Width
Shoulder Width (ft)	☐		Retain Shoulder Width
Shoulder Type	☐		Paved Shoulder
Roadside Slope	☑	1V:6H	1V:6H
Centerline Rumble Strip	☐		Retain Centerline Rumble Strip
Shoulder Rumble Strip	☑		Install
Enhanced Striping/Delineation	☑		Improve

ENHANCED PAVEMENT MARKING AND DELINEATION DATA	
Total Length of Section with Delineator Posts (mi)	6.400 mi

Figure 40. Alternatives to consider selection for the rural four-lane highway in Example 3

Include Projected Right-of-Way Cost	
☐	$0.00

Figure 41. Project right-of-way cost inclusion option for the rural four-lane highways in Example 3

The benefit-cost analysis results are shown in Figure 42.

RESULTS	Calculated	User Supplied	Value Used
PV MODIFIED TOTAL COST ($)*	$1,091,554		$1,091,554

*total cost minus milling and resurfacing cost for existing traveled way

ANNUAL SAFETY BENEFIT ($)	$261,953	BENEFIT-COST RATIO	2.542
PRESENT VALUE OF SAFETY BENEFIT ($)	$2,775,129	NET BENEFIT ($)	$1,683,575

Figure 42. Results of analysis for the rural four-lane highway in Example 3

The results of the economic analysis indicate an economically justifiable 3R project, with a benefit-cost ratio of 2.5.

To verify that slope flattening, shoulder rumble strip installation, and enhanced pavement marking and delineation should all be included in the project, either Tool 1 should be run for each of these improvements individually or Tool 2 should be used to look at all combinations of them.

In fact, the highway agency planning the project also wants consider widening the paved shoulders, however the agency is unsure whether widening would be cost-effective and, if so, how shoulder widening should be considered. To address this issue, Tool 2 is run for all combinations of slope flattening (1V:2H to 1V:6H), shoulder rumble strip installation, enhanced pavement marking and delineation, and shoulder widening (2 to 8 ft).

The results of the analysis with Tool 2 are shown in Table 54. The table shows the 15 improvement alternatives that Tool 2 indicates will produce the highest net benefits. All of the shoulder widening alternatives shown in Table 54 produce net benefits smaller than the alternatives in which the existing shoulder width of 2 ft is retained. Thus, it can be concluded that shoulder widening is not cost-effective and need not be considered as part of the 3R project, unless an existing crash pattern or a traffic operational analysis indicates the need for wider shoulders.

In fact, the alternative improvement with the highest net benefits shown in Table 54 is the same combination of slope flattening, shoulder rumble strip installation, and striping/delineation assessed in Figure 40. This confirms that slope flattening to 1V:6H, shoulder rumble strip installation, and striping/delineation are cost-effective individually and, together represent the most cost-effective combination of alternatives. The results indicate that any shoulder widening will result in a net benefit lower than the net benefit produced by flattening the roadside slope to 1V:6H, installing shoulder rumble strips, and improving the striping and delineation. If the improvement cost estimate of $1,091,554 is within the agency's budget, strong consideration should be given to including the slope flattening, shoulder rumble strip installation, and striping/delineation improvement as part of the 3R project.

Table 54. Results of Analysis for Shoulder Widening, Slope Flattening and Installing Shoulder Rumble Strips

Net Benefit ($)	B/C Ratio	Improved Shoulder Width (ft)	Improved Slope	Install Shoulder Rumble Strip	Improve Striping/ Delineation	Total Benefit ($)	Total Cost ($)
$1,683,575	2.542	2	1V:6H	Yes	Yes	$2,775,129	$1,091,554
$1,602,645	2.488	2	1V:6H	No	Yes	$2,679,533	$1,076,888
$1,462,796	2.429	2	1V:4H	Yes	Yes	$2,486,452	$1,023,657
$1,375,492	2.363	2	1V:4H	No	Yes	$2,384,483	$1,008,991
$1,373,026	2.387	2	1V:3H	Yes	Yes	$2,362,734	$989,708
$1,351,152	2.522	2	1V:2H	Yes	Yes	$2,239,015	$887,863
$1,282,991	2.316	2	1V:3H	No	Yes	$2,258,033	$975,043
$1,258,386	2.441	2	1V:2H	No	Yes	$2,131,584	$873,197
$1,207,517	1.739	3	1V:6H	Yes	Yes	$2,840,435	$1,632,918
$1,128,029	1.697	3	1V:6H	No	Yes	$2,746,281	$1,618,252
$1,073,659	1.586	4	1V:6H	Yes	Yes	$2,905,742	$1,832,082
$995,612	1.548	4	1V:6H	No	Yes	$2,813,029	$1,817,417
$991,091	1.633	3	1V:4H	Yes	Yes	$2,556,112	$1,565,021
$939,801	1.463	5	1V:6H	Yes	Yes	$2,971,048	$2,031,247
$905,326	1.584	3	1V:4H	No	Yes	$2,455,681	$1,550,356

5.7.4 Example 4—Freeway Assessment

Example 4 is presented to illustrate the application of Tool 1 to a rural freeway. Example 4 is presented primarily to illustrate the data entry procedures for freeways, and this example is not intended to be as comprehensive as Example 1.

In Example 4, a 3R project is planned for a section of rural freeway. Tool 1 is used to assess whether specific proposed improvements, to supplement resurfacing, are economically justifiable. The example uses default values provided for all data elements in the FWY_Setup worksheet.

The existing freeway attributes are shown in Table 55.

Table 55. Freeway Attributes for Example 4

Section Length	3 mi
AADT	45,000 veh/day
Terrain	Rolling
Pavement	Flexible
Percent of Section Length on Horizontal Curves	15%
Typical Curve Radius	3,250 ft
Number of Horizontal Curves	4
Number of Through Lanes	4
Lane Width	12 ft
Outside Shoulder Width	4 ft
Inside Shoulder Width	2 ft
Outside Roadside Slope	1V:3H
Median Width	30 ft
Median Cross Slope	1V:6H
Presence of Median Barriers	No
Presence of Outside Barriers	Yes
Clear Zone Width	20 ft
Rumble Strips Present	Inside and Outside Shoulders
Proportion of AADT During Hours Where Volume Exceeds 1,000 veh/h/ln	0

Characteristics of the four existing outside barriers within the project limits are presented in Table 56.

Table 56. Outside Barrier Characteristics for Example Problem

Outside Barrier	Length of Outside Barrier (mi)	Horizontal Clearance (ft)	Barrier Type
1	0.125 mi	5.0 ft	Guardrail
2	0.400 mi	8.0 ft	Cable Barrier
3	0.100 mi	6.0 ft	Concrete Barrier
4	0.100 mi	6.0 ft	Concrete Barrier

The highway agency has decided to investigate possible implementation of widening the outside shoulder width to 12 ft and widening the inside shoulder width to 12 ft. It is assumed that right-of-way acquisition is not needed.

Figures 43 through 51 show how this example problem should be setup in the spreadsheet-based tool.

ROADWAY DATA	
Area Type	Rural
Section Length (mi)	3.000
AADT (veh/day)	45,000
Terrain	Rolling
Pavement Type	Flexible

Figure 43. Roadway data input for a freeway in Example 4

ALIGNMENT DATA	
Enter average curve data	◉
Enter specific curve data	○

Figure 44. Alignment option input for a freeway in Example 4

AVERAGE CURVE DATA	
% of Section Length on Curves	15.00%
Typical Curve Radius (ft)	3250 ft
Number of Curves on Section	4

Figure 45. Average curve data input for a freeways in Example 4

CRASH HISTORY	
Consider existing crash history?	
Yes ○	No ◉

Figure 46. Crash history option input for a freeway in Example 4

EXISTING CROSS SECTION	
Number of Through Lanes	4
Lane Width (ft)	12.0 ft
Outside Shoulder Width (ft)	4 ft
Inside Shoulder Width (ft)	2 ft
Outside Roadside Slope	1V:3H
Median Width (ft)	30.0 ft
Median Slope	1V:6H
Median Barrier	No Median Barrier
Outside Barrier	Yes
Clear Zone Width (ft)	20.0 ft
Inside Shoulder Rumble Strip	Yes
Outside Shoulder Rumble Strip	Yes
% of AADT during high volume	0.0%

Figure 47. Existing cross section data input for a freeway in Example 4

OUTSIDE BARRIER	
Number of Outside Barriers	4

Figure 48. Outside barrier count input for a freeway in Example 4

Outside Barrier	Length of Outside Barrier (mi)	Horizontal Clearance (ft)	Barrier Type
1	0.125 mi	5.0 ft	Guardrail
2	0.400 mi	8.0 ft	Cable Barrier
3	0.100 mi	6.0 ft	Concrete Barrier
4	0.100 mi	6.0 ft	Concrete Barrier

Figure 49. Outside barrier data input for a freeway in Example 4

Alternatives to Consider	Consider for Improvement/ Modification	User Selection	Value Selected
Lane Width (ft)	☐		Retain Lane Width
Outside Shoulder Width (ft)	☑	12 ft	12 ft
Inside Shoulder Width (ft)	☑	12 ft	12 ft
Median Barrier	☐	Install Continuous Offset Barrier	No Change
Outside Barrier	☐		Retain Existing Outside Barriers
Inside Rumble Strip	☐		Retain Inside Rumble Strip
Outside Rumble Strip	☐		Retain Outside Rumble Strip

Figure 50. Data entry table for selecting alternatives to consider for a freeway in Example 4.

Include Projected Right-of-Way Cost	
☐	$0.00

Figure 51. Right-of-way cost inclusion option for a freeway in Example 4.

The results of the analysis are shown in Figure 52.

RESULTS	Calculated	User Supplied	Value Used
PV MODIFIED TOTAL COST ($)*	$2,066,662 ◉	○	$2,066,662
*total cost minus milling and resurfacing cost for existing traveled way			
ANNUAL SAFETY BENEFIT ($)	$803,216	BENEFIT-COST RATIO	4.117
PRESENT VALUE OF SAFETY BENEFIT ($)	$8,509,284	NET BENEFIT ($)	$6,442,622

Figure 52. Benefit-cost analysis results for inside and outside shoulder widening for a freeway in Example 4

Table 57 shows the observed and estimated crash frequencies before and after the 3R project.

Table 57. Before, After and Reduced Crash Frequencies on Freeway 3R Project in Example 4

Before FI Crashes	8.513 crashes/yr
Before PDO Crashes	17.283 crashes/yr
After FI Crashes	5.224 crashes/yr
After PDO Crashes	14.544 crashes/yr
Reduced FI Crashes	3.289 crashes/yr
Reduced PDO Crashes	2.739 crashes/yr

The results of the economic analysis indicate the proposed inside and outside shoulder widening is economically justified with a positive net benefit of $6,442,622.

Tool 2 was then used to verify that both the inside and outside shoulder widening are cost-effective individually and that the widening of both the inside and outside shoulders to 12 ft is the combination of alternatives with the highest net benefit.

Some highway agencies have policies that limit inside shoulder width to 4 ft to encourage drivers that need to stop to use the outside shoulder. Nothing in the results of a benefit-cost analysis like that shown here would require a highway agency to make the inside shoulders wider than indicated in their policy.

Chapter 6.
3R Project Design Guidelines for Specific Roadway Types

This chapter presents design guidelines for 3R projects. The design guidelines are based on explicit consideration of crash reduction effectiveness estimates for design improvements, where available, and on the use of before-after benefit-cost analysis tools. The design guidelines are organized by roadway type and, within roadway type, by design element.

6.1 Rural Two-Lane Highways

6.1.1 Lane Widening

Lane widening should be considered for each 3R project on a rural two-lane highway with existing lane widths less than 12 ft. Decisions about lane widening for 3R projects should be based on benefit-cost analysis. Lane widening is a desirable investment only where the analysis indicates that the expected crash reduction benefits from lane widening will exceed the improvement costs or a crash analysis finds existing crash patterns that can potentially be reduced by lane widening. Where there are no existing crash patterns that can potentially be reduced by lane widening and the expected crash reduction benefits from lane widening are less than the improvement cost, lane widening would be a poor investment and available funds would be better invested at another location where the crash reduction benefits would be larger.

Two benefit-cost analysis approaches are applicable to lane widening. The most desirable approach (Option 1) for cost-effective lane widening decisions is to conduct a site-specific benefit-cost analysis for each individual 3R project. Site-specific benefit-cost analyses are desirable because even nominally similar sites may differ in roadway characteristics, traffic volumes, crash history, and improvement costs, such that lane widening may be cost-effective at one site and not at another. The crash reduction effectiveness of lane widening on rural two-lane highways is documented in Section 4.3.1.1. Procedures for site-specific benefit-cost analysis are illustrated in Section 5.2.2. The benefit-cost analysis tool provided with these guidelines enables site-specific benefit-cost analyses to be performed efficiently.

The example presented below illustrates the application of Spreadsheet Tools 1 and 2 for site-specific benefit-cost analysis of lane widening. The example shows a rural two-lane highway with existing 9-ft lanes for which the alternative with the maximum net benefit is to widen the lanes to 11 ft. It should be noted that the HSM Chapter 10 (*2*) crash prediction procedures show that the benefits of lane widening from 11 to 12 ft on rural two-lane highways is relatively small. Therefore, widening narrower lanes to 11 ft will often be the most cost-effective improvement for rural two-lane highways. Widening to 12 ft lanes may only be the most cost-effective improvement for roads with relatively high traffic volumes.

Lane Widening on Rural Two-Lane Highways

Existing Conditions

Section Length	1.000 mi
AADT	2,000 veh/day
Terrain	Level
Pavement Type	Flexible
Lane Width	9.0 ft
Shoulder Width	2 ft
Shoulder Type	Unpaved
Roadside Slope	1V:2H
Centerline Rumble Strip	No
Shoulder Rumble Strip	No
Crash History	No
Number of Curves in Roadway Section	2
Maximum Superelevation Rate	8%
Design Speed	55 mph

Horizontal Curve	Curve Length (mi)	Radius (ft)	Presence of Spiral Transitions	Existing Superelevation Rate (%)
1	0.156	400	No	2.4
2	0.125	600	No	3.8

Benefit-Cost Evaluation Results for Widening to 11-ft lanes from Tool 1

RESULTS	Calculated	User Supplied	Value Used
PV MODIFIED TOTAL COST ($)*	$87,216		$87,216

*total cost minus milling and resurfacing cost for existing traveled way

ANNUAL SAFETY BENEFIT ($)	$17,455	BENEFIT-COST RATIO	2.120
PRESENT VALUE OF SAFETY BENEFIT ($)	$184,917	NET BENEFIT ($)	$97,701

Widening the existing 9-ft lanes to 11 ft produces the highest net benefit for a rural two-lane highway with these roadway characteristics. Thus, if lane widening was being considered for inclusion in a 3R project on this roadway section, the lane width to be widened to should be 11 ft to get the highest return on investment.

Evaluation of a Full Range of Lane Widening Scenarios with Tool 2

Tool 2 can be used to evaluate all lane widening possibilities at one time. The results of the Tool 2 analysis, shown below, indicate that widening to 11-ft lanes provides the largest net benefit.

Improved Lane Width (ft)	Net Benefit ($)	B/C Ratio	Total Benefit ($)	Total Cost ($)
11.0	$97,701	2.120	$184,917	$87,216
11.5	$92,159	1.894	$195,200	$103,041
12.0	$86,617	1.729	$205,482	$118,865
10.5	$62,114	1.870	$133,506	$71,391
10.0	$26,527	1.477	$82,094	$55,567
9.5	$1,305	1.033	$41,047	$39,742

A less desirable, but still acceptable, approach (Option 2) for cost-effective lane widening decisions in 3R projects is to develop agency-specific guidelines for minimum traffic volumes that justify lane widening, analogous to the example shown in Table 37. Minimum traffic volume guidelines analogous to Table 37 can be developed by each highway agency (or in some cases by individual districts or regions within a highway agency) as a basis for lane widening decisions. Section 5.4 illustrates procedures for developing minimum traffic volume guidelines like Table 37.

The example benefit-cost analysis to develop minimum AADT guidelines, whose results presented in Table 37, shows that lane widening to 12 ft is likely to be cost-effective for 3R projects on rural two-lane highways with existing lane widths of 10 ft or less with traffic volumes greater than approximately 3,000 to 4,000 veh/day, even for projects in level terrain that generally cost less to implement than projects in rolling or mountainous terrain. On rural two-lane highways with lower traffic volumes, lane widening would not be cost-effective and, therefore, should not be considered unless a site-specific crash pattern that indicates a need for lane widening is present. Lane widening to 12 ft is likely to be cost-effective for 3R projects on rural two-lane highways with existing lane widths of 11 ft only for traffic volumes of approximately 16,000 veh/day or more, even in level terrain. Higher traffic volumes are needed to justify widening of existing 11-ft lanes because HSM Chapter 10 (*2*) indicates that the differences in crash frequency between rural two-lane highways with 11- and 12-ft lanes are relatively small. The traffic volumes thresholds presented above are merely examples, since the results of benefit-cost analyses can vary from site to site and from agency to agency based on roadway characteristics, crash history, and improvement cost levels. Highway agencies also differ in the crash cost values used in benefit-cost analyses. For this reason, Table 37 is not intended for direct application, but tables analogous to Table 37 can be developed by individual highway agencies, following the procedures in Section 5.4.

6.1.2 Shoulder Widening and Paving

Shoulder widening should be considered for each 3R project on a rural two-lane highway with existing shoulder widths less than 6 ft. Decisions about shoulder widening for 3R projects should be based on benefit-cost analysis, and shoulder widening is a desirable investment only where the analysis indicates that the expected crash reduction benefits from shoulder widening will exceed the improvement costs or a crash analysis finds existing crash patterns that can potentially be reduced by shoulder widening. Where there are no existing crash patterns that can potentially be reduced by shoulder widening and the expected crash reduction benefits from shoulder widening are less than the improvement cost, shoulder widening would be a poor investment and available funds would be better invested at another location where the crash reduction benefits would be larger.

Two benefit-cost analysis approaches are applicable to shoulder widening analysis. The most desirable approach (Option 1) for cost-effective shoulder widening decisions is to conduct a site-specific benefit-cost analysis for each individual 3R project. Site-specific benefit-cost analyses are desirable because even nominally similar sites may differ in roadway characteristics, traffic volumes, crash history, and improvement costs, such that shoulder widening may be cost-effective at one site and not at another. The crash reduction effectiveness of shoulder widening on rural two-lane highways is documented in Section 4.3.1.2. Procedures for site-specific benefit-cost analysis are illustrated in Section 5.2.2. The benefit-cost analysis tool provided with these guidelines enables site-specific benefit-cost analyses to be performed efficiently.

Shoulder Widening on Rural Two-Lane Highways

Benefit-Cost Evaluation Results for Widening to 8-ft Shoulders from Tool 1

Using the same rural two-lane highway section used in the previous lane widening example, Tool 1 can be used to find what width to widen the shoulders to in order to produce the highest net benefit. Widening the unpaved shoulders to 8 ft produces the highest net benefit, shown in the following results.

RESULTS	Calculated	User Supplied	Value Used
PV MODIFIED TOTAL COST ($)*	$101,627		$101,627

*total cost minus milling and resurfacing cost for existing traveled way

ANNUAL SAFETY BENEFIT ($)	$17,983	BENEFIT-COST RATIO	1.875
PRESENT VALUE OF SAFETY BENEFIT ($)	$190,508	NET BENEFIT ($)	$88,882

Evaluation of a Full Range of Shoulder Widening Scenarios with Tool 2

Tool 2 can be employed to analyze all shoulder widening scenarios at one time. The result of the Tool 2 analysis, shown below, indicate that widening to 8-ft shoulders provides the largest net benefit.

Improved Shoulder Width (ft)	Net Benefit ($)	B/C Ratio	Total Benefit ($)	Total Cost ($)
8	$88,882	1.875	$190,508	$101,627
7	$68,943	1.751	$160,746	$91,804
6	$49,004	1.598	$130,984	$81,981
5	$26,899	1.373	$99,056	$72,157
4	$5,130	1.082	$67,465	$62,334
3	-$18,779	0.642	$33,732	$52,511

A less desirable, but still acceptable, approach (Option 2) for cost-effective shoulder widening decisions in 3R projects is to develop agency-specific guidelines for minimum traffic volumes that justify shoulder widening, analogous to the example shown in Table 38. Minimum traffic volume guidelines analogous to Table 38 can be developed by each highway agency (or in some cases by individual districts or regions within a highway agency) as a basis for shoulder widening decisions. Section 5.4 illustrates procedures for developing minimum traffic volume guidelines like Table 38.

Benefit-cost analyses can also be applied to rural two-lane highway sites with unpaved shoulders to consider whether the shoulder should be paved. The most desirable approach is to consider shoulder paving alternatives for each shoulder width alternative evaluated. A less desirable, but still acceptable approach is to determine the optimal shoulder width for the project and then evaluate whether the shoulder should be paved. Many highway agencies have design policies that utilize paved shoulders only for specific roadway types or above specific traffic volume levels. Nothing in these guidelines requires a highway agency to provide paved shoulders on projects where the agency's design policy calls for unpaved shoulders.

6.1.3 Horizontal Curve Improvements

Horizontal curve improvements on rural two-lane highways may be considered 3R projects in some cases. Where the superelevation of an existing curve is less than the design superelevation value in the AASHTO *Green Book* (*4*) by more than 1 percent, HSM Chapter 10 (*2*) indicates that there will be a safety benefit from restoring the superelevation to the *Green Book* value. Spreadsheet Tool 1 can be used to assess the cost-effectiveness of such superelevation improvements. An example of benefit-cost analysis for a superelevation improvement using Tool 1 is presented below.

Superelevation Improvement on Rural Two-Lane Highway

This example considers the same rural two-lane highway segment considered in the land widening example in Section 6.1.1. This example segment contains two horizontal curves. These two curves have existing superelevation rates that are less than superelevation rates recommended in the *Green Book*. Tool 1 is used to determine if improving superelevation rates to *Green Book* recommended rates produces a safety benefit as well as if the benefit outweighs the implementation cost. For both curves, the improved superelevation rate will be 8.0%. The Tool 1 results indicate that the superelevation improvement is cost effective with a benefit-cost ratio exceeding 8 and a net benefit of $32,538.

RESULTS	Calculated	User Supplied	Value Used	
PV MODIFIED TOTAL COST ($)*	$4,590		$4,590	
*total cost minus milling and resurfacing cost for existing traveled way				
ANNUAL SAFETY BENEFIT ($)	$3,505		BENEFIT-COST RATIO	8.088
PRESENT VALUE OF SAFETY BENEFIT ($)	$37,128		NET BENEFIT ($)	$32,538

Realignment of an isolated horizontal curve on a rural two-lane highway can also be considered as part of a 3R project. Typically, such an improvement would involve flattening the radius and, therefore, lengthening the curve. The spreadsheet tools do not address improvements of this type, so their safety benefits would need to be assessed with the HSM Chapter 10 procedures. Realignment of multiple horizontal curves on a roadway section would generally be considered as reconstruction and, therefore, out of the scope of 3R improvements.

6.1.4 Sight Distance Improvements

Stopping sight distance (SSD) is provided along roadways to assist drivers in detecting and responding to situations on the roadway ahead that may require drivers to slow or stop. Sight distance limitations may include crest vertical curves or objects on the inside of horizontal curves. The SSD design criteria used by most states are based on the SSD values in the AASHTO *Green Book* (*4*).

Recent research (*5*) has shown that limited SSD on rural two-lane highways is unlikely to lead to crashes unless the portion of the roadway hidden from the driver's view by the sight distance limitation includes a roadway feature where drivers need to take steering or braking action, such as an intersection, a driveway, or a horizontal curve. Where an area with SSD less than the *Green Book* SSD design criteria is present on a rural two-lane highway, but there are no hidden features such as intersections, driveways, or horizontal curves and no history of crashes related to limited SSD, sight distance improvements are unlikely to have any effect on crash frequency or severity, are, therefore, unlikely to be cost-effective, and need not be considered in 3R projects. By contrast, where a portion of the highway has SSD less than the *Green Book* SSD design criteria, and an intersection, driveway, or horizontal curve is present in the area with limited SSD, or the crash history shows a pattern of crashes potentially related to limited SSD, an SSD improvement is desirable. SSD improvements can include realigning a crest vertical curve or removing or relocating objects on the inside of a horizontal curve. Where the cost of the SSD improvement is substantial, consideration may be given to mitigation measures such as providing wider shoulders and/or advance warning signs.

6.1.5 Bridge Width

Recent research (*5*) has shown that narrow bridges on rural two-lane highways, defined as bridges where the curb-to-curb bridge roadway width is less than the approach roadway width (lanes and shoulders combined) are not typically associated with increases in crash frequency. Crash reductions are not likely to result from bridge widening or replacement for bridges on rural two-lane highways, even narrow bridges. Bridges on two-lane highways should remain in place in 3R projects unless (a) there is either a structural need to strengthen or replace the bridge or (b) there is a documented pattern of crashes at the bridge that can potentially be reduced by widening or replacing the bridge.

6.1.6 Normal Pavement Cross Slope

Pavement cross slope is needed for drainage so that water flows off the pavement during and after precipitation. Each highway agency has their own design criteria for normal pavement cross slope; these criteria are typically selected as suitable for local climate conditions. Where the pavement cross section within a 3R project does not have sufficient cross slope for drainage, the pavement cross slope should be restored to meet the highway agency's applicable design criteria for pavement cross slope. Given the importance of pavement cross slope to drainage, no benefit-cost analysis is needed to justify restoration of normal pavement cross slope in a 3R project on a rural two-lane highway.

6.1.7 Rumble Strip Improvements

Centerline rumble strips are provided between the two directions of travel on rural two-lane highways to provide an audible and tactile warning to drivers when their vehicle leaves its intended travel lane and begins to cross the roadway centerline. Similarly, shoulder rumble strips are provided on a paved shoulder or at the edge of the traveled way on rural two-lane highways to provide an audible and tactile warning to drivers when their vehicle is leaving the roadway and begins to encroach on the shoulder. These warnings alert the driver to take corrective action —steering and, where appropriate, braking—to return to their intended travel lane.

The crash reduction effectiveness of rumble strip installation on rural two-lane highways is documented in Sections 4.3.1.5 and 4.3.1.6. An example benefit-cost analysis (*6*) has shown that installation of centerline or shoulder rumble strips in conjunction with a resurfacing project can become cost-effective on rural two-lane highways at AADTs as low as 400 veh/day. This AADT threshold is merely an example, and agency-specific minimum AADT guidelines can be developed with Spreadsheet Tool 1. However, such agency-specific guidelines are likely to show that installation of centerline or shoulder rumble strips is cost-effective for most rural two-lane highways, other than very low-volume roads.

Benefit-cost analysis examples presented below show that both centerline and shoulder rumble strips can be highly cost-effective on rural two-lane highways, even at a modest traffic volume level of 2,000 veh/day.

Install Centerline Rumble Strip on Rural Two-Lane Highway

This example considers the same rural two-lane highway segment considered in the lane widening example in Section 6.1.1. The economic impact of installing a centerline rumble strip on the rural two-lane highway example segment is analyzed with Tool 1. The benefit-cost ratio is exceptionally high and the net benefit of the treatment installation is $52,438. Due to the low installation cost and high safety benefit, centerline rumble strip installation will almost always be economically justified.

RESULTS	Calculated	User Supplied	Value Used
PV MODIFIED TOTAL COST ($)*	$2,883 ◉	○	$2,883

*total cost minus milling and resurfacing cost for existing traveled way

ANNUAL SAFETY BENEFIT ($)	$5,222	BENEFIT-COST RATIO	19.190
PRESENT VALUE OF SAFETY BENEFIT ($)	$55,321	NET BENEFIT ($)	$52,438

Install Shoulder Rumble Strip on Rural Two-Lane Highway

This example considers the same rural two-lane highway segment considered in the lane widening example in Section 6.1.1. Tool 1 is used to analyze the economic impact of installing shoulder rumble strips on the rural two-lane highway example segment. Similar to the centerline rumble strip result, the benefit-cost ratio is exceptionally high and the net benefit is $67,443.

RESULTS	Calculated	User Supplied	Value Used
PV MODIFIED TOTAL COST ($)*	$4,613		$4,613

*total cost minus milling and resurfacing cost for existing traveled way

ANNUAL SAFETY BENEFIT ($)	$6,802	BENEFIT-COST RATIO	15.622
PRESENT VALUE OF SAFETY BENEFIT ($)	$72,056	NET BENEFIT ($)	$67,443

For any traffic volume level on rural two-lane highways where rumble strip installation would be cost-effective, highway agencies are encouraged to provide centerline or shoulder rumble strips as part of 3R projects, where they are not already present, and to restore existing rumble strips when the pavement and/or shoulder is resurfaced. Rumble strips should be designed and located in accordance with each agency's current practices. Rumble strips are appropriate at most rural locations, except where the noise created by the rumble strips may disturb nearby residents. Rumble strips on paved shoulders need to be located sufficiently close to the traveled way that the effectiveness of the paved shoulder as a travel path for bicyclists is not reduced. Where rumble strips are cost-effective, either centerline or shoulder rumble strips, or both, may be used. Use of both centerline and shoulder rumble strips together is very effective, but may not be desirable on two-lane highways if the distance between the centerline and shoulder rumble strips is less than 12 ft. Limited separation between the centerline and shoulder rumble strips is undesirable because normal variations in lateral positioning of vehicles within a lane may lead drivers to strike one rumble strip or the other with enough frequency to become annoying.

6.1.8 Striping and Delineation Improvements

Nearly every 3R project includes pavement resurfacing, so the cost of restoring pavement markings after resurfacing is automatically part of most 3R projects. These guidelines assume that, as a default, highway agencies will restore the pavement markings with the equivalent of the existing pavement markings. Conventional paint is the least expensive pavement marking material, and typically has a service life of one to two years, depending on traffic volume and climate conditions.

Highway agencies may choose to consider more durable pavement markings with longer life and higher retroreflectivity, as well as an increased implementation cost, as part of some 3R projects. Other delineation improvements may also be considered as part of an overall striping and delineation package. Spreadsheet Tool 1 provides the capability to assess the cost-effectiveness of striping and delineation packages for inclusion in 3R projects. The implementation cost for the striping and delineation package is the full striping and delineation cost minus the cost of the pavement markings that would have been implemented as a default. The crash reduction effectiveness of improved striping and delineation on rural two-lane highways is documented in Section 4.3.1.7.

The following example presents benefit-cost analysis results for adding enhanced striping and delineation on a rural two-lane highway.

Adding Enhanced Striping and Delineation on a Rural Two-Lane Highway

Using the same rural two-lane highway example segment considered for lane widening in Section 6.1.1, Tool 1 is used to examine the economic impact of adding enhanced striping and delineation. The following table presents additional inputs needed about the example roadway for Tool 1 to perform the analysis.

Percent of Roadway Section with Dashed Centerline Striping	20.00%
Percent of Roadway Section with Solid-Dash Centerline Striping	25.00%
Percent of Roadway Section with Double Solid Centerline Striping	55.00%
Total Length of Roadway Section with Delineator Posts (Includes each side separately)	2.000 mi

The net benefit of adding this treatment is $130,410 with a benefit-cost ratio of 2.435, based on the Tool 1 results.

RESULTS	Calculated	User Supplied	Value Used
PV MODIFIED TOTAL COST ($)*	$90,875		$90,875

*total cost minus milling and resurfacing cost for existing traveled way

ANNUAL SAFETY BENEFIT ($)	$20,888	BENEFIT-COST RATIO	2.435
PRESENT VALUE OF SAFETY BENEFIT ($)	$221,285	NET BENEFIT ($)	$130,410

6.1.9 Roadside Slope Flattening

Roadside slope flattening should be considered for each 3R project on a rural two-lane highway with roadside slopes steeper than 1V:4H where sufficient right-of-way for slope flattening is available (or could be acquired) and where slope flattening would not adversely affect adjacent properties, structures, or environmentally sensitive areas, such as wetlands. Decisions about roadside slope flattening for 3R projects should be based on benefit-cost analysis, and roadside slope flattening is a desirable investment only where the analysis indicates that the expected crash reduction benefits from roadside slope flattening will exceed the improvement costs or a crash analysis finds existing crash patterns (e.g., run-off-road crashes) that can potentially be reduced by roadside slope flattening. In many cases, roadside slope flattening will not be cost-effective because of high project implementation costs. Where there are no existing crash patterns that can potentially be reduced by roadside slope flattening and the expected crash reduction benefits from roadside slope flattening are less than the improvement cost, roadside slope flattening would be a poor investment and available funds would be better invested at another location where the crash reduction benefits would be larger.

Roadside slope flattening should be considered only where a benefit-cost analysis with the site-specific benefit-cost analysis tool (Spreadsheet Tool 1) or with the RSAP model (*23*, *24*, *25*) indicates that the present value of the benefits of the slope flattening project would exceed the cost (i.e., the net benefits would exceed zero). The crash reduction effectiveness of roadside slope flattening on rural two-lane highways is documented in Section 4.3.1.8. Procedures for site-specific benefit-cost analysis are illustrated in Section 5.4. The benefit-cost analysis tool provided with these guidelines enables site-specific benefit-cost analyses to be performed efficiently.

There is no option for developing minimum AADT guidelines for roadside slope flattening projects because the costs of such projects can vary widely from site to site, so site-specific cost estimates are needed.

Roadside Slope Flattening on a Rural Two-Lane Highway

Using the same two-lane highway example segment considered for lane widening in Section 6.1.1, Tool 1 can be used to determine if roadside slope flattening is cost effective. By analyzing each possible slope flattening scenario one at a time, it can be determined which improved roadside slope generates the highest net benefit. The results shown below are for flattening the roadside slopes to a 1V:6H slope, which produces the highest net benefit.

RESULTS	Calculated	User Supplied	Value Used
PV MODIFIED TOTAL COST ($)*	$64,064		$64,064

*total cost minus milling and resurfacing cost for existing traveled way

ANNUAL SAFETY BENEFIT ($)	$10,340	BENEFIT-COST RATIO	1.710
PRESENT VALUE OF SAFETY BENEFIT ($)	$109,547	NET BENEFIT ($)	$45,483

Tool 2 can be used to examine all possible slope flattening scenarios at one time. The results of the Tool 2 analysis are shown below.

Improved Slope	Net Benefit ($)	B/C Ratio	Total Benefit ($)	Total Cost ($)
1V:6H	$45,483	1.710	$109,547	$64,064
1V:4H	$12,064	1.282	$54,774	$42,709
1V:3H	-$22,903	0.285	$9,129	$32,032

Where roadside slope flattening is considered, but not implemented, in a 3R project, consideration may also be given to mitigation measures such as removing roadside objects (see Section 6.1.10) or providing traffic barriers (see Section 6.1.11), where such improvements are found to be cost-effective using the RSAP model.

6.1.10 Removal of Roadside Objects

Where roadside objects are present within the clear zone width on a rural two-lane highway, their removal should be considered on the basis of a cost-effectiveness analysis, using the RSAP model (*23*, *24*, *25*). Generally, only objects greater than 4 inches in diameter and not of breakaway design need to be considered. Where roadside objects are present continuously or at regular intervals throughout all or part of the length of a 3R project, removal of those objects is not likely to be cost-effective and a formal RSAP analysis is not needed.

As alternatives to removing roadside objects, consideration may also be given to replacing the object with a similar object of breakaway design, relocating the object behind an existing guardrail or traffic barrier, or installing a new guardrail or traffic barrier. Decisions concerning the cost-effectiveness of new guardrail or other traffic barriers should be made with the RSAP model (see Section 6.1.11)

6.1.11 Installation/Rehabilitation of Guardrail and Other Traffic Barriers

Existing guardrail or other traffic barriers that have reached the end of their useful life or are of obsolete design should generally be rehabilitated or replaced as part of a 3R project. The decision to rehabilitate or replace a guardrail or traffic barrier does not require a formal economic analysis, as long as the highway agency believes that the guardrail or traffic barrier is needed and warranted at its location. If the highway agency has reason to believe that the existing guardrail or traffic barrier may not be warranted, the warrants and length of need for the barrier can be assessed with the AASHTO *Roadside Design Guide* (*30*).

Installation of new guardrail or other traffic barriers may be considered by highway agencies as part of 3R projects on rural two-lane highways. The RSAP model should be used to evaluate the cost-effectiveness of any new guardrail or traffic barrier installations that are considered.

6.1.12 Passing Lanes

Passing Lanes may be added as part of 3R projects on rural two-lane highways to increase passing opportunities. Passing lanes can be added in one or both directions of travel. Where a passing lane is added on an upgrade to allow vehicles to pass trucks or other heavy vehicles slowed by the upgrade, the added lane is known as a climbing lane.

The traffic operational analysis procedures in the *Highway Capacity Manual* (*11*) can be used to assess the effect of added passing or climbing lanes on the traffic operational level of service for a rural two-lane highway. The AASHTO *Green Book* (*4*) presents criteria for where climbing lanes should be considered on rural two-lane highways. Passing and climbing lanes should generally be installed only where a *Highway Capacity Manual* analysis established that there is a traffic operational need for the added lane. For climbing lanes, the traffic operational criteria in the AASHTO *Green Book* should also be met.

In most cases for which an added passing or climbing lane is needed for traffic operational reasons, it will also have sufficient safety benefit to be cost-effective as a safety improvement. This can be verified with Spreadsheet Tool 1.

6.1.13 Intersection Turn Lane Improvements

The crash reduction effectiveness of intersection turn lane improvements on rural two-lane highways is documented in Section 4.3.1.10. Benefit-cost analyses (*7*) have shown that intersection turn-lane improvements, including installation of left- and right-turn lanes, are likely to be cost-effective at any intersection where installation to the turn lane makes traffic operational sense. Highway agencies should, therefore, assess the traffic operational need to intersection turn lanes using established access management policies or traffic operational analysis tools. If the highway agency concludes that installation of the turn lane is justified on a traffic operational basis, there is little doubt that the turn lane will be cost-effective on a safety basis as well.

6.1.14 Other Intersection Improvements

A 3R project may provide an opportunity for implementing other intersection improvements, involving traffic control, signing, delineation, marking, or sight distance. Highway agencies should implement such improvements if a need is identified based on a crash history review.

6.2 Rural Multilane Undivided Highways

6.2.1 Lane Widening

Lane widening should be considered for each 3R project on a rural multilane undivided highway with existing lane widths less than 12 ft. Decisions about lane widening for 3R projects should be based on benefit-cost analysis. Lane widening is a desirable investment only where the analysis indicates that the expected crash reduction benefits from lane widening will exceed the improvement costs or a crash analysis finds existing crash patterns that can potentially be reduced by lane widening. Where there are no existing crash patterns that can potentially be reduced by lane widening and the expected crash reduction benefits from lane widening are less than the improvement cost, lane widening would be a poor investment and available funds would be better invested at another location where the crash reduction benefits would be larger.

Two benefit-cost analysis approaches applicable to lane widening analysis are discussed below. The most desirable approach (Option 1) for cost-effective lane widening decisions is to conduct a site-specific benefit-cost analysis for each individual 3R project. Site-specific benefit-cost analyses are desirable because even nominally similar sites may differ in roadway characteristics, traffic volumes, crash history, and improvement costs, such that lane widening may be cost-effective at one site and not at another. The crash reduction effectiveness of lane widening on rural multilane undivided highways is documented in Section 4.3.2.1. Procedures for site-specific benefit-cost analysis are illustrated in Section 5.2.2. The benefit-cost analysis tool provided with these guidelines enables site-specific benefit-cost analyses to be performed efficiently.

An example of the application of Spreadsheet Tool 1 to a lane widening improvement on a rural two-lane highway has been presented above in Section 6.1.1. Analysis of lane widening for rural multilane undivided highways can be performed in the same manner, with the only difference in input data being the roadway type.

A less desirable, but still acceptable, approach (Option 2) for cost-effective lane widening decisions in 3R projects is to develop agency-specific guidelines for minimum traffic volumes that justify lane widening, analogous to the example shown in Table 37. Minimum traffic volume guidelines analogous to Table 37 can be developed by each highway agency (or in some cases by individual districts or regions within a highway agency) as a basis for lane widening decisions. Section 5.4 illustrates procedures for developing minimum traffic volume guidelines like Table 37.

An example benefit-cost analysis to develop minimum AADT guidelines for rural two-lane highways has been presented in Table 37. The same analysis approach can be applied to lane widening on rural multilane undivided highways.

6.2.2 Shoulder Widening and Paving

Shoulder widening should be considered for each 3R project on a rural multilane undivided highway with existing shoulder widths less than 6 ft. Decisions about shoulder widening for 3R projects should be based on benefit-cost analysis, and shoulder widening is a desirable investment only where the analysis indicates that the expected crash reduction benefits from shoulder widening will exceed the improvement costs or a crash analysis finds existing crash patterns that can potentially be reduced by shoulder widening. Where there are no existing crash patterns that can potentially be reduced by shoulder widening and the expected crash reduction benefits from shoulder widening are less than the improvement cost, shoulder widening would be a poor investment and available funds would be better invested at another location where the crash reduction benefits would be larger.

Two benefit-cost analysis approaches applicable to shoulder widening analysis are discussed below. The most desirable approach (Option 1) for cost-effective shoulder widening decisions is to conduct a site-specific benefit-cost analysis for each individual 3R project. Site-specific benefit-cost analyses are desirable because even nominally similar sites may differ in roadway characteristics, traffic volumes, crash history, and improvement costs, such that shoulder widening may be cost-effective at one site and not at another. The crash reduction effectiveness of shoulder widening on rural multilane undivided highways is documented in Section 4.3.2.2. Procedures for site-specific benefit-cost analysis are illustrated in Section 5.2.2. The benefit-cost analysis tool provided with these guidelines enables site-specific benefit-cost analyses to be performed efficiently.

An example of the application of Spreadsheet Tool 1 to a shoulder widening improvement on a rural two-lane highway has been presented above in Section 6.1.2. Analysis of shoulder widening for rural multilane undivided highways can be performed in the same manner, with the only difference in input data being the roadway type.

A less desirable, but still acceptable, approach (Option 2) for cost-effective shoulder widening decisions in 3R projects is to develop agency-specific guidelines for minimum traffic volumes that justify shoulder widening, analogous to the example shown in Table 38. Minimum traffic volume guidelines analogous to Table 38 can be developed by each highway agency (or in some cases by individual districts or regions within a highway agency) as a basis for shoulder widening decisions. Section 5.4 illustrates procedures for developing minimum traffic volume guidelines like Table 38.

Benefit-cost analyses can also be applied to rural multilane undivided highway sites with unpaved shoulders to consider whether the shoulder should be paved. The most desirable approach is to consider shoulder paving alternatives for each shoulder width alternative evaluated. A less desirable, but still acceptable approach is to determine the optimal shoulder width for the project and then evaluate whether the shoulder should be paved. Many highway agencies have design policies that utilize paved shoulders only for specific roadway types or above specific traffic volume levels. Nothing in these guidelines requires a highway agency to provide paved shoulders on projects where the agency’s design policy calls for unpaved shoulders.

6.2.3 Horizontal Curve Improvements

Horizontal curve improvements on rural multilane undivided highways may be considered 3R projects in some cases. Superelevation variances greater than 1 percent on horizontal curves on rural multilane undivided highways should be restored in 3R projects.

Realignment of an isolated horizontal curve on a rural multilane undivided highway can also be considered as part of a 3R project. Typically, such an improvement would involved flattening the radius and, therefore, lengthening the curve. The spreadsheet tools do not address improvements of this type, so their safety benefits would need to be assessed by other means. The HSM Chapter 11 procedures do not address the effects of horizontal curve radius and length, so some other assessment would need to be made. The HSM Chapter 10 procedures could provide a conservative approach to such an analysis. Realignment of multiple horizontal curves on a roadway section would generally be considered as reconstruction and, therefore, out of the scope of 3R improvements.

6.2.4 Sight Distance Improvements

Stopping sight distance (SSD) is provided along roadways to assist drivers in detecting and responding to situations on the roadway ahead that may require drivers to slow or stop. Sight distance limitations may include crest vertical curves or objects on the inside of horizontal curves. The SSD design criteria used by most states are based on the SSD values in the AASHTO *Green Book* (*4*).

Recent research (*5*) has shown that limited SSD on rural two-lane highways is unlikely to lead to crashes unless the portion of the roadway hidden from the driver's view by the sight distance limitation includes a roadway feature that may require drivers to take steering or braking action, such as an intersection, a driveway, or a horizontal curve. There has been no similar research on rural multilane undivided highways, but the research findings for rural two-lane highways can logically be extended to rural multilane highways as well. Where an area with SSD less than the Green Book SSD design criteria is present on a rural multilane undivided highway, but there are no hidden features such as intersections, driveways, or horizontal curves and no history of crashes related to limited SSD, sight distance improvements are unlikely to be cost-effective and need not be considered in 3R projects. By contrast, where a portion of the highway has SSD less than the Green Book SSD design criteria, and an intersection, driveway, or horizontal curve is present in the area with limited SSD, or the crash history shows a pattern of crashes potentially related to limited SSD, an SSD improvement is desirable. SSD improvements can include realigning a crest vertical curve or removing or relocating objects on the inside of a horizontal curve. Where the cost of the SSD improvement is substantial, consideration may be given to mitigation measures such as providing wider shoulders and/or advance warning signs.

6.2.5 Bridge Width

Recent research (*5*) has shown that narrow bridges on rural two-lane highways, defined as bridges where the curb-to-curb bridge roadway width is less than the approach roadway width (lanes and shoulders combined) are not typically associated with increases in crash frequency. Crash reductions are not likely to result from bridge widening or replacement for bridges on two-lane highways, even narrow bridges. There has been no similar research on rural multilane undivided highways, but the research findings for rural two-lane highways can logically be extended to rural multilane highways as well. Bridges on rural multilane undivided highways should remain in place in 3R projects unless (a) there is either a structural need to strengthen or replace the bridge or (b) there is a documented pattern of crashes at the bridge that can potentially be reduced by widening or replacing the bridge.

6.2.6 Normal Pavement Cross Slope

Pavement cross slope is needed for drainage so that water flows off the pavement during and after precipitation. Each highway agency has their own design criteria for normal pavement cross slope; these criteria are typically selected as suitable for local climate conditions. Where the pavement cross section within a 3R project does not have sufficient cross slope for drainage, the pavement cross slope should be restored to meet the highway agency's applicable design criteria for pavement cross slope. Given the importance of pavement cross slope to drainage, no benefit-cost analysis is needed to justify restoration of normal pavement cross slope in a 3R project on a rural multilane undivided highway.

6.2.7 Rumble Strip Improvements

Centerline rumble strips are provided between the two directions of travel on rural multilane undivided highways to provide an audible and tactile warning to drivers when their vehicle leaves its intended travel lane and begins to cross the roadway centerline. Similarly, shoulder rumble strips are provided on a paved shoulder or at the edge of the traveled way on rural two-lane highways to provide an audible and tactile warning to drivers when their vehicle is leaving the roadway and begins to encroach on the shoulder. These warnings alert the driver to take corrective action—steering and, where appropriate, braking—to return to their intended travel lane.

An example benefit-cost analysis (*5*) has shown that installation of centerline or shoulder rumble strips in conjunction with a resurfacing project can become cost-effective on rural two-lane highways at AADTs as low as 300 veh/day. This AADT threshold is merely an example, and agency-specific minimum AADT guidelines can be developed with Spreadsheet Tool 1. However, there are essentially no rural multilane undivided highways with AADTs as low as 300 veh/day, so any agency-specific guidelines are likely to show that installation of centerline or shoulder rumble strips is cost-effective for all rural multilane undivided highways.

Highway agencies are encouraged to provide centerline or shoulder rumble strips as part of 3R projects, where they are not already present, and to restore existing rumble strips when the pavement and/or shoulder is resurfaced. Rumble strips should be designed and located in accordance with each agency’s current practices. Rumble strips are appropriate at most rural locations, except where the noise created by the rumble strips may disturb nearby residents. Rumble strips on paved shoulders need to be located sufficiently close to the traveled way that the effectiveness of the paved shoulder as a travel path for bicyclists is not reduced. Where rumble strips are cost-effective, either centerline or shoulder rumble strips, or both, may be used. Use of both centerline and shoulder rumble strips together is very effective, and should be considered, consistent with each agency’s current practices.

6.2.8 Striping and Delineation Improvements

Nearly every 3R project includes pavement resurfacing, so the cost of restoring pavement markings after resurfacing is automatically part of most 3R projects. These guidelines assume that, as a default, highway agencies will restore the pavement markings with the equivalent of the existing pavement markings. Conventional paint is the least expensive pavement marking material, and typically has a service life of one to two years, depending on traffic volume and climate conditions.

Highway agencies may choose to consider more durable pavement markings with longer life and higher retroreflectivity, as well as an increased implementation cost, as part of some 3R projects. Other delineation improvements may also be considered as part of an overall striping and delineation package. Spreadsheet Tool 1 provides the capability to assess the cost-effectiveness of striping and delineation packages for inclusion in 3R projects. The implementation cost for the striping and delineation package is the full striping and delineation cost minus the cost of the pavement markings that would have been implemented as a default. The crash reduction effectiveness of improved striping and delineation on rural multilane undivided highways is documented in Section 4.3.2.6.

6.2.9 Roadside Slope Flattening

Roadside slope flattening should be considered for each 3R project on a rural multilane undivided highway with roadside slopes steeper than 1V:4H where sufficient right-of-way for slope flattening is available (or could be acquired) and where slope flattening would not adversely affect adjacent properties, structures, or environmentally sensitive areas, such as wetlands. Decisions about roadside slope flattening for 3R projects should be based on benefit-cost analysis, and roadside slope flattening is a desirable investment only where the analysis indicates that the expected crash reduction benefits from roadside slope flattening will exceed the improvement costs or a crash analysis finds existing crash patterns (e.g., run-off-road crashes) that can potentially be reduced by roadside slope flattening. In many cases, roadside slope flattening will not be cost-effective because of high project implementation costs. Where there are no existing crash patterns that can potentially be reduced by roadside slope flattening and the expected crash reduction benefits from roadside slope flattening are less than the improvement cost, roadside slope flattening would be a poor investment and available funds would be better invested at another location where the crash reduction benefits would be larger.

Roadside slope flattening should be considered only where a benefit-cost analysis with the site-specific benefit-cost analysis tool (Spreadsheet Tool 1) or with the RSAP model (*23, 24, 25*) indicates that the present value of the benefits of the slope flattening project would exceed the cost. The crash reduction effectiveness of roadside slope flattening on rural multilane undivided highways is documented in Section 4.3.1.7. Procedures for site-specific benefit-cost analysis are illustrated in Section 5.2.2. The benefit-cost analysis tool provided with these guidelines enables site-specific benefit-cost analyses to be performed efficiently.

There is no option for developing minimum AADT guidelines for roadside slope flattening projects because the costs of such projects can vary widely from site to site, so site-specific cost estimates are needed.

Where roadside slope flattening is considered, but not implemented, in a 3R project, consideration may also be given to mitigation measures such as removing roadside objects (see Section 6.2.10) or providing traffic barriers (see Section 6.2.11), where such improvements are found to be cost-effective using the RSAP model.

6.2.10 Removal of Roadside Objects

Where roadside objects are present within the clear zone width on a rural multilane undivided highway, their removal should be considered on the basis of a cost-effectiveness analysis, using the RSAP model (*23, 24, 25*). Generally, only objects greater than 4 inches in diameter and not of breakaway design need to be considered. Where roadside objects are present continuously or at regular intervals throughout all or part of the length of a 3R project, removal of those objects is not likely to be cost-effective and a formal RSAP analysis is not needed.

As alternatives to removing roadside objects, consideration may also be given to replacing the object with a similar object of breakaway design, relocating the object behind an existing guardrail or traffic barrier, or installing a new guardrail or traffic barrier. Decisions concerning the cost-effectiveness of new guardrail or other traffic barriers should be made with the RSAP model (see Section 6.2.11)

6.2.11 Installation/Rehabilitation of Guardrail and Other Traffic Barriers

Existing guardrail or other traffic barriers that have reached the end of their useful life or are of obsolete design should generally be rehabilitated or replaced as part of a 3R project. The decision to rehabilitate or replace a guardrail or traffic barrier does not require a formal economic analysis, as long as the highway agency believes that the guardrail or traffic barrier is needed and warranted at its location. If the highway agency has reason to believe that the existing guardrail or traffic barrier may not be warranted, the warrants and length of need for the barrier can be assessed with the AASHTO *Roadside Design Guide* (*30*).

Installation of new guardrail or other traffic barriers may be considered by highway agencies as part of 3R projects on rural multilane undivided highways. The RSAP model should be used to evaluate the cost-effectiveness of any new guardrail or traffic barrier installations that are considered.

6.2.12 Intersection Turn Lane Improvements

The crash reduction effectiveness of intersection turn lane improvements on rural multilane undivided highways is documented in Section 4.3.2.9. Benefit-cost analyses (*5*) have shown that intersection turn-lane improvements, including installation of left- and right-turn lanes, are likely to be cost-effective at any intersection where installation to the turn lane makes traffic operational sense. Highway agencies should, therefore, assess the traffic operational need to intersection turn lanes using established access management policies or traffic operational analysis tools. If the highway agency concludes that installation of the turn lane is justified on a traffic operational basis, there is little doubt that the turn lane will be cost-effective on a safety basis as well.

6.2.13 Other Intersection Improvements

A 3R project may provide an opportunity for implementing other intersection improvements, involving traffic control, signing, delineation, marking, or sight distance. Highway agencies should implement such improvements if a need is identified based on a crash history review.

6.3 Rural Multilane Divided Highways (Nonfreeways)

6.3.1 Lane Widening

Lane widening should be considered for each 3R project on a rural multilane divided nonfreeway with existing lane widths less than 12 ft. Decisions about lane widening for 3R projects should be based on benefit-cost analysis. Lane widening is a desirable investment only where the analysis indicates that the expected crash reduction benefits from lane widening will exceed the improvement costs or a crash analysis finds existing crash patterns that can potentially be reduced by lane widening. Where there are no existing crash patterns that can potentially be reduced by lane widening and the expected crash reduction benefits from lane widening are less than the improvement cost, lane widening would be a poor investment and available funds would be better invested at another location where the crash reduction benefits would be larger.

Two benefit-cost analysis approaches applicable to lane widening analysis are presented below. The most desirable approach (Option 1) for cost-effective lane widening decisions is to conduct a site-specific benefit-cost analysis for each individual 3R project. Site-specific benefit-cost analyses are desirable because even nominally similar sites may differ in roadway characteristics, traffic volumes, crash history, and improvement costs, such that lane widening may be cost-effective at one site and not at another. The crash reduction effectiveness of lane widening on rural multilane divided nonfreeways is documented in Section 4.3.3.1. Procedures for site-specific benefit-cost analysis are illustrated in Section 5.2.2. The benefit-cost analysis tool provided with these guidelines enables site-specific benefit-cost analyses to be performed efficiently.

An example of the application of Spreadsheet Tool 1 to a lane widening improvement on a rural two-lane highway has been presented above in Section 6.1.1. Analysis of lane widening for rural multilane divided nonfreeways can be performed in the same manner, with the only differences in input data being the roadway type and the addition of a value for the existing median width.

A less desirable, but still acceptable, approach (Option 2) for cost-effective lane widening decisions in 3R projects is to develop agency-specific guidelines for minimum traffic volumes that justify lane widening, analogous to the example shown in Table 37. Minimum traffic volume guidelines analogous to Table 37 can be developed by each highway agency (or in some cases by individual districts or regions within a highway agency) as a basis for lane widening decisions. Section 5.4 illustrates procedures for developing minimum traffic volume guidelines like Table 37.

An example benefit-cost analysis to develop minimum AADT guidelines for rural two-lane highways has been presented in Table 37. The same analysis approach can be applied to lane widening on rural multilane divided highways.

6.3.2 Shoulder Widening and Paving

Shoulder widening should be considered for each 3R project on a rural multilane divided nonfreeway with existing shoulder widths less than 8 ft. Decisions about shoulder widening for 3R projects should be based on benefit-cost analysis, and shoulder widening is a desirable investment only where the analysis indicates that the expected crash reduction benefits from shoulder widening will exceed the improvement costs or a crash analysis finds existing crash patterns that can potentially be reduced by shoulder widening. Where there are no existing crash patterns that can potentially be reduced by shoulder widening and the expected crash reduction benefits from shoulder widening are less than the improvement cost, shoulder widening would be a poor investment and available funds would be better invested at another location where the crash reduction benefits would be larger.

Two benefit-cost analysis approaches applicable to shoulder widening analysis are presented below. The most desirable approach (Option 1) for cost-effective shoulder widening decisions is to conduct a site-specific benefit-cost analysis for each individual 3R project. Site-specific benefit-cost analyses are desirable because even nominally similar sites may differ in roadway characteristics, traffic volumes, crash history, and improvement costs, such that shoulder widening may be cost-effective at one site and not at another. The crash reduction effectiveness of shoulder widening on rural multilane divided nonfreeways is documented in Section 4.3.3.2. Procedures for site-specific benefit-cost analysis are illustrated in Section 5.2.2. The benefit-cost analysis tool provided with these guidelines enables site-specific benefit-cost analyses to be performed efficiently.

An example of the application of Spreadsheet Tool 1 to a shoulder widening improvement on a rural two-lane highway has been presented above in Section 6.1.2. Analysis of shoulder widening for rural multilane divided nonfreeways can be performed in the same manner, with the only difference in input data being the roadway type.

A less desirable, but still acceptable, approach (Option 2) for cost-effective shoulder widening decisions in 3R projects is to develop agency-specific guidelines for minimum traffic volumes that justify shoulder widening, analogous to the example shown in Table 38. Minimum traffic volume guidelines analogous to Table 38 can be developed by each highway agency (or in some cases by individual districts or regions within a highway agency) as a basis for shoulder widening decisions. Section 5.4 illustrates procedures for developing minimum traffic volume guidelines like Table 38.

Benefit-cost analyses can also be applied to rural multilane divided nonfreeway sites with unpaved shoulders to consider whether the shoulder should be paved. The most desirable approach is to consider shoulder paving alternatives for each shoulder width alternative evaluated. A less desirable, but still acceptable approach is to determine the optimal shoulder width for the project and then evaluate whether the shoulder should be paved. Many highway agencies have design policies that utilize paved shoulders only for specific roadway types or above specific traffic volume levels. Nothing in these guidelines requires a highway agency to provide paved shoulders on projects where the agency's design policy calls for unpaved shoulders.

6.3.3 Horizontal Curve Improvements

Realignment of horizontal curves on rural multilane divided highways is considered reconstruction and is, therefore, outside the scope of a 3R project. Superelevation variances greater than 1 percent on horizontal curves on rural multilane divided highways should be restored in 3R projects.

6.3.4 Sight Distance Improvements

Stopping sight distance (SSD) is provided along roadways to assist drivers in detecting and responding to situations on the roadway ahead that may require drivers to slow or stop. Sight distance limitations may include crest vertical curves or objects on the inside of horizontal curves. The SSD design criteria used by most states are based on the SSD values in the AASHTO *Green Book* (*4*).

Recent research (*5*) has shown that limited SSD on rural two-lane highways is unlikely to lead to crashes unless the portion of the roadway hidden from the driver's view by the sight distance limitation includes a roadway feature that may require drivers to take steering or braking action, such as an intersection, a driveway, or a horizontal curve. There has been no similar research on rural multilane divided nonfreeways, but the research findings for rural two-lane highways can logically be extended to rural multilane highways as well. Where an area with SSD less than the *Green Book* SSD design criteria is present on a rural multilane divided nonfreeway, but there are no hidden features such as intersections, driveways, ramp terminals, or horizontal curves and no history of crashes related to limited SSD, sight distance improvements are unlikely to be cost-effective and need not be considered in 3R projects. By contrast, where a portion of the highway has SSD less than the *Green Book* SSD design criteria, and an intersection, driveway, or horizontal curve is present in the area with limited SSD, or the crash history shows a pattern of crashes potentially related to limited SSD, an SSD improvement is desirable. SSD improvements can include realigning a crest vertical curve or removing or relocating objects on the inside of a horizontal curve. Where the cost of the SSD improvement is substantial, consideration may be given to mitigation measures such as providing wider shoulders and/or advance warning signs.

6.3.5 Bridge Width

Recent research (*5*) has shown that narrow bridges on rural two-lane highways, defined as bridges where the curb-to-curb bridge roadway width is less than the approach roadway width (lanes and shoulders combined) are not typically associated with increases in crash frequency. Crash reductions are not likely to result from bridge widening or replacement for bridges on two-lane highways, even narrow bridges. There has been no similar research on rural multilane divided nonfreeways, but the research findings for rural two-lane highways can logically be extended to rural multilane highways as well. Bridges on rural multilane divided nonfreeways should remain in place in 3R projects unless (a) there is either a structural need to strengthen or replace the bridge or (b) there is a documented pattern of crashes at the bridge that can potentially be reduced by widening or replacing the bridge.

6.3.6 Normal Pavement Cross Slope

Pavement cross slope is needed for drainage so that water flows off the pavement during and after precipitation. Each highway agency has their own design criteria for normal pavement cross slope; these criteria are typically selected as suitable for local climate conditions. Where the pavement cross section within a 3R project does have sufficient cross slope for drainage, the pavement cross slope should be restored to meet the highway agency's applicable design criteria for pavement cross slope. Given the importance of pavement cross slope to drainage, no benefit-cost analysis is needed to justify restoration of normal pavement cross slope in a 3R project on a rural multilane divided nonfreeway.

6.3.7 Rumble Strip Improvements

Shoulder rumble strips are provided on a paved shoulder or at the edge of the traveled way on rural multilane divided nonfreeways to provide an audible and tactile warning to drivers when their vehicle is leaving the roadway and begins to encroach on the shoulder. These warnings alert the driver to take corrective action—steering and, where appropriate, braking—to return to their intended travel lane. Shoulder rumble strips are typically used on both the right (outside) and left (inside) shoulders of rural multilane divided nonfreeways.

An example benefit-cost analysis (*7*) has shown that installation of shoulder rumble strips in conjunction with a resurfacing project can become cost-effective on rural multilane divided nonfreeways at AADTs as low as 400 veh/day. This AADT threshold is merely an example, and agency-specific minimum AADT guidelines can be developed with Spreadsheet Tool 1. However, there are essentially no rural multilane divided nonfreeways with AADTs as low as 400 veh/day, so any agency-specific guidelines are likely to show that installation of shoulder rumble strips is cost-effective for all rural multilane divided nonfreeways.

Highway agencies are encouraged to provide shoulder rumble strips as part of 3R projects, where they are not already present, and to restore existing rumble strips when the pavement and/or shoulder is resurfaced. Rumble strips should be designed and located in accordance with each agency's current practices. Rumble strips are appropriate at most rural locations, except where the noise created by the rumble strips may disturb nearby residents. Rumble strips on paved shoulders need to be located sufficiently close to the traveled way that the effectiveness of the paved shoulder as a travel path for bicyclists is not reduced.

6.3.8 Striping and Delineation Improvements

Nearly every 3R project includes pavement resurfacing, so the cost of restoring pavement markings after resurfacing is automatically part of most 3R projects. These guidelines assume that, as a default, highway agencies will restore the pavement markings with the equivalent of the existing pavement markings. Conventional paint is the least expensive pavement marking material, and typically has a service life of one to two years, depending on traffic volume and climate conditions.

Highway agencies may choose to consider more durable pavement markings with longer life and higher retroreflectivity, as well as an increased implementation cost, as part of some 3R projects. Other delineation improvements may also be considered as part of an overall striping and delineation package. Spreadsheet Tool 1 provides the capability to assess the cost-effectiveness of striping and delineation packages for inclusion in 3R projects. The implementation cost for the striping and delineation package is the full striping and delineation cost minus the cost of the pavement markings that would have been implemented as a default. The crash reduction effectiveness of improved striping and delineation on rural multilane nonfreeways is documented in Section 4.3.3.6.

6.3.9 Roadside Slope Flattening

Roadside slope flattening should be considered for each 3R project on a rural multilane divided nonfreeway with roadside slopes steeper than 1V:4H where sufficient right-of-way for slope flattening is available (or could be acquired) and where slope flattening would not adversely affect adjacent properties, structures, or environmentally sensitive areas, such as wetlands. Decisions about roadside slope flattening for 3R projects should be based on benefit-cost analysis, and roadside slope flattening is a desirable investment only where the analysis indicates that the expected crash reduction benefits from roadside slope flattening will exceed the improvement costs or a crash analysis finds existing crash patterns (e.g., run-off-road crashes) that can potentially be reduced by roadside slope flattening. In many cases, roadside slope flattening will not be cost-effective because of high project implementation costs. Where there are no existing crash patterns that can potentially be reduced by roadside slope flattening and the expected crash reduction benefits from roadside slope flattening are less than the improvement cost, roadside slope flattening would be a poor investment and available funds would be better invested at another location where the crash reduction benefits would be larger.

Roadside slope flattening should be considered only where a benefit-cost analysis with the site-specific benefit-cost analysis tool (Spreadsheet Tool 1) or with the RSAP model (*23*, *24*, *25*) indicates that the present value of the benefits of the slope flattening project would exceed the cost. The crash reduction effectiveness of roadside slope flattening on rural multilane divided nonfreeways is documented in Section 4.3.2.7 and 4.3.3.7. Procedures for site-specific benefit-cost analysis are illustrated in Section 5.4. The benefit-cost analysis tool provided with these guidelines enables site-specific benefit-cost analyses to be performed efficiently.

There is no option for developing minimum AADT guidelines for roadside slope flattening projects because the costs of such projects can vary widely from site to site, so site-specific cost estimates are needed.

Where roadside slope flattening is considered, but not implemented, in a 3R project, consideration may also be given to mitigation measures such as removing roadside objects (see Section 6.3.10) or providing traffic barriers (see Section 6.3.11), where such improvements are found to be cost-effective using the RSAP model.

6.3.10 Removal of Roadside Objects

Where roadside objects are present within the clear zone width on a rural multilane divided nonfreeway, their removal should be considered on the basis of a cost-effectiveness analysis, using the RSAP model (*23, 24, 25*). Generally, only objects greater than 4 inches in diameter and not of breakaway design need to be considered. Where roadside objects are present continuously or at regular intervals throughout all or part of the length of a 3R project, removal of those objects is not likely to be cost-effective and a formal RSAP analysis is not needed.

As alternatives to removing roadside objects, consideration may also be given to replacing the object with a similar object of breakaway design, relocating the object behind an existing guardrail or traffic barrier, or installing a new guardrail or traffic barrier. Decisions concerning the cost-effectiveness of new guardrail or other traffic barriers should be made with the RSAP model (see Section 6.3.11)

6.3.11 Installation/Rehabilitation of Guardrail and Other Traffic Barriers

Existing guardrail or other traffic barriers that have reached the end of their useful life or are of obsolete design should generally be rehabilitated or replaced as part of a 3R project. The decision to rehabilitate or replace a guardrail or traffic barrier does not require a formal economic analysis, as long as the highway agency believes that the guardrail or traffic barrier is needed and warranted at its location. If the highway agency has reason to believe that the existing guardrail or traffic barrier may not be warranted, the warrants and length of need for the barrier can be assessed with the AASHTO *Roadside Design Guide* (*30*).

Installation of new guardrail or other traffic barriers may be considered by highway agencies as part of 3R projects on rural multilane divided nonfreeways. The RSAP model should be used to evaluate the cost-effectiveness of any new guardrail or traffic barrier installations that are considered.

6.3.12 Intersection Turn Lane Improvements

The crash reduction effectiveness of intersection turn lane improvements on rural multilane divided nonfreeways is documented in Section 4.3.3.9. Benefit-cost analyses (*5*) have shown that intersection turn-lane improvements, including installation of left- and right-turn lanes, are likely to be cost-effective at any intersection where installation of the turn lane makes traffic operational sense. Highway agencies should, therefore, assess the traffic operational need to intersection turn lanes using established access management policies or traffic operational analysis tools. If the highway agency concludes that installation of the turn lane is justified on a traffic operational basis, there is little doubt that the turn lane will be cost-effective on a safety basis as well.

6.3.13 Other Intersection Improvements

A 3R project may provide an opportunity for implementing other intersection improvements, involving traffic control, signing, delineation, marking, or sight distance. Highway agencies should implement such improvements if a need is identified based on a crash history review.

6.4 Urban and Suburban Arterials

6.4.1 Lane Widening

Benefit-cost analyses cannot be applied to lane widening on urban and suburban arterials at this time, because there are no documented CMFs for lane widening in HSM Chapter 12. However, the AASHTO *Green Book* (*4*) provides broad flexibility for use of 10-, 11-, and 12-ft lanes on urban and suburban arterials. Recent research (see Section 4.3.4.1) also suggests that, in most cases, there are no substantial differences in safety performance between 10-, 11-, and 12-ft lanes on urban and suburban arterials. In addition, narrower through travel lanes can have substantive advantages on urban and suburban arterials by providing space in the cross section for turn lanes, median treatments, bicycle lanes, and shorter pedestrian crossings, all of which can themselves reduce crashes. Therefore, lane widening is not a desirable investment in 3R projects on urban and suburban arterials with existing lane widths of 10 ft or more unless there is a documented crash pattern that can potentially be mitigated with wider lanes or there is a documented traffic operational need for wider lanes.

6.4.2 Shoulder Widening

Benefit-cost analyses cannot be applied to shoulder widening on urban and suburban arterials at this time, because there are no documented CMFs for shoulder widening in HSM Chapter 12. However, the AASHTO *Green Book* (*4*) provides broad flexibility for use of shoulders with a range of widths on urban and suburban arterials including, in appropriate speed ranges, the use of curb-and-gutter sections with no shoulder. For many low- and intermediate-speed roads, curb-and-gutter sections without shoulders are appropriate because they enhance drainage. Therefore, shoulder widening is not a desirable investment in 3R projects on urban and suburban arterials unless there is a documented crash pattern that can potentially be mitigated with wider shoulders or there is a documented traffic operational need for wider shoulders.

6.4.3 Horizontal Curve Improvements

Realignment of horizontal curves on urban and suburban arterials is considered reconstruction and is, therefore, outside the scope of a 3R project.

6.4.4 Striping and Delineation Improvements

Nearly every 3R project includes pavement resurfacing, so the cost of restoring pavement markings after resurfacing is automatically part of most 3R projects. These guidelines assume that, as a default, highway agencies will restore the pavement markings with the equivalent of the existing pavement markings. Conventional paint is the least expensive pavement marking material, and typically has a service life of one to two years, depending on traffic volume and climate conditions.

Highway agencies may choose to consider more durable pavement markings with longer life and higher retroreflectivity, as well as an increased implementation cost, as part of some 3R projects. Other delineation improvements may also be considered as part of an overall striping and delineation package. There are no documented crash reduction effectiveness measures for striping and delineation packages on urban and suburban arterials, so highway agencies should exercise judgement based on their experience with striping and delineation packages on other roadway types to assess when striping and delineation improvements are appropriate on urban and suburban arterials.

Spreadsheet Tool 1 provides the capability to assess the cost-effectiveness of striping and delineation packages for inclusion in 3R projects. The implementation cost for the striping and delineation package is the full striping and delineation cost minus the cost of the pavement markings that would have been implemented as a default. The crash reduction effectiveness of improved striping and delineation on rural two-lane highways is documented in Section 4.3.1.7.

6.4.5 Rumble Strip Improvements

Centerline and shoulder rumble strips are effective in reducing crashes on urban and suburban arterials, although there are no documented crash reduction effectiveness estimates for rumble strips in HSM Chapter 12. The literature includes the crash reduction effectiveness for one application on urban and suburban arterials—centerline rumble strips on urban two-lane arterials (see Section 4.3.4.5). Nevertheless, it is expected that most urban and suburban arterials have traffic volumes sufficiently high to make rumble strips cost-effective for use on urban and suburban arterials. Noise that can potentially disturb nearby residents is an elevated concern in urban and suburban areas. Highway agencies should exercise judgment based on current agency policies about locations where installation of centerline and shoulder rumble strips is or is not desirable on urban and suburban arterials.

6.4.6 Removal of Roadside Objects

Where roadside objects are present within the clear zone width on an urban or suburban arterial, their removal may be considered on the basis of a cost-effectiveness analysis, using the RSAP model (*23, 24, 25*). Generally, only objects greater than 4 inches in diameter and not of breakaway design are considered. Where roadside objects are present continuously or at regular intervals throughout all or part of the length of a 3R project, as is the case on many urban and suburban arterials, removal of those objects is not likely to be cost-effective and a formal RSAP analysis is not needed.

As alternatives to removing roadside objects, consideration may also be given to replacing the object with a similar object of breakaway design, relocating the object behind an existing guardrail or traffic barrier, or installing a new guardrail or traffic barrier. Decisions concerning the cost-effectiveness of new guardrail or other traffic barriers should be made with the RSAP model (see Section 6.4.7).

6.4.7 Installation/Rehabilitation of Guardrail and Other Traffic Barriers

Existing guardrail or other traffic barriers that have reached the end of their useful life or are of obsolete design should generally be rehabilitated or replaced as part of a 3R project. The decision to rehabilitate or replace a guardrail or traffic barrier does not require a formal economic analysis, as long as the highway agency believes that the guardrail or traffic barrier is needed and warranted at its location. If the highway agency has reason to believe that the existing guardrail or traffic barrier may not be warranted, the warrants and length of need for the barrier can be assessed with the AASHTO *Roadside Design Guide* (*30*).

Installation of new guardrail or other traffic barriers may be considered by highway agencies as part of 3R projects on urban and suburban arterials. The RSAP model should be used to evaluate the cost-effectiveness of any new guardrail or traffic barrier installations that are considered.

6.4.8 Intersection Turn Lane Improvements

Benefit-cost analyses (*5*) have shown that intersection turn-lane improvements, including installation of left- and right-turn lanes, are likely to be cost-effective at any intersection where installation of the turn lane makes traffic operational sense. Highway agencies should, therefore, assess the traffic operational need for intersection turn lanes using established access management policies or traffic operational analysis tools. If the highway agency concludes that installation of the turn lane is justified on a traffic operational basis, there is little doubt that the turn lane will be cost-effective on a safety basis as well.

6.4.9 Other Intersection Improvements

A 3R project may provide an opportunity for implementing other intersection improvements, involving traffic control, signing, delineation, marking, or sight distance. Highway agencies should implement such improvements if a need is identified based on a crash history review.

6.5 Rural and Urban Freeways

6.5.1 Lane Widening

Most urban and rural freeways have existing 12-ft lanes, except at locations where a highway agency has made a previous decision to use narrower lanes to provide space for additional through lanes. At locations that were built with lanes less than 12 ft in width, Spreadsheet Tool 1 can be used for benefit-cost evaluation of lane widening alternatives. In such cases, widening to 12-ft lanes is likely to be cost-effective over the typical range of freeway volumes. Site-specific analyses with Tool 1 are recommended, however, to justify such projects.

6.5.2 Outside Shoulder Widening

Existing freeways may have a range of outside shoulder widths. Most existing freeways have outside shoulder widths of at least 10 ft, although a few sites may have narrower shoulders. At locations that were built with outside shoulders less than 12 ft in width, Spreadsheet Tool 1 can be used for benefit-cost evaluation of shoulder widening alternatives. In such cases, widening to 12-ft shoulders is likely to be cost-effective over the typical range of freeway volumes. Site-specific analyses with Tool 1 are recommended, however, to justify such projects.

6.5.3 Inside Shoulder Widening

Existing freeways may have a range of inside (median) shoulder widths. Most existing freeways have inside shoulder widths of at least 4 ft, although a few sites may have narrower shoulders. At locations that were built with inside shoulders less than 12 ft in width, Spreadsheet Tool 1 can be used for benefit-cost evaluation of shoulder widening alternatives. In such cases, widening to 12-ft shoulders is likely to be cost-effective over the typical range of freeway volumes. Site-specific analyses with Tool 1 are recommended, however, to justify such projects.

Many highway agencies prefer to limit inside shoulder widths to a maximum of 4 ft to encourage motorists to stop on the outside shoulder, rather than the inside shoulder, when the need to stop arises. Nothing in these guidelines suggests that highway agencies should change such policies if highway agency experience indicates that vehicles stopping on the inside shoulder are undesirable.

6.5.4 Install Median Barriers

While Spreadsheet Tools 1 and 2 can be used to assess the cost-effectiveness of median barrier installation, these spreadsheet tools for 3R projects based on HSM Chapter 18 (*3*) are not well suited to assessing the shifts in crash severity distributions that may result from median-barrier installation. Research generally indicates that median-barrier installation reduces the frequency of fatal-and-serious injury crashes, but may increase the frequency of less severe crashes. In general, the AASHTO *Roadside Design Guide* (*30*) is better suited to assessing the need for median barriers than the HSM Chapter 18 predictive models. Therefore, the *Roadside Design Guide* is preferred to Spreadsheet Tools 1 and 2 for such analyses.

6.5.5 Install or Restore Guardrail or Other Barrier Types on the Roadside Outside the Traveled Way

While Spreadsheet Tools 1 and 2 can be used to assess the cost-effectiveness of guardrail or other roadside barrier installation, these spreadsheet tools for 3R projects based on HSM Chapter 18 (*3*) are not well suited to assessing the shifts in crash severity distributions that may result from guardrail and other roadside barrier installation. Research generally indicates that barrier installation reduces fatal-and-serious injury crashes, but may increase less severe crashes. In general, the AASHTO *Roadside Design Guide* (*30*) is better suited to assessing the need for guardrail or other roadside barriers than the HSM Chapter 18 predictive models. Therefore, the *Roadside Design Guide* is preferred to Spreadsheet Tools 1 and 2 for such analyses.

6.5.6 Shoulder Rumble Strips

Spreadsheet Tools 1 and 2 are well suited to estimating the anticipated cost-effectiveness for installation of centerline and rumble strips. Calculations with these spreadsheet tools indicate that shoulder rumble strips on either or both sides of the roadway are generally cost-effective on rural and urban freeways over the full range of traffic volume levels typically present on those freeways.

6.5.7 Horizontal Curve Improvements

Where the superelevation of an existing curve is less than the design superelevation value in the AASHTO *Green Book* (*4*) by more than 1 percent, restoration of superelevation to the *Green Book* value should be considered as part of any 3R project conducted. There is no formal benefit-cost tool for superelevation improvement in this situation, so decisions should be based on engineering judgment.

Realignment of one or more horizontal curves on a freeway is considered reconstruction and is outside the scope of 3R work.

6.5.8 Sight Distance Improvements

As on rural two-lane highways, stopping sight distance improvements on freeways are only likely to be cost-effective where the sight distance limitation hides key roadway features from the driver's view. On freeways, the roadway features whose presence may indicate the need for a sight distance improvement or mitigation measures include horizontal curves, ramp terminals, and locations where standing queues are frequently present (e.g., on a daily basis). Where such features are present in an area with limited sight distance, alignment improvements to provide more sight distance should be considered. However, projects to realign freeways are generally considered reconstruction rather than 3R work.

6.5.9 Normal Pavement Cross Slope

Pavement cross slope is needed for drainage so that water flows off the pavement during and after precipitation. Each highway agency has their own design criteria for normal pavement cross slope; these criteria are typically selected as suitable for local climate conditions. Where the pavement cross section within a 3R project does not have sufficient cross slope for drainage, the pavement cross slope should be restored to meet the highway agency's applicable design criteria for pavement cross slope. Given the importance of pavement cross slope to drainage, no benefit-cost analysis is needed to justify restoration of normal pavement cross slope in a 3R project on a freeway.

Chapter 7. Summary of 3R Design Guidelines

This chapter presents a summary of the design guidelines presented in this document.

1. The guidance presented in this document is applicable only to 3R projects; i.e., projects whose scope includes only resurfacing, restoration, or rehabilitation. The guidelines are not applicable to new construction or reconstruction projects. Therefore, 3R projects should not involve a substantial amount of construction on new alignment, removal of the entire pavement structure down to the subgrade, realignment of a substantial portion of the project, or a change in the basic roadway cross section; projects that involve these changes would more properly be classified as new construction or reconstruction. If a limited or isolated portion of a project involves new construction or reconstruction, the remainder of the project can be designed as 3R work. For freeway projects, any change in the existing roadway alignment should be considered as reconstruction.
2. The guidance presented in this document is applicable to projects that fall within the scope of 3R work, as defined above in Guideline 1, regardless of the funding source for the project. These guidelines are intended for application to any project involving 3R work, not just projects funded from the Federal 3R program or the 3R program of any highway agency.
3. The primary objective of most 3R projects is to preserve and extend the life of the pavement by resurfacing. Thus, 3R projects are normally initiated because the need for pavement resurfacing has been identified by a pavement management system or by other means. However, the guidelines presented in this document may be applied to any project that falls within the scope of 3R work (i.e., does not involve new construction or reconstruction) regardless of the means by which the need for the project was identified.
4. While the primary objective of most 3R projects is to preserve and extend the life of the pavement, 3R projects may also provide an opportunity to make additional design improvements that may reduce crash frequency or severity or may improve traffic operations. As part of the design process for 3R projects, an assessment should be made as to whether such design improvements should be incorporated in the 3R project.
5. Design guidance for 3R projects based on dimensional design criteria, such as the 3R design criteria presented in TRB Special Report 214 (*1*) are no longer recommended. Research has shown that application of any set of fixed dimensional design criteria for 3R projects is likely to produce smaller crash reduction benefits than the performance-based approach recommended in Guideline 6 (*7*).
6. Design improvements should be incorporated in 3R projects when any of the following three criteria are met:
    a. An analysis of the crash history of the existing road identifies one or more crash patterns that are potentially correctable by a specific design improvement,
    b. An analysis of the traffic operational level of service (LOS) indicates that the LOS is currently lower than the highway agency's target LOS for the facility or will become

lower than the target LOS within the service life of the planned pavement resurfacing (typically 7 to 12 years), or

c. A design improvement would be expected to reduce sufficient crashes over its service life to be cost-effective; i.e., the anticipated crash reduction benefits over the service life of the project should exceed the improvement implementation cost.

Procedures for applying the types of analyses identified in Guidelines 6a, 6b, and 6c are presented in Chapters 3, 4, and 5 of this document.

7. A crash history analysis or a traffic operational analysis (as described in Guidelines 6a and 6b, respectively), by itself, provides sufficient justification for implementing an appropriate design improvement that addresses the identified need and for which the highway agency has sufficient funding available. The assessment of the appropriateness and affordability of the improvement should be made by the highway agency.

8. If neither the crash history analysis nor the traffic operations analysis identifies a need for a design improvement, implementation of an improvement may still be appropriate if an assessment of the anticipated crash reduction benefits and costs of the design or traffic control improvements indicate that the improvements would be cost-effective (see Guideline 6c). The benefits and costs considered in such an analysis are those above and beyond the anticipated benefits and costs of the pavement resurfacing, which is already planned and which will likely be accomplished whether or not additional improvements are made. Design or traffic control improvements in addition to pavement resurfacing should be considered where their anticipated benefits exceed their anticipated costs. Spreadsheet Tools 1 and 2 presented in Chapter 5 of this document can be used to assess the anticipated benefits and costs, and the cost-effectiveness, of specific design improvements. The benefits of design improvements are assessed in the spreadsheet tools based on the crash prediction methods from Part C of the *Highway Safety Manual* (*2*,*3*). The assessment of the appropriateness and the affordability of the improvement should be made by the highway agency.

9. The spreadsheet tools discussed in Guideline 8 can be used to conduct three types of benefit-cost analyses:

   - benefit-cost analysis for a single design alternative at a single site
   - benefit-cost analysis to choose among several design alternatives for a single site
   - benefit-cost analyses to develop agency-specific minimum AADT guidelines for application in design decisions

   The first two types of benefit-cost analyses listed above are preferred. The third type of benefit-cost analysis is less desirable than the first two approaches, but should provide acceptable results. The three analysis approaches are discussed in Chapter 5 of this document.

10. A few design improvements, such as normal cross slope restoration, are recommended in 3R projects where a need is identified, even where formal tools to assess the cost-effectiveness of such improvements do not exist. The design guidelines discussion in Chapter 6 of this document identifies situations in which benefit-cost analyses are feasible and are recommended to assess the need for specific design improvements and

situations where specific restoration or rehabilitation work may be appropriate even where benefit-cost analyses are not currently feasible.

11. Where none of the three criteria in Guideline 6 are met and no design improvements of the type discussed in Guideline 10 are needed, 3R projects should generally be limited in scope to pavement resurfacing. It makes little sense to invest scarce resources in design improvements as part of a 3R project where the existing roadway is performing well and where the potential design improvement would not be cost-effective. Making improvements that are not needed and/or not cost-effective will likely provide only small benefits and the costs may be substantial. The same funds, invested elsewhere where the need for improvement is documented and/or the cost-effectiveness of the improvement is demonstrated, would be expected to provide greater benefits, including more lives saved, more injuries prevented, and more crashes eliminated. Since available funds for 3R projects are limited, Guideline 11 encourages highway agencies to take a systemwide perspective in planning 3R projects, investing available funds where they will provide the greatest crash reduction and avoiding investments that will provide little crash reduction. With this approach—focusing design improvements on the projects with the best opportunities to reduce crashes and implementing only resurfacing on projects without accompanying design improvements where opportunities to reduce crashes are more limited—the total crash reduction expected from each year's 3R projects can be increased.

Chapter 8.
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Appendix A.
Users Guide for Spreadsheet Tool 1

Spreadsheet Tool 1 is a spreadsheet-based benefit-cost analysis tool that can be used to assess the cost-effectiveness of specific improvement alternatives for implementation in conjunction with a 3R project. The tool helps highway agencies in making the decision as to whether the 3R project should consist of pavement resurfacing only or should also include geometric design improvements. Tool 1 is used to assess one improvement alternative (or combination of alternatives) at a time. Tool 2, for which a users guide is presented in Appendix B, can assess multiple alternatives (and combinations of alternatives) in a single analysis.

Tool 1 can be applied as part of the planning process for 3R projects. If a specific project site has no observed crash patterns or no traffic operational needs that would justify a design improvement, then geometric design improvements are recommended for implementation as part of a 3R project only if it is anticipated that such improvements would be cost-effective. Tool 1 provides a capability to assess any particular improvement (or combination of alternatives) to determine if it is anticipated to be cost effective. Tool 1 addresses candidate 3R projects on rural two-lane highways, rural four-lane undivided and divided highways (nonfreeways), and rural and urban freeways. The tool does not address 3R projects on urban and suburban arterials (nonfreeways).

The input data to Tool 1 include a description of the existing roadway conditions and selection of the improvement(s) to be assessed. The tool considers a single set of AADT, terrain, and cross-section geometrics for the roadway between intersections within the candidate project being assessed. Variations in cross-section geometrics at intersections or on intersection approaches do not need to be considered in using the tool. Where there are minor variations in AADT on the project or in cross-section geometrics on the roadway between intersections within the project, use the average AADT and the most common cross-section geometrics as input to the tool. Thus, the tool can be applied even where the cross section throughout the project is not entirely homogeneous. Where there are major changes in cross-section geometrics on the roadway between intersections (e.g., half the project has 6-ft paved shoulders and half has 2-ft unpaved shoulders), the project can be broken into separate sections and each section analyzed separately. Breaking the project into separate sections for analysis is only appropriate where the differences in cross-section geometrics are substantial.

Tool 1 includes logic to estimate the implementation cost of the improvement alternatives evaluated. The project costs are estimated from default values of unit construction costs that are built into the tool. An option is available to change these default unit costs to match a particular agency's experience or to replace the project cost estimated by the tool with the agency's own site-specific estimate. An option is also available for any given analysis as to whether the cost of right-of-way acquisition is included in the project implementation cost estimate. Right-of-way costs can also be based on default values built into the tool, user-specific unit costs for right-of-way, or site-specific cost estimates made by the agency.

The safety performance of the roadway being analyzed and the safety benefits of improvement alternatives estimated in Tool 1 are based on the crash prediction procedures presented in Part C of the AASHTO *Highway Safety Manual* (HSM) including HSM Chapters 10, 11, and 18 (*2*,*3*).

The tool analyzes roadway segment (i.e., nonintersection) crashes only. The HSM crash prediction procedures are applied first to predict the crash frequencies by severity level for the existing roadway based on safety performance functions (SPFs), crash modification factors (CMFs), and local calibration factors (if available). The crash reduction effectiveness of improvements is based on the CMFs presented in Section 4.3 of this guide. An option is available to replace the default SPFs from the HSM with an agency-specific SPFs for all roadway types other than freeways. The local calibration factor is set equal to 1.0 by default, but may optionally be replaced with an agency-specific value. An option is available to provide site-specific crash history data and apply the Empirical Bayes (EB) method for converting predicted crash frequencies to expected crash frequencies, using the procedures presented in the Appendix to HSM Part C (*2*). Crash costs by severity level are set by default to values built into the tool, but may be replaced with agency-specific values. The user of Tool 1 has the option to select which improvement alternative (or combination of alternatives) will be considered in the benefit-cost analysis. The improvement alternatives that may be considered include:

- Lane widening
- Shoulder widening (outside shoulder only on two-lane and four-lane nonfreeways; both outside and inside shoulders on freeways)
- Shoulder paving
- Roadside slope flattening (two-lane and four-lane nonfreeways only)
- Centerline rumble strips (undivided highways only)
- Shoulder rumble strips (outside shoulder only on undivided roads; both outside and inside shoulders on divided nonfreeways and freeways)
- Enhanced striping/delineation (nonfreeways only)
- Add or modify median barrier (freeways only)
- Add or modify roadside barrier (freeways only)
- Add passing lane(s) (rural two-lane highways only)
- Improve/restore curve superelevation (nonfreeways only)

The results provided by Tool 1 for the analysis of any improvement alternative (or combination of alternatives include:

- Project implementation cost ($)
- Annual safety benefit ($)
- Present value of safety benefit ($)
- Benefit-cost ratio (benefit divided by cost)
- Net benefit (benefit minus cost) ($)
- Fatal-and injury (FI) crashes per year in before period
- Property-damage-only (PDO) crashes per year in before period
- FI crashes per year in after period
- PDO crashes per year after period
- FI crashes per year reduced by project
- PDO crashes per year reduced by project

Tool 1 has been developed entirely in Microsoft Excel worksheets without any supplementary Visual Basic programming. This should make Tool 1 easily implementable on computers with nearly any operating system and nearly any version of Microsoft Excel. By contrast, Tool 2, presented in Appendix B, incorporates supplementary programming in Visual Basic; therefore, macros must be enabled on the user's computer for the tool to function.

The users guide for Tool 1 is presented with separate sections on rural two-lane highways, rural four-lane highways, and freeways, because the input data and improvement alternatives considered differ to some extent for each roadway type.

A.1 Rural Two-lane Highways

This section presents the application of Tool 1 to candidate 3R projects on rural two-lane highways. The guidance addresses setup defaults (which you can either accepted unchanged or modify), data entry for existing conditions on a specific roadway, specifying the alternative(s) to be considered, reviewing analysis results, and reviewing calculations.

A.1.1 Setup Defaults

Before performing any benefit-cost analyses, first visit the R2U_Setup worksheet.

The purpose of the R2U_Setup worksheet is to establish default values for assessment of 3R projects on rural two-lane highways. The R2U_Setup worksheet contains default values for all non-site-specific data elements needed by Tool 1 to perform the benefit-cost calculations. Thus, you can perform analyses without changing any values in the R2U_Setup worksheet. However, you have the option to modify any of the default values to other values that are consistent with your agency's policies, practices, and experience. To change a default value, enter your value into the cell in the *User Supplied* column and click the option button in that cell. This user-supplied value will appear in the *Values Used* column as a replacement for the default value that was initially shown.

The example in Figure A-1 shows a user-supplied value of 1.5 ft for the average embankment height on level terrain.

ROAD ELEMENTS		Default	User Supplied	Values Used
Average Embankment Height (ft) by Terrain	Level	2.5 ft ○	1.5 ft ◉	1.5 ft
	Rolling	3.0 ft ◉	○	3.0 ft
	Mountainous	4.5 ft ◉	○	4.5 ft

Figure A-1. Declaring Values Used in the R2U_Setup Worksheet

Each of the data elements on the R2U_Setup worksheet is described in the following sections.

A.1.1.1 Road Elements

Figure A-2 shows a screenshot of the road element defaults. Each item in the figure is discussed below.

ROAD ELEMENTS		Default	User Supplied	Values Used
Average Embankment Height (ft) by Terrain	Level	2.5 ft		2.5 ft
	Rolling	3.0 ft		3.0 ft
	Mountainous	4.5 ft		4.5 ft
Existing Base Depth (in)	Traveled-way	8.0 in		8.0 in
	Shoulder	8.0 in		8.0 in
Milling Depth (in), Flexible Pavement	Traveled-way	2.0 in		2.0 in
	Shoulder	2.0 in		2.0 in
Pavement Depth (in), Flexible Pavement	Traveled-way	5.0 in		5.0 in
	Shoulder	5.0 in		5.0 in
Average Delineator Spacing (ft)		500 ft		500 ft

Figure A-2. Defaults for Road Elements for Rural Two-Lane Highways

- **Average Embankment Height:** Average representation of the embankment height of the roadway cross section in feet for level, rolling, and mountainous terrain.
- **Existing Base Depth:** Depth in inches of base material in inches underneath the traveled-way and shoulder.
- **Milling Depth:** Depth in inches to which flexible pavement of traveled-way and shoulder will be milled as part of pavement resurfacing. This applies only to flexible pavement.
- **Pavement Depth:** Depth in inches of flexible pavement for traveled-way and shoulder. This applies only to flexible pavement.
- **Average Delineator Spacing:** Average spacing in feet between roadside delineators, where delineators are to be added.

A.1.1.2 Cost Elements

Figures A-3 and A-4 show the cost element defaults for rural two-lane highways. Each cost element is discussed in detail below the figures. All costs are in dollars.

COST ELEMENTS		Default	User Supplied	Values Used
Base Unit Cost	$/CY	$ 10.00 ◉	○	$ 10.00
Milling Unit Cost	$/SY	$ 2.00 ◉	○	$ 2.00
Flexible Pavement Unit Cost	$/CY	$ 55.00 ◉	○	$ 55.00
Rigid Pavement Unit Cost	$/SY	$ 40.00 ◉	○	$ 40.00
Unpaved Shoulder Unit Cost	$/SY	$ 1.00 ◉	○	$ 1.00
Embankment Unit Cost	$/CY	$ 8.00 ◉	○	$ 8.00
Right-of-way Unit Cost	$/acre	$ 5,000 ◉	○	$ 5,000
Centerline Rumble Strip Unit Cost	$/LF	$ 0.50 ◉	○	$ 0.50
Shoulder Rumble Strip Unit Cost	$/LF (both sides of road included)	$ 0.40 ◉	○	$ 0.40
Durable Pavement Marking Unit Cost	$/LF	$ 4.00 ◉	○	$ 4.00
Delineator Cost	$/each	$ 60.00 ◉	○	$ 60.00

Figure A-3. Defaults for Cost Elements for Rural Two-Lane Highways, Part 1 of 2

- **Base Unit Cost:** Cost of base material per cubic yard.
- **Milling Unit Cost:** Cost of pavement milling per square yard.
- **Flexible Pavement Unit Cost:** Material and installation cost of flexible pavement per cubic yard.
- **Rigid Pavement Unit Cost:** Material and installation cost of rigid pavement per square yard.
- **Unpaved Shoulder Unit Cost:** Material and installation cost of unpaved shoulder per square yard.
- **Embankment Unit Cost:** Cost of embankment material per cubic yard.
- **Right-of-way Unit Cost:** Cost of acquiring right-of-way per acre.
- **Centerline Rumble Strip Unit Cost:** Cost of installing a centerline rumble strip per linear foot.
- **Shoulder Rumble Strip Unit Cost:** Cost of installing a shoulder rumble strip per linear foot.
- **Durable Pavement Marking Unit Cost:** Material and installation cost of a durable pavement marking per linear foot.
- **Delineator Cost:** Material and installation cost of one roadside delineator.

Incidentals (% of Total Project Cost w/o ROW Cost)	Drainage	0.9%		0.9%
	Erosion Control	0.3%		0.3%
	Traffic Control	8.0%		8.0%
	Signing and PM	7.5%		7.5%
MARR/discount rate	%	7%		7%
Service Life (yrs)	Slope Flattening	20 yrs	5 yrs	20 yrs
	Lane Widening			
	Shoulder Widening			
	Rumble Strip Install	20 yrs	5 yrs	20 yrs
	Striping/Delineation	5 yrs	10 yrs	5 yrs
	Superelevation Restoration	20 yrs	5 yrs	20 yrs
Crash Cost by Severity ($/crash)	Fatal	$ 4,008,900		$ 4,008,900
	Disabling Injury	$ 216,000		$ 216,000
	Evident Injury	$ 79,000		$ 79,000
	Possible Injury	$ 44,900		$ 44,900
	Property Damage Only	$ 7,400		$ 7,400

Figure A-4. Defaults for Cost Elements for Rural Two-Lane Highways, Part 2 of 2.

- **Incidentals:** Each incidental cost is calculated as a percentage of the project total cost not including the right-of-way cost.
  - Signing and PM: Signing and pavement markings.
- **MARR/discount rate:** Minimum attractive rate of return (MARR) for analysis of 3R project investments. Federal guidelines suggest an MARR value at 7 percent. The MARR is also referred to as discount rate.
- **Service Life:** Expected useful life or service life in years for the roadway improvement.
  - *Slope Flattening:* Service life of slope flattening, including flattening the roadside foreslope only.
  - *Lane Widening:* Service life for widening of the traveled-way.
  - *Shoulder Widening:* Service life for widening of the shoulder adjacent to the traveled-way.
    - *NOTE:* Slope Flattening, Lane Widening, and Shoulder Widening should always be assigned identical service lives.
  - *Rumble Strip Installation:* Service life of centerline and shoulder rumble strips.
  - *Striping/Delineation:* Service life of roadway striping and roadside delineators.
  - *Superelevation Restoration:* Service life of restoring or changing horizontal curve superelevation.

- **Crash Cost by Severity:** Societal crash costs by crash severity level. Crash severity levels are defined in a manner consistent with the HSM.
    - *Fatal:* Cost of a fatal crash.
    - *Disabling Injury:* Cost of a disabling injury crash.
    - *Evident Injury:* Cost of an evident injury crash.
    - *Possible Injury:* Cost of a possible injury crash.
    - *Property Damage Only:* Cost of a property damage only crash.

A.1.1.3 Safety Elements

Figure A-5 shows the safety element defaults for rural two-lane highways. Each element is discussed in detail below.

SAFETY ELEMENTS		Default	User Supplied	Values Used
Rural 2-lane SPF		HSM ◉	=f(AADT, L) ○	HSM SPF
Calibration Factor		1.00 ◉	○	1.00
Crash Type Proportion		◉	○	
	Single-vehicle crashes			
	Collision with animal	12.1%		12.1%
	Collision with bicycle	0.2%		0.2%
	Collision with pedestrian	0.3%		0.3%
	Overturned	2.5%		2.5%
	Ran off road	52.1%		52.1%
	Other single-vehicle crash	2.1%		2.1%
	Multiple-vehicle crashes			
	Angle collision	8.5%		8.5%
	Head-on collision	1.6%		1.6%
	Rear-end collision	14.2%		14.2%
	Sideswipe collision	3.7%		3.7%
	Other multi-vehicle collision	2.7%		2.7%
	Total crashes	100.0%	0.0%	100.0%
Crash Severity Proportion		◉	○	
	Fatal (K)	1.3%		1.3%
	Disabling Injury (A)	5.4%		5.4%
	Evident Injury (B)	10.9%		10.9%
	Possible Injury (C)	14.5%		14.5%
	Property Damage Only (PDO)	67.9%		67.9%
	Total crashes	100.0%	0.0%	100.0%

Figure A-5. Defaults for Safety Elements for Rural Two-Lane Highways

- **Rural 2-lane safety performance function (SPF):** The user has the option to retain the SPF applicable to rural two-lane highways from HSM Chapter 10 or to modify it. The SPF for rural two-lane highways used in the HSM is:

$$Predicted\ Crash\ Frequency = AADT \times Length \times 365 \times 10^{-6} e^{-0.312}$$

You can supply your own SPF as a function of AADT and roadway section length. An example of how to enter a revised SPF is shown in Figure A-6. In the cell provided (Cell I74 in the R2U_Setup worksheet), type in a formula that is a function of cells I70 and I72, which represent AADT and roadway section length, respectively. Enter the overdispersion parameter for the rural two-lane SPF in cell I75.

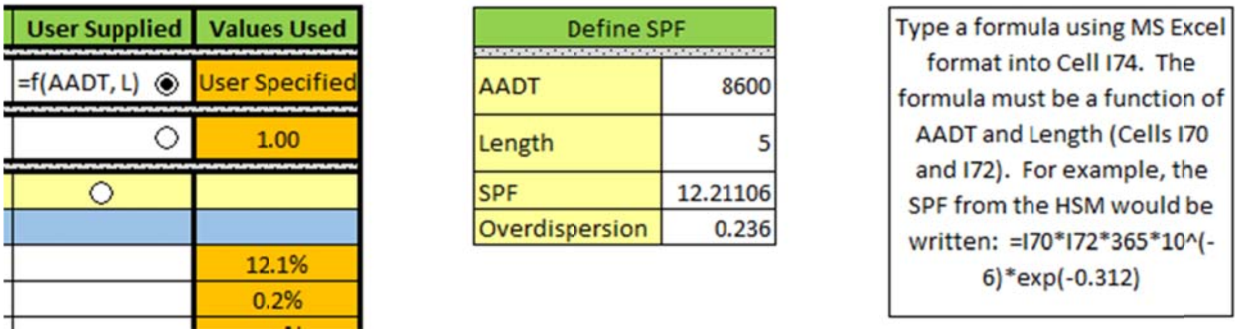
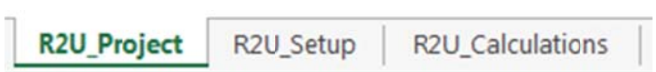


Figure A-6. Specify an Agency-Specific SPF for Rural Two-lane Highways.

- **Calibration Factor:** This is a factor to adjust crash frequency estimates produced from the safety prediction procedure to approximate your local conditions. A default value of 1.0 is built into the tool.
- **Crash Type Proportions:** These are the percentage of all crashes for each crash type shown. Default values of these percentages from HSM Chapter 10 are built into the tool. You may also enter agency-specific values. All percentages must add to 100 percent. If the sum of all percentages is between 95 and 105 percent, then the tool will automatically adjust each individual percentage proportionally to add to 100 percent. The tool will not consider user-supplied percentages if the sum of all percentages is less than 95 percent or greater than 105 percent. In this case, an error message will be displayed.
- **Crash Severity Proportions:** These are the percentage of all crashes for each crash severity level. Default values of these percentages from HSM Chapter 10 are built into the tool. You may also enter agency-specific values. All percentages must add to 100 percent. If the sum of all percentages is between 95 and 105 percent, then the tool will adjust each individual percentage proportionally to add to 100 percent. The tool will not consider user-supplied percentages if the sum of all percentages is less than 95 percent or greater than 105 percent. In this case, an error message will be displayed.

A.1.2 Data Entry

After the setup defaults have been either retained or modified, as you wish, the tool is ready to perform benefit-cost analyses for rural two-lane highways. Proceed to the R2U_Project worksheet.



Use the R2U_Project worksheet to enter all existing roadway attributes and select specific improvements to consider in the benefit-cost analysis.

The following sections step through each input table in the R2U_Project worksheet.

A.1.2.1 Roadway Data

Roadway data for the candidate 3R project site to be assessed are entered in the table shown in Figure A-7.

ROADWAY DATA	
Section Length (mi)	5.000
AADT (veh/day)	8,600
Terrain	Rolling
Pavement Type	Flexible

Figure A-7. Roadway Data Entry for Rural Two-Lane Highways

- **Section Length:** Length in miles of the roadway section.
- **AADT:** Annual average daily traffic in vehicles per day on the roadway section.
- **Terrain:** The terrain in which the roadway section is located.
- **Pavement Type:** Type of pavement of the roadway section, either flexible or rigid.

A.1.2.2 Alignment Data

The alignment data table shown in Figure A-8 addresses the method that will be used to describe horizontal curvature of the roadway section of interest. Use the option buttons in Figure A-8 to select either entry of average curve data or entry of specific curve data. Depending on which option button you select, different entry forms will appear on the worksheet. Note that if you plan on considering superelevation restoration/improvement as part of your 3R project, you must enter specific curve data.

ALIGNMENT DATA	
Enter average curve data	○
*Enter specific curve data	◉

*Use this if improving superelevation

Figure A-8. Alignment Data Entry Options for Rural Two-Lane Highways

The following two figures show the data entry for average curve data (see Figure A-9) and specific curve data (see Figure A-10). Note that you will only see the entry form corresponding to the option that you chose for entering alignment data.

AVERAGE CURVE DATA	
% of Section Length on Curves	60.00%
Typical Curve Radius (ft)	1000 ft
Number of Curves on Section	16
Presence of Spiral Transitions	Yes

Figure A-9. Average Curve Data Entry for Rural Two-Lane Highways

- **% of Section Length on Curves:** Enter the percent of the roadway section that is on horizontal curves. Include spiral transitions in the percentage if present.
- **Typical Curve Radius:** Enter the average horizontal curve radius of the roadway section.
- **Number of Curves on Section:** Enter the number of horizontal curves on the roadway section.
- **Presence of Spiral Transitions:** If spiral transitions are present with the horizontal curves, use the dropdown in this cell to select “Yes”. Otherwise, select “No.”

SPECIFIC CURVE DATA							
Number of Curves in Roadway Section				4			
Maximum Superelevation Rate (e_{max})				8%			
Design Speed (mph)				55 mph			
Curve #	Curve Length (mi)	Transition Length (mi)	Radius (ft)	Spiral	Existing e (%)	Consider for Improvement	Improved e (%)
1	0.156 mi	0.089 mi	1300.00 ft	Yes	2.4%	Yes	7.6%
2	0.237 mi	0.122 mi	940.00 ft	Yes	3.8%	Yes	8.0%
3	0.155 mi	0.098 mi	2000.00 ft	Yes	6.0%	No	[illegible]
4	0.222 mi	0.095 mi	1500.00 ft	Yes	3.0%	Yes	7.0%

Figure A-10. Specific Curve Data Entry for Rural Two-Lane Highways

- **Number of Curves in Roadway Section:** Enter the number of horizontal curves that exist on the roadway section. A maximum of 10 curves can be entered in the specific curve data form.
- **Maximum Superelevation Rate (e_{max}):** Enter your agency’s maximum superelevation rate for horizontal curves on rural two-lane highways.
- **Design Speed:** Enter the design speed of the roadway section in miles per hour.

- You will need to enter the following data for each horizontal curve on the roadway section:
  - *Curve Length:* Enter the length of horizontal curve in miles, not including spiral transitions.
  - *Transition Length:* Enter the length of spiral transition in miles for one end of the horizontal curve. If there are no spiral transitions, enter “0”.
  - *Radius:* Enter the radius of the horizontal curve in feet.
  - *Spiral:* Select “Yes” from the embedded dropdown menu if spiral curves are present. Otherwise, select “No.”
  - *Existing e:* Enter the existing superelevation rate of the horizontal curve expressed as a percentage.
  - *Consider for Improvement:* Select “Yes” from the embedded dropdown menu if you want to consider superelevation restoration/improvement on this specific curve in the 3R project. Otherwise, select “No.”
  - *Improved e:* If you selected “Yes” in the *Consider for Improvement* column, then the *Improved e* cell will be shown. Enter the improved superelevation rate of the horizontal curve in percent.

A.1.2.3 Existing Cross Section Data

Use the Existing Cross Section data entry form shown in Figure A-11 to define the following features of the roadway section:

EXISTING CROSS SECTION	
Lane Width (ft)	10.5 ft
Shoulder Width (ft)	4 ft
Shoulder Type	Unpaved
Roadside Slope	1V:4H
Centerline Rumble Strip	Yes
Shoulder Rumble Strip	Yes

Figure A-11. Existing Cross Section Data Entry for Rural Two-Lane Highways

- **Lane Width:** Select the existing lane width on the traveled way in feet from the dropdown menu.
- **Shoulder Width:** Select the existing shoulder width in feet from the dropdown menu.
- **Shoulder Type:** Select the existing shoulder type from the dropdown menu.

- **Roadside Slope:** Select the existing roadside foreslope from the dropdown menu.
- **Centerline Rumble Strip:** Select "Yes" from the dropdown menu if centerline rumble strips are present on the roadway section. Otherwise, select "No."
- **Shoulder Rumble Strip:** Select "Yes" from the dropdown menu if shoulder rumble strips are present on the roadway section. Otherwise, select "No."

A.1.2.4 Crash History Option

At your option, you can choose to use the existing site-specific crash history of the roadway section to assist in calculating potential crash savings with the 3R project. Otherwise, you can simply use the estimate given by the HSM crash prediction method. The choice between these options is made in the form shown in Figure A-12. The advantage of using site-specific crash history is that the benefit estimate may better reflect local conditions.

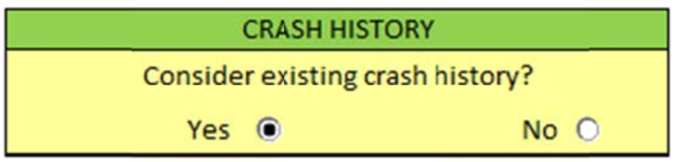


Figure A-12. Crash History Option Data Entry Form for Rural Two-Lane Highways

- **Consider existing crash history?:** Select the "Yes" option if you want to use the site-specific crash history for the roadway section. Otherwise, select "No."

The *Crash Data* entry form shown in Figure A-13 will appear when "Yes" is selected for the consideration of existing crash history.

CRASH DATA	
Crash History Period (yrs)	3
Total Fatal-and-Injury Crashes	1
Total Property-Damage-Only Crashes	10

Figure A-13. Crash Data Entry for Rural Two-Lane Highways

- **Crash History Period:** Enter the number of years of available crash data.
- **Total Fatal-and-Injury Crashes:** Enter the total number of crashes on the roadway segment that fall into the following crash severity levels:
  - Fatal crash
  - Disabling injury crash
  - Evident injury crash
  - Possible injury crash

- **Total Property-Damage-Only Crashes:** Enter the total number of crashes on the roadway segment that fall into the property-damage-only crash severity level.

A.1.3 Alternatives to Consider

Near the bottom of the R2U_Project worksheet is a table in which to specify which improvement alternatives should be considered in the benefit-cost analysis (see Figure A-14). Check the appropriate checkboxes to select the appropriate improvement alternatives to consider in the analysis.

Alternatives to Consider	Consider for Improvement	User Selection	Value Selected
Lane Width (ft)	☐		Retain Lane Width
Shoulder Width (ft)	☐		Retain Shoulder Width
Shoulder Type	☐		Unpaved Shoulder
Roadside Slope	☐		Retain Roadside Slope
Centerline Rumble Strip	☐		Retain Centerline Rumble Strip
Shoulder Rumble Strip	☐		Retain Shoulder Rumble Strip
Enhanced Striping/Delineation	☐		Not Selected
Add New Passing Lane(s)	☐		Not Selected

Figure A-14. Data Entry Form to Select Alternatives to Consider for Rural Two-Lane Highways

Each potential improvement alternative that can be selected is described below in more detail.

- **Lane Width:** If you have checked the Lane Width box, select the width to which the through travel lanes will be widened from the choices offered on the dropdown menu in the *User Selection* column. Only values greater than the existing lane width can be selected, up to a maximum lane width of 12 ft.
- **Shoulder Width:** If you have checked the Shoulder Width box, select the width to which the shoulders will be widened from the choices offered on the dropdown menu in the *User Selection* column. Only values greater than the existing shoulder width can be selected, up to a maximum shoulder width of 8 ft.
- **Shoulder Type:** If you have checked the Shoulder Type box, select the improved shoulder type from the dropdown menu in the *User Selection* menu. A paved shoulder is

the only available option, and this option is only applicable if the existing shoulder is unpaved.

- **Roadside Slope:** If you have checked the Roadside Slope box, select the improved roadside slope from the dropdown menu in the *User Selection* column. Only slopes flatter than the existing roadside slope can be selected. The flattest slope that may be considered is 1V:6H.
- **Centerline Rumble Strip:** If you have checked the Centerline Rumble Strip box, no further data entry is necessary. Installation of a centerline rumble strip along the entire length of the roadway section will be considered. Note that if centerline rumble strips are already present on the roadway section, checking the centerline rumble strip box will have no effect. In this case, the cost of installing the rumble strip after repaving will automatically be added into the project cost of the 3R project.
- **Shoulder Rumble Strip:** If you have checked the Shoulder Rumble Strip box, no further data entry is necessary. Installation of a shoulder rumble strip along the entire length of both sides of the roadway section will be considered. Note that if shoulder rumble strips are already present on the roadway section, checking the shoulder rumble strip box will have no effect. In this case, the cost of installing the rumble strips after repaving will automatically be added into the project cost of the 3R project.
- **Enhanced Striping/Delineation:** If you have checked the Enhanced Striping/Delineation box, installation of durable pavement markings will be considered for both centerline and edge striping as well as installing roadside delineators. The data entry table shown in Figure A-15 will appear if you select this option.
- **Add New Passing Lane(s):** If you have checked the Add New Passing Lane(s) box, addition of one or more new passing lanes will be considered. The data entry table shown in Figure A-16 will appear if you select this option.

ENHANCED PAVEMENT MARKING AND DELINEATION DATA	
% of Section with Dashed Centerline	25.00%
% of Section with Solid-Dash Centerline	25.00%
% of Section with Double Solid Centerline	50.00%
Total Length of Section with Delineator Posts (mi)	2.500 mi

Figure A-15. Enhanced Pavement Marking and Delineation Data Entry Form for Rural Two-Lane Highways

- **% of Section with Dashed Centerline:** Enter the percentage of the roadway section in which the centerline striping is dashed only.

- **% of Section with Solid-Dash Centerline:** Enter the percentage of the roadway section in which the centerline striping is a solid-dash combination.
- **% of Section with Double Solid Centerline:** Enter the percentage of the roadway section in which the centerline striping is double-solid.
- **Total Length of Section with Delineator Posts:** Enter the length of the roadway section in miles that will have roadside delineator posts. Include both sides of the roadway separately (i.e. enter 2 mi if a 1-mi roadway section will have roadside delineators on both sides of the roadway.

PASSING LANE DATA	
Number of New Passing Lanes in Roadway Section	2
Design Speed (mph)	55
New Length of Passing Lanes in Road Section (mi)	1.000 mi
New Length of Overlapping Passing Lanes (mi)	0.100 mi
Width of New Passing Lanes (ft)	12.0 ft

Figure A-16. Passing Lane Data Entry Form for Rural Two-Lane Highways

- **Number of New Passing Lanes in Roadway Section:** Enter the number of passing lanes that will be added to the roadway section. Passing lanes in each direction of travel are counted separately. Each passing lane should be determined to be operationally justified before being considered in this tool.
- **Design Speed:** Enter the design speed of the new passing lanes in miles per hour.
- **New Length of Passing Lanes in Road Section:** Enter the total length in miles of new passing lanes to be added to the roadway section. The length of each passing lane is measured from the beginning of the lane addition taper to the end of the lane drop taper of the passing lane. If more than one passing lane is added, sum the passing lane lengths.
- **New Length of Overlapping Passing Lanes:** Enter the total roadway length in miles in which passing lanes on both sides of the roadway overlap.
- **Width of New Passing Lanes:** Enter the lane width in feet of the new passing lanes.

A.1.4 Analysis Results

The results of the benefit-cost analysis are shown in the Results table at the top of the R2U_Project worksheet (see Figure A-17).

RESULTS	Calculated	User Supplied	Value Used
PV MODIFIED TOTAL COST ($)*	$242,484		$242,484

*total cost minus milling and resurfacing cost for existing traveled way

ANNUAL SAFETY BENEFIT ($)	$27,225	BENEFIT-COST RATIO	1.189
PRESENT VALUE OF SAFETY BENEFIT ($)	$288,421	NET BENEFIT ($)	$45,936

Figure A-17. Results of Benefit-Cost Analysis for Rural Two-Lane Highways

The Results table presents the following information:

- **PV Modified Total Cost:**
  - *Calculated:* The present value of the modified total project cost is shown in this cell. The modified total cost is the total project cost not including the cost of milling and resurfacing the existing traveled way.
  - *User Supplied:* You can supply your own total project cost in this cell. Click the option button in this cell for the tool to use this user-supplied total cost in place of the value calculated by the tool.
- **Annual Safety Benefit:** This is the calculated annual crash savings in dollars that is estimated to result from the selected 3R project roadway improvements (other than milling and resurfacing which will be implemented whether or not the other improvements are made).
- **Present Value of Safety Benefit:** This is the present value of the annual crash savings over the service life of the roadway improvements.
- **Benefit-Cost Ratio:** The benefit-cost ratio is the ratio of the present value of safety benefit divided by the present value of the modified total cost.
- **Net Benefit:** The net benefit is the present value of safety benefit minus the present value of the modified total cost.

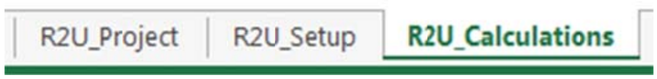
The annual number of crashes predicted before and after the 3R project, along with the annualized crash reductions, are shown to the right of the Results table (see Figure A-18).

Before FI Crashes	2.157 crashes/yr
Before PDO Crashes	4.564 crashes/yr
After FI Crashes	2.053 crashes/yr
After PDO Crashes	4.343 crashes/yr
Reduced FI Crashes	0.104 crashes/yr
Reduced PDO Crashes	0.220 crashes/yr

Figure A-18. Crash Frequencies Before and After 3R Project for Rural Two-Lane Highways

A.1.5 View Calculations

You may access the R2U_Calculations worksheet to review all of the intermediate values calculated in assessing the benefits and costs of the project. This is a read-only worksheet that enables you to review the calculations, but does not allow you to change any results.



A.2 Rural Four-Lane Highways

This section presents the application of Tool 1 to candidate 3R projects on rural four-lane undivided and divided highways. The guidance addresses setup defaults (which you can either accepted unchanged or modify), data entry for existing conditions on a specific roadway, specifying the alternative(s) to be considered, reviewing analysis results, and reviewing calculations.

A.2.1 Setup Defaults

Before performing any benefit-cost analyses for rural four-lane highways, first visit the "R4UD_Setup" worksheet.

The purpose of the R4UD_Setup worksheet is to establish default values for assessment of 3R projects on rural four-lane undivided and divided highways (nonfreeways). The R4UD_Setup worksheet contains default values for all non-site-specific data elements needed by Tool 1 to perform the benefit-cost calculations. Thus, you can perform analyses without changing any values in the R4UD_Setup worksheet. However, you have the option to modify any of the default values to other values that are consistent with your agency's policies, practices, and experience. To change a default value, enter your value into the cell in the *User Supplied* column and click the option button in that cell. This user-supplied value will appear in the *Values Used* column as a replacement for the default value that was initially shown.

Each of the data elements on the R4UD_Setup worksheet is described in the following sections.

A.2.1.1 Road Elements

Figure A-19 shows a screenshot of the road element defaults. Each item in the figure is discussed below.

ROAD ELEMENTS		Default	User Supplied	Values Used
Average Embankment Height (ft) by Terrain	Level	2.5 ft		2.5 ft
	Rolling	3.0 ft		3.0 ft
	Mountainous	4.5 ft		4.5 ft
Existing Base Depth (in)	Traveled-way	8.0 in		8.0 in
	Shoulder	8.0 in		8.0 in
Milling Depth (in), Flexible Pavement	Traveled-way	2.0 in		2.0 in
	Shoulder	2.0 in		2.0 in
Pavement Depth (in), Flexible Pavement	Traveled-way	5.0 in		5.0 in
	Shoulder	5.0 in		5.0 in
Average Delineator Spacing (ft)		500 ft		500 ft

Figure A-19. Entry Form for Road Element Defaults for Rural Four-Lane Highways

- **Average Embankment Height:** Average representation of the embankment height of the roadway cross section in feet for level, rolling, and mountainous terrain.
- **Existing Base Depth:** Depth in inches of base material in inches underneath the traveled-way and shoulder.
- **Milling Depth:** Depth in inches to which flexible pavement of traveled-way and shoulder will be milled as part of pavement resurfacing. This applies only to flexible pavement.
- **Pavement Depth:** Depth in inches of flexible pavement for traveled-way and shoulder. This applies only to flexible pavement.
- **Average Delineator Spacing:** Average spacing in feet between roadside delineators, where delineators are to be added.

A.2.1.2 Cost Elements

Figure A-20 and Figure A-21 show the cost element defaults for rural multilane highways. Each element is discussed in detail below the figures. All costs are in dollars.

COST ELEMENTS		Default	User Supplied	Values Used
Base Unit Cost	$/CY	$ 10.00		$ 10.00
Milling Unit Cost	$/SY	$ 2.00		$ 2.00
Flexible Pavement Unit Cost	$/CY	$ 55.00		$ 55.00
Rigid Pavement Unit Cost	$/SY	$ 40.00		$ 40.00
Unpaved Shoulder Unit Cost	$/SY	$ 1.00		$ 1.00
Embankment Unit Cost	$/CY	$ 8.00		$ 8.00
Right-of-way Unit Cost	$/acre	$ 5,000		$ 5,000
Centerline Rumble Strip Unit Cost	$/LF	$ 0.50		$ 0.50
Shoulder Rumble Strip Unit Cost	$/LF (both sides of road included)	$ 0.40		$ 0.40
Durable Pavement Marking Unit Cost	$/LF	$ 4.00		$ 4.00
Delineator Cost	$/each	$ 60.00		$ 60.00

Figure A-20. Entry Form for Cost Element Defaults for Rural Four-Lane Highways, Part 1 of 2

- **Base Unit Cost:** Cost of base material per cubic yard.
- **Milling Unit Cost:** Cost of pavement milling per square yard.
- **Flexible Pavement Unit Cost:** Material and installation cost of flexible pavement per cubic yard.
- **Rigid Pavement Unit Cost:** Material and installation cost of rigid pavement per square yard.
- **Unpaved Shoulder Unit Cost:** Material and installation cost of unpaved shoulder per square yard.
- **Embankment Unit Cost:** Cost of embankment material per cubic yard.
- **Right-of-way Unit Cost:** Cost of acquiring right-of-way per acre.
- **Centerline Rumble Strip Unit Cost:** Cost of installing a centerline rumble strip per linear foot.
- **Shoulder Rumble Strip Unit Cost:** Cost of installing a shoulder rumble strip per linear foot.
- **Durable Pavement Marking Unit Cost:** Material and installation cost of a durable pavement marking per linear foot.
- **Delineator Cost:** Material and installation cost of one roadside delineator.

Incidentals (% of Total Project Cost w/o ROW Cost)	Drainage	0.4%		0.4%
	Erosion Control	0.1%		0.1%
	Traffic Control	8.0%		8.0%
	Signing and PM	5.0%		5.0%
MARR/discount rate	%	7%		7%
Service Life (yrs)	Slope Flattening	20 yrs	5 yrs	20 yrs
	Lane Widening			
	Shoulder Widening			
	Rumble Strip Install	20 yrs	5 yrs	20 yrs
	Striping/Delineation	5 yrs	10 yrs	5 yrs
	Superelevation Restoration	20 yrs	5 yrs	20 yrs
Crash Cost by Severity ($/crash)	Fatal	$ 4,008,900		$ 4,008,900
	Disabling Injury	$ 216,000		$ 216,000
	Evident Injury	$ 79,000		$ 79,000
	Possible Injury	$ 44,900		$ 44,900
	Property Damage Only	$ 7,400		$ 7,400

Figure A-21. Entry Form for Cost Element Defaults for Rural Four-Lane Highways, Part 2 of 2

- **Incidentals:** Each incidental cost is calculated as a percentage of the project total cost not including the right-of-way cost.
  - *Signing and PM:* Signing and pavement markings.
- **MARR/discount rate:** Minimum attractive rate of return (MARR) for analysis of 3R project investments. Federal guidelines suggest an MARR value at 7 percent. The MARR is also referred to as discount rate.
- **Service Life:** Expected useful life or service life in years for the roadway improvement.
  - *Slope Flattening:* Service life for slope flattening, including flattening the roadside foreslope only.
  - *Lane Widening:* Service life for widening of the traveled-way.
  - *Shoulder Widening:* Service life for widening of the shoulder adjacent to the traveled-way.
    - *NOTE:* Slope Flattening, Lane Widening, and Shoulder Widening should always be assigned identical service lives.
  - *Rumble Strip Installation:* Service life of centerline and shoulder rumble strips.
  - *Striping/Delineation:* Service life of roadway striping and roadside delineators.
  - *Superelevation Restoration:* Service life of restoring or changing horizontal curve superelevation.

- **Crash Cost by Severity:** Societal crash costs by crash severity level. Crash severity levels are defined in a manner consistent with the HSM.
    - *Fatal:* Cost of a fatal crash.
    - *Disabling Injury:* Cost of a disabling injury crash.
    - *Evident Injury:* Cost of an evident injury crash.
    - *Possible Injury:* Cost of a possible injury crash.
    - *Property Damage Only:* Cost of a property damage only crash.

A.2.1.3 Safety Elements

Figures A-22 through A-25 show screenshots of the safety element defaults for rural four-lane highways. Each element is discussed in detail below.

SAFETY ELEMENTS	Default	User Supplied	Values Used
Rural 4-lane Undivided SPF	HSM ◉	=f(AADT, L) ○	HSM SPF
Rural 4-lane Divided SPF	HSM ◉	=f(AADT, L) ○	HSM SPF
Undivided Calibration Factor	1.00 ◉	○	1.00
Divided Calibration Factor	1.00 ◉	○	1.00

Figure A-22. Entry Form for Safety Element Defaults for Rural Four-Lane Highways, Part 1 of 3

- **Rural 4-lane Undivided SPF:** The user has the option to retain the SPF applicable to rural four-lane undivided highways (nonfreeways) from HSM Chapter 11 or to modify it. The SPF used for rural four-lane undivided highways used in the HSM is:

$$Predicted\ Crash\ Frequency = e^{-9.653+1.176ln(AADT)+ln(Length)}$$

You can supply your own SPF as a function of AADT and roadway section length. An example to how to enter a revised SPF is shown in Figure A-23. In the cell provided (Cell I72 in the R4UD_Setup worksheet), type in a formula that is a function of cells I70 and I71, which are AADT and roadway section length, respectively. Enter the overdispersion parameter for the rural four-lane undivided SPF in Cell I73.

- **Rural 4-lane Divided SPF:** The user has the option to retain the SPF applicable to rural four-lane divided highways (nonfreeways) from HSM Chapter 11 or to modify it. The SPF used for rural four-lane divided highways used in the HSM is:

$$Predicted\ Crash\ Frequency = e^{-9.025+1.049ln(AADT)+ln(Length)}$$

You can supply your own SPF as a function of AADT and roadway section length (see Figure A-23). In the cell provided (Cell I80), type in a formula that is a function of cells I78 and I79, which are AADT and roadway section length, respectively. Enter the overdispersion parameter for your rural four-lane divided SPF in Cell I81.

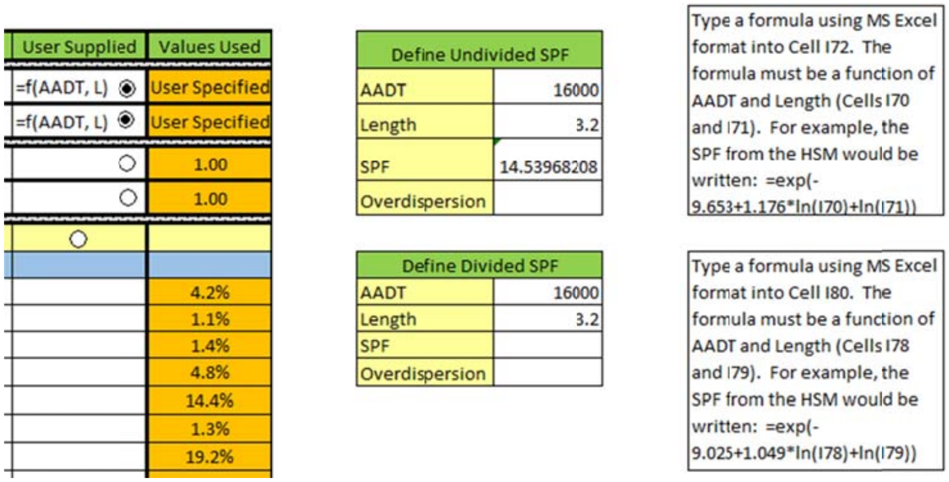


Figure A-23. User Specified SPFs for Rural Four-Lane Highways

- **Calibration Factor:** This is a factor to adjust crash frequency estimates produced from the safety prediction procedure to approximate your local conditions. A default value of 1.0 is built into the tool.

Crash Type Proportion		◉	○	
	Rural Multilane Undivided			
	Collision with animal	4.2%		4.2%
	Collision with bicycle	1.1%		1.1%
	Collision with pedestrian	1.4%		1.4%
	Overturned	4.8%		4.8%
	Ran off road	14.4%		14.4%
	Other single-vehicle crash	1.3%		1.3%
	Angle collision	19.2%		19.2%
	Head-on collision	0.5%		0.5%
	Rear-end collision	25.5%		25.5%
	Sideswipe collision	6.5%		6.5%
	Other multi-vehicle collision	21.1%		21.1%
	Total crashes	100.0%	0.0%	100.0%
	Rural Multilane Divided			
	Collision with animal	12.8%		12.8%
	Collision with bicycle	0.1%		0.1%
	Collision with pedestrian	0.2%		0.2%
	Overturned	15.9%		15.9%
	Ran off road	29.9%		29.9%
	Other single-vehicle crash	3.6%		3.6%
	Angle collision	12.4%		12.4%
	Head-on collision	0.6%		0.6%
	Rear-end collision	14.1%		14.1%
	Sideswipe collision	4.6%		4.6%
	Other multi-vehicle collision	5.8%		5.8%
	Total crashes	100.0%	0.0%	100.0%

Figure A-24. Entry Form for Safety Element Defaults for Rural Four-Lane Highways, Part 2 of 3

- **Crash Type Proportions:** These are the percentage of all crashes for each crash type shown. Default values of these percentages from HSM Chapter 11 are built into the tool. You may also enter agency-specific values. All percentages must add to 100 percent. If the sum of all percentages is between 95 and 105 percent, then the tool will automatically adjust each individual percentage proportionally to add to 100 percent. The tool will not consider user-supplied percentages if the sum of all percentages is less than 95 percent or greater than 105 percent. In this case, an error message will be displayed.

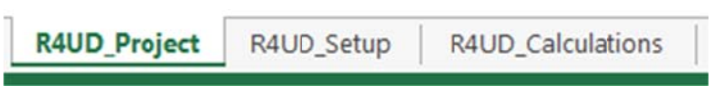
Crash Severity Proportion	Rural Multilane Undivided			
	Fatal (K)	0.7%		0.7%
	Disabiling Injury (A)	3.1%		3.1%
	Evident Injury (B)	10.4%		10.4%
	Possible Injury (C)	18.8%		18.8%
	Property Damage Only (PDO)	67.0%		67.0%
	Total crashes	100.0%	0.0%	100.0%
	Rural Multilane Divided			
	Fatal (K)	1.3%		1.3%
	Disabiling Injury (A)	4.0%		4.0%
	Evident Injury (B)	17.1%		17.1%
	Possible Injury (C)	17.4%		17.4%
	Property Damage Only (PDO)	60.2%		60.2%
	Total crashes	100.0%	0.0%	100.0%

Figure A-25. Entry Form for Safety Element Defaults for Rural Four-Lane Highways, Part 3 of 3

- **Crash Severity Proportions:** These are the percentage of all crashes for each crash severity level. Default values of these percentages from HSM Chapter 11 are built into the tool. You may also enter agency-specific values. All percentages must add to 100 percent. If the sum of all percentages is between 95 and 105 percent, then the tool will adjust each individual percentage proportionally to add to 100 percent. The tool will not consider user-supplied percentages if the sum of all percentages is less than 95 percent or greater than 105 percent. In this case, an error message will be displayed.

A.2.2 Data Entry

After the setup defaults have been either retained or modified, as you wish, the tool is ready to perform benefit-cost analyses for rural two-lane highways. Proceed to the R4UD_Project worksheet.



Use the R4UD_Project worksheet to enter all existing roadway attributes and select roadway improvements to consider in the benefit-cost analysis.

The following sections step through each input table in the “R4UD_Project” worksheet.

A.2.2.1 Roadway Data

ROADWAY DATA	
Divided or Undivided	4-lane Undivided
Section Length (mi)	3.200
AADT (veh/day)	16,000
Terrain	Level
Pavement Type	Rigid

Figure A-26. Roadway Data Entry Form for Rural Four-Lane Highways

- **Divided or Undivided:** Select either 4-lane Undivided or 4-lane Divided from the dropdown menu.
- **Section Length:** Length in miles of the roadway section.
- **AADT:** Average annual daily traffic in vehicles per day on the roadway section.
- **Terrain:** The terrain in which the roadway section is located.
- **Pavement Type:** Type of pavement of the roadway section, either flexible or rigid.

A.2.2.2 Alignment Data

Alignment data represent the horizontal curvature on the roadway section of interest. Unlike the rural two-lane highway procedures, there is no need for an average curve data option for rural four-lane nonfreeways. For rural four-lane nonfreeways, alignment data are used only for the assessment of superelevation improvements. If there are no curves on the roadway section of interest or you do not wish to consider superelevation improvement as an option for the 3R project, then enter "0" for number of curves in roadway section (see Figure A-27).

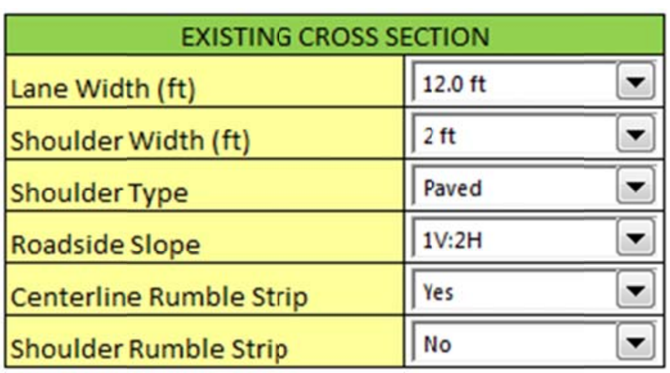
SPECIFIC CURVE DATA							
Number of Curves in Roadway Section				1			
Maximum Superelevation Rate (e_{max})				8%			
Design Speed (mph)				65 mph			
Curve #	Curve Length (mi)	Transition Length (mi)	Radius (ft)	Spiral	Existing e (%)	Consider for Improvement	Improved e (%)
1	0.102 mi	0.000 mi	4000.00 ft	No	4.4%	Yes	7.4%

Figure A-27. Specific Curve Data Entry Form for Rural Four-Lane Highways

- **Number of Curves in Roadway Section:** Enter the number of horizontal curves that exist on the roadway section. A maximum of 10 curves can be entered in the specific curve data form. If there are no curves or you do not wish to consider superelevation improvement as an option for the 3R project, then enter "0" for number of curves.
- **Maximum Superelevation Rate (e_{max}):** Enter your agency's maximum superelevation rate on rural multilane highways.
- **Design Speed:** Enter the design speed of the roadway section in miles per hour.
- You will need to enter the following data for each horizontal curve on the roadway section:
  - *Curve Length:* Enter the length of horizontal curve in miles, not including spiral transitions.
  - *Transition Length:* Enter the length of spiral transition in miles for one end of the horizontal curve. If there are no spiral transitions, enter "0".
  - *Radius:* Enter the radius of the horizontal curve in feet.
  - *Spiral:* Select "Yes" from the embedded dropdown menu if spiral curves are present. Otherwise, select "No."
  - *Existing e:* Enter the existing superelevation rate of the horizontal curve expressed as a percentage.
  - *Consider for Improvement:* Select "Yes" from the embedded dropdown menu if you want to consider superelevation restoration/improvement on this specific curve in the 3R project. Otherwise, select "No."
  - *Improved e:* If you selected "Yes" in the *Consider for Improvement* column, then the *Improved e* cell will be shown. Enter the improved superelevation rate of the horizontal curve in percent.

A.2.2.3 Existing Cross Section Data

Use the Existing Cross Section entry form shown in Figure A-28 to define the following features of the roadway section:



EXISTING CROSS SECTION	
Lane Width (ft)	12.0 ft
Shoulder Width (ft)	2 ft
Shoulder Type	Paved
Roadside Slope	1V:2H
Centerline Rumble Strip	Yes
Shoulder Rumble Strip	No

Figure A-28. Existing Cross Section Data Entry Form for Rural Four-Lane Highways

- **Lane Width:** Select the existing lane width on the traveled way in feet from the dropdown menu.
- **Shoulder Width:** Select the existing shoulder width in feet from the dropdown menu.
- **Shoulder Type:** Select the existing shoulder type from the dropdown menu.
- **Roadside Slope:** Select the existing roadside foreslope from the dropdown menu.
- **Centerline Rumble Strip:** Select "Yes" from the dropdown menu if centerline rumble strips are present on the roadway section. Otherwise, select "No."
- **Shoulder Rumble Strip:** Select "Yes" from the dropdown menu if shoulder rumble strips are present on the roadway section. Otherwise, select "No."

A.2.2.4 Crash History Option

At your option, you can choose to use the existing site-specific crash history of the roadway section to assist in calculating potential crash savings with the 3R project. Otherwise, you can simply use the estimate given by the HSM crash prediction method. The choice between these options is made in the form shown in Figure A-29. The advantage of using site-specific crash history is that the benefit estimate may better reflect local conditions.

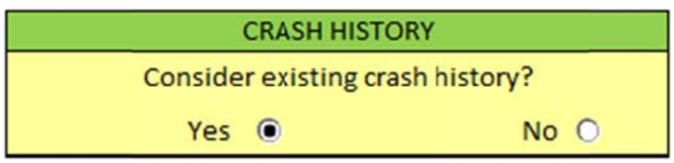


Figure A-29. Crash History Option Data Entry Form for Rural Four-Lane Highways

- **Consider existing crash history?:** Select the "Yes" option if you want to use the crash history for the roadway section. Otherwise, select "No."

CRASH DATA	
Crash History Period (yrs)	3
Total Fatal-and-Injury Crashes	1
Total Property-Damage-Only Crashes	10

Figure A-30. Crash Data Entry Form for Rural Four-Lane Highways

The *Crash Data* entry form shown in Figure A-30 will appear when "Yes" is selected for the consideration of existing crash history.

- **Crash History Period:** Enter the number of years of available crash data.
- **Total Fatal-and-Injury Crashes:** Enter the total number of crashes on the roadway segment that fall into the following crash severity levels:

  - Fatal crash
  - Disabling injury crash
  - Evident injury crash
  - Possible injury crash

- **Total Property-Damage-Only Crashes:** Enter the total number of crashes on the roadway segment that fall into the property-damage-only crash severity level.

A.2.3 Alternatives to Consider

Near the bottom of the R4UD_Project worksheet is a table in which to specify which alternatives should be considered in the benefit-cost analysis (see Figure A-31). Check the appropriate checkboxes to select the appropriate improvement alternatives to consider in the analysis.

Alternatives to Consider	Consider for Improvement	User Selection	Value Selected
Lane Width (ft)			Retain Lane Width
Shoulder Width (ft)			Retain Shoulder Width
Shoulder Type			Paved Shoulder
Roadside Slope			Retain Roadside Slope
Centerline Rumble Strip			Retain Centerline Rumble Strip
Shoulder Rumble Strip			Not Selected
Enhanced Striping/Delineation			Not Selected

Figure A-31. Data Entry Form to Select Alternatives to Consider for Rural Four-Lane Highways

Each potential improvement alternative is described in more detail below.

- **Lane Width:** If you have checked the Lane Width box, select the width to which the through travel lanes will be widened from the choices offered on the dropdown menu in the *User Selection* column. Only values greater than the existing lane width can be selected, up to a maximum lane width of 12 ft.
- **Shoulder Width:** If you have checked the Shoulder Width box, select the width to which the shoulders will be widened from the choices offered on the dropdown menu in the *User Selection* column. Only values greater than the existing shoulder width can be selected, up to a maximum shoulder width of 8 ft.

- **Shoulder Type:** If you have checked the Shoulder Type box, select the improved shoulder type from the dropdown menu in the *User Selection* menu. A paved shoulder is the only available option, and this option is only applicable if the existing shoulder is unpaved.
- **Roadside Slope:** If you have checked the Roadside Slope box, select the improved roadside slope from the dropdown menu in the *User Selection* column. Only slopes flatter than the existing roadside slope can be selected. The flattest slope that may be considered is 1V:6H.
- **Centerline Rumble Strip:** If you have checked the Centerline Rumble Strip box, no further data entry is necessary. Installation of a centerline rumble strip along the entire length of the roadway section will be considered. Note that if a centerline rumble strip already exists on the roadway section, checking the centerline rumble strip box will have no effect. In this case, the cost of installing the rumble strip after repaving will automatically be added into the project cost of the 3R project. This option is considered for four-lane undivided highways only.
- **Shoulder Rumble Strip:** If you have checked the Shoulder Rumble Strip box, no further data entry is necessary. Installation of a shoulder rumble strip along the entire length of the outside shoulders on both sides of the roadway section (and the inside shoulders on divided roadways) will be considered. Note that if a shoulder rumble strip already exists on the roadway section, checking the shoulder rumble strip box will have no effect. In this case, the cost of installing the rumble strip after repaving will automatically be added into the project cost of the 3R project.
- **Enhanced Striping/Delineation:** If you have checked the Enhanced Striping/Delineation box, installation of durable pavement markings will be considered for both centerline and edge striping as well as installing roadside delineators. The data entry table shown in Figure A-15 will appear if you select this option.

ENHANCED PAVEMENT MARKING AND DELINEATION DATA	
Total Length of Section with Delineator Posts (mi)	6.400 mi

Figure A-32. Enhanced Pavement Marking and Delineation Data for Rural Four-Lane Highways

- **Total Length of Section with Delineator Posts:** Enter the length of the roadway section in miles that will have roadside delineator posts. Include both sides of the roadway separately (i.e. enter 2 mi if a 1-mi roadway section has roadside delineators on both sides of the roadway.

A.2.4 Results

The results of the economic analysis are shown in the Results table at the top of the R4UD_Project worksheet (see Figure A-33).

RESULTS	Calculated	User Supplied	Value Used
PV MODIFIED TOTAL COST ($)*	$242,484		$242,484

*total cost minus milling and resurfacing cost for existing traveled way

ANNUAL SAFETY BENEFIT ($)	$27,225	BENEFIT-COST RATIO	1.189
PRESENT VALUE OF SAFETY BENEFIT ($)	$288,421	NET BENEFIT ($)	$45,936

Figure A-33. Results of Benefit-Cost Analysis for Rural Four-Lane Highways

The Results table presents the following information:

- **PV Modified Total Cost:**
  - *Calculated:* The present value of the modified total project cost is shown in this cell. The modified total cost is the total project cost not including the cost of milling and resurfacing the existing traveled way.
  - *User Supplied:* You can supply your own total project cost in this cell. Click the option button in this cell for the tool to use this user-supplied total cost in place of the value calculated by the tool.
- **Annual Safety Benefit:** This is the calculated annual crash savings in dollars that is estimated to result from the selected 3R project roadway improvements (other than milling and resurfacing which will be implemented whether or not the other improvements are made).
- **Present Value of Safety Benefit:** This is the present value of the annual crash savings over the service life of the roadway improvements.
- **Benefit-Cost Ratio:** The benefit-cost ratio is the ratio of the present value of safety benefit divided by the present value of the modified total cost.
- **Net Benefit:** The net benefit is the present value of safety benefit minus the present value of the modified total cost.

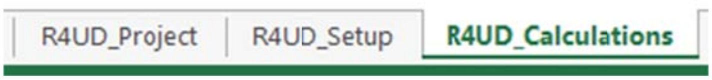
The annual number of crashes predicted before and after the 3R project, along with the annualized crash reductions, are shown to the right of the Results table (see Figure A-34).

Before FI Crashes	2.157 crashes/yr
Before PDO Crashes	4.564 crashes/yr
After FI Crashes	2.053 crashes/yr
After PDO Crashes	4.343 crashes/yr
Reduced FI Crashes	0.104 crashes/yr
Reduced PDO Crashes	0.220 crashes/yr

Figure A-34. Crash Frequencies Before and After 3R Project for Rural Four-Lane Highways

A.2.5 View Calculations

You may access the R4UD_Calculations worksheet to review all of the intermediate values calculated in assessing the benefits and costs of the project. This is a read-only worksheet that enables you to review the calculations, but does not allow you to change any results.



A.3 Freeways

This section presents the application of Tool 1 to candidate 3R projects on rural and urban freeways. These procedures can be applied to rural freeways with four, six, and eight through lanes, and to urban freeways with four, six, eight, and ten through lanes. The guidance addresses setup defaults (which can be either accepted unchanged or modified by the user), data entry for existing conditions on a specific roadway, specifying the alternative(s) to be considered, reviewing analysis results, and reviewing calculations.

A.3.1 Setup Defaults

Before performing any benefit-cost analyses, first visit the FWY_Setup worksheet.

The purpose of the FWY_Setup worksheet is to establish default values for assessment of 3R projects on freeways. The FWY_Setup worksheet contains default values for all non-site-specific data elements needed by Tool 1 to perform the benefit-cost calculations. Thus, you can perform analyses without changing any values in the FWY_Setup worksheet. However, you have the option to modify any of the default values to other values that are consistent with your agency's policies, practices, and experience. To change a default value, enter your value into the cell in the

User Supplied column and click the option button in that cell. This user-supplied value will appear in the *Values Used* column as a replacement for the default value that was initially shown.

Each of the data elements on the FWY_Setup worksheet is described in the following sections.

A.3.1.1 Road Elements

Figure A-35 shows a screenshot of the road element defaults. Each item in the figure is discussed below.

ROAD ELEMENTS		Default	User Supplied	Values Used
Average Embankment Height (ft) by Terrain	Level	2.5 ft	3.0 ft	2.5 ft
	Rolling	3.0 ft	4.5 ft	3.0 ft
	Mountainous	4.5 ft	6.0 ft	4.5 ft
Existing Base Depth (in)	Traveled-way	8.0 in	7.0 in	8.0 in
	Shoulder	8.0 in	7.0 in	8.0 in
Milling Depth (in), Flexible Pavement	Traveled-way	2.0 in	3.0 in	2.0 in
	Shoulder	2.0 in		2.0 in
Pavement Depth (in), Flexible Pavement	Traveled-way	5.0 in	6.0 in	5.0 in
	Shoulder	5.0 in	4.0 in	5.0 in

Figure A-35. Data Entry Form for Road Element Defaults for Freeways

- **Average Embankment Height:** Average representation of the embankment height of the roadway cross section in feet for level, rolling, and mountainous terrain.
- **Existing Base Depth:** Depth in inches of base material in inches underneath the traveled-way and shoulder.
- **Milling Depth:** Depth in inches to which flexible pavement of traveled-way and shoulder will be milled as part of pavement resurfacing. This applies only to flexible pavement.
- **Pavement Depth:** Depth in inches of flexible pavement for traveled-way and shoulder. This applies only to flexible pavement.

A.3.1.2 Cost Elements

Figure A-36 through Figure A-40 show the cost element defaults for freeways. Each element is discussed in detail below the figures. All costs are in dollars.

COST ELEMENTS		Default	User Supplied	Values Used
Base Unit Cost	$/CY	$ 10.00 ◉	$ 12.50 ○	$ 10.00
Milling Unit Cost	$/SY	$ 2.00 ◉	$ 2.70 ○	$ 2.00
Flexible Pavement Unit Cost	$/CY	$ 55.00 ◉	○	$ 55.00
Rigid Pavement Unit Cost	$/SY	$ 40.00 ◉	○	$ 40.00
Embankment Unit Cost	$/CY	$ 8.00 ◉	$ 7.00 ○	$ 8.00
Right-of-way Unit Cost ($/acre)	Rural 4-Lane Freeway	$ 25,000 ◉	$ 50,000 ○	$ 25,000
	Rural 6-Lane Freeway	$ 50,000 ◉	○	$ 50,000
	Rural 8-Lane Freeway	$ 50,000 ◉	○	$ 50,000
	Urban 4-Lane Freeway	$ 100,000 ◉	○	$ 100,000
	Urban 6-Lane Freeway	$ 250,000 ◉	○	$ 250,000
	Urban 8-Lane Freeway	$ 500,000 ◉	○	$ 500,000
	Urban 10-Lane Freeway	$ 500,000 ◉	○	$ 500,000

Figure A-36. Data Entry Form for Cost Element Defaults for Freeways, Part 1 of 5

- **Base Unit Cost:** Cost of base material per cubic yard.
- **Milling Unit Cost:** Cost of pavement milling per square yard.
- **Flexible Pavement Unit Cost:** Material and installation cost of flexible pavement per cubic yard.
- **Rigid Pavement Unit Cost:** Material and installation cost of rigid pavement per square yard.
- **Unpaved Shoulder Unit Cost:** Material and installation cost of unpaved shoulder per square yard.
- **Embankment Unit Cost:** Cost of embankment material per cubic yard.
- **Right-of-way Unit Cost:** Cost of acquiring right-of-way per acre for each freeway type.

Shoulder Rumble Strip Unit Cost	$/LF (both sides of road included)	$ 0.40 ◉	$ 0.45 ○	$ 0.40
Guardrail Unit Cost	$/LF	$ 40.00 ◉	○	$ 40.00
Cable Barrier Unit Cost	$/LF	$ 15.00 ◉	○	$ 15.00
Concrete Barrier Unit Cost	$/LF	$ 165.00 ◉	○	$ 165.00
Guardrail Removal Unit Cost	$/LF	$ 2.00 ◉	○	$ 2.00
Cable Barrier Removal Unit Cost	$/LF	$ 1.50 ◉	○	$ 1.50
Concrete Barrier Removal Unit Cost	$/LF	$ 10.00 ◉	○	$ 10.00

Figure A-37. Data Entry Form for Cost Element Defaults for Freeways, Part 2 of 5

- **Shoulder Rumble Strip Unit Cost:** Cost per linear foot of installing a shoulder rumble strip.
- **Guardrail Unit Cost:** Cost per linear foot of installing a w-shape guardrail.
- **Cable Barrier Unit Cost:** Cost per linear foot of installing a cable barrier.
- **Concrete Barrier Unit Cost:** Cost per linear foot of installing a concrete barrier.
- **Guardrail Removal Unit Cost:** Cost per linear foot of removing a guardrail.
- **Cable Barrier Removal Unit Cost:** Cost per linear foot of removing a cable barrier.
- **Concrete Barrier Removal Unit Cost:** Cost per linear foot of removing a concrete barrier.

Incidentals (% of Total Project Cost w/o ROW Cost)	Rural 4-Lane Freeway			
	Drainage	0.9% ◉	○	0.9%
	Erosion Control	0.3% ◉	○	0.3%
	Traffic Control	8.0% ◉	○	8.0%
	Signing and PM	5.0% ◉	○	5.0%
	Lighting	0.0% ◉	○	0.0%
	Rural 6-Lane Freeway			
	Drainage	0.4% ◉	○	0.4%
	Erosion Control	0.3% ◉	○	0.3%
	Traffic Control	8.0% ◉	○	8.0%
	Signing and PM	6.0% ◉	○	6.0%
	Lighting	0.0% ◉	○	0.0%
	Rural 8-Lane Freeway			
	Drainage	0.4% ◉	○	0.4%
	Erosion Control	0.3% ◉	○	0.3%
	Traffic Control	8.0% ◉	○	8.0%
	Signing and PM	6.0% ◉	○	6.0%
	Lighting	0.0% ◉	○	0.0%

Figure A-38. Data Entry Form for Cost Element Defaults for Freeways, Part 3 of 5

Incidentals (% of Total Project Cost w/o ROW Cost)	**Urban 4-Lane Freeway**			
	Drainage	8.0% ◉	○	8.0%
	Erosion Control	0.4% ◉	○	0.4%
	Traffic Control	8.5% ◉	○	8.5%
	Signing and PM	7.0% ◉	○	7.0%
	Lighting	1.0% ◉	○	1.0%
	Urban 6-Lane Freeway			
	Drainage	7.0% ◉	○	7.0%
	Erosion Control	0.4% ◉	○	0.4%
	Traffic Control	9.0% ◉	○	9.0%
	Signing and PM	10.0% ◉	○	10.0%
	Lighting	1.0% ◉	○	1.0%
	Urban 8-Lane Freeway			
	Drainage	6.0% ◉	○	6.0%
	Erosion Control	0.5% ◉	○	0.5%
	Traffic Control	9.5% ◉	○	9.5%
	Signing and PM	10.0% ◉	○	10.0%
	Lighting	1.0% ◉	○	1.0%
	Urban 10-Lane Freeway			
	Drainage	6.0% ◉	○	6.0%
	Erosion Control	0.5% ◉	○	0.5%
	Traffic Control	9.5% ◉	○	9.5%
	Signing and PM	10.0% ◉	○	10.0%
	Lighting	1.0% ◉	○	1.0%

Figure A-39. Data Entry Form for Cost Element Defaults for Freeways, Part 4 of 5

- **Incidentals:** Each incidental cost is calculated as a percentage of the project total cost not including the right-of-way cost for each freeway type.
  - *Signing and PM:* Signing and pavement markings.

MARR/discount rate	%	7%		7%
Service Life (yrs)	Lane Widening Shoulder Widening	20 yrs	5 yrs	20 yrs
	Rumble Strip Install	20 yrs	5 yrs	20 yrs
	Guardrail Install	20 yrs	5 yrs	20 yrs
	Cable Barrier Install	20 yrs	20 yrs	20 yrs
	Concrete Barrier Install	20 yrs	10 yrs	20 yrs
Crash Cost by Severity ($/crash)	Fatal	$ 4,008,900		$ 4,008,900
	Disabling Injury	$ 216,000		$ 216,000
	Evident Injury	$ 79,000		$ 79,000
	Possible Injury	$ 44,900		$ 44,900
	Property Damage Only	$ 7,400		$ 7,400

Figure A-40. Data Entry Form for Cost Element Defaults for Freeways, Part 5 of 5

- **MARR/discount rate:** Minimum attractive rate of return (MARR) for analysis of 3R project investments. Federal guidelines suggest an MARR value at 7 percent. The MARR value is also referred to as discount rate.
- **Service Life:** Expected useful life or service life in years for the roadway improvement.
  - *Lane Widening:* Service life for widening of the traveled-way.
  - *Shoulder Widening:* Service life for widening of the shoulder adjacent to the traveled-way.
    - *NOTE:* Lane Widening and Shoulder Widening should always be assigned identical service lives.
  - *Rumble Strip Installation:* Service life of centerline and shoulder rumble strips.
  - *Guardrail Installation:* Service life of guardrails.
  - *Cable Barrier Installation:* Service life of cable barriers.
  - *Concrete Barrier Installation:* Service life of concrete barriers.
- **Crash Cost by Severity:** Societal crash costs by crash severity level. Crash severity levels are defined in a manner consistent with the HSM.
  - *Fatal:* Cost of a fatal crash.
  - *Disabling Injury:* Cost of a disabling injury crash.
  - *Evident Injury:* Cost of an evident injury crash.
  - *Possible Injury:* Cost of a possible injury crash.
  - *Property Damage Only:* Cost of a property damage only crash.

A.3.1.3 Safety Elements

Figure A-41 shows a screenshot of the safety element defaults for freeways. Each element is discussed in detail below.

The only safety defaults that can be modified for freeways are the calibration factors (see Figure A-41).

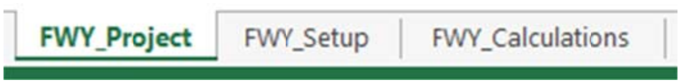
SAFETY ELEMENTS	Default	User Supplied	Values Used
Multi-vehicle FI SPF Calibration Factor	1.00 ◉	○	1.00
Multi-vehicle PDO SPF Calibration Factor	1.00 ◉	○	1.00
Single-vehicle FI SPF Calibration Factor	1.00 ◉	○	1.00
Single-vehicle PDO SPF Calibration Factor	1.00 ◉	○	1.00
SDF Calibration Factor	1.00 ◉	○	1.00

Figure A-41. Data Entry Form for Safety Element Defaults for Freeways

- **Calibration Factor:** This is a factor to adjust crash frequency estimates produced from the safety prediction procedure to approximate your local conditions. A default value of 1.0 is built into the tool.

A.3.2 Data Entry

After the setup defaults have been either retained or modified, as you wish, the tool is ready to perform benefit-cost analyses for freeways. Proceed to the FWY_Project worksheet.



Use the “FWY_Project” worksheet to enter all existing roadway attributes and select roadway improvements to consider in the benefit-cost analysis.

The following sections step through each input table in the FWY_Project worksheet.

A.3.2.1 Roadway Data

ROADWAY DATA	
Area Type	Urban
Section Length (mi)	2.000
AADT (veh/day)	85,000
Terrain	Level
Pavement Type	Rigid

Figure A-42. Roadway Data Entry Form for Freeways

- **Area Type:** Select either urban or rural from the dropdown menu for the area in which the freeway resides.
- **Section Length:** Length in miles of the roadway section in miles.
- **AADT:** Enter the average annual daily traffic in vehicles per day on the roadway section.
- **Terrain:** The terrain in which the roadway section is located.
- **Pavement Type:** Type of pavement of the roadway section, which is either flexible or rigid.

A.3.2.2 Alignment Data

The alignment data table shown in Figure A-43 addresses the method that will be used to describe horizontal curvature of the roadway section of interest. Use the option buttons in Figure A-43 to select either entry of average curve data or entry of specific curve data. Depending on which option button you select, different entry forms will appear on the worksheet.

ALIGNMENT DATA	
Enter average curve data	◉
Enter specific curve data	○

Figure A-43. Alignment Data Entry Option for Freeways

The following two figures show the data entry for average curve data (see Figure A-44) and specific curve data (see Figure A-45). Note that you will only see the entry form corresponding to the option that you chose for entering alignment data.

AVERAGE CURVE DATA	
% of Section Length on Curves	0.00%
Typical Curve Radius (ft)	3250 ft
Number of Curves on Section	0

Figure A-44. Average Curve Data Entry Form for Freeways

- **% of Section Length on Curves:** Enter the percent of the roadway section that is on horizontal curves. Include spiral transitions in the percentage if present.
- **Typical Curve Radius:** Enter the average horizontal curve radius of the roadway section.
- **Number of Curves on Section:** Enter the number of horizontal curves on the roadway section for both roadways of the freeway. For example, if a freeway section that has two horizontal curves in each direction of travel, then enter four in this cell.
- **Presence of Spiral Transitions:** If spiral transitions are present with the horizontal curves, use the dropdown in this cell to select “Yes”. Otherwise, select “No.”

SPECIFIC CURVE DATA		
Number of Curves in Roadway Section (enter curves separately for each roadbed)		3
Curve #	Curve Length in Segment (mi)	Curve Radius (ft)
1	0.250 mi	2200.00 ft
2	0.200 mi	2500.00 ft
3	0.150 mi	3000.00 ft

Figure A-45. Specific Curve Data Entry Form for Freeways

- **Number of Curves in Roadway Section:** Enter the total number of horizontal curves on the roadway section for both roadways of the freeway. For example, if a freeway section that has two horizontal curves in each direction of travel, then enter four in this cell. A maximum of 10 curves can be entered in the specific curve data form.
- You will need to enter the following data for each horizontal curve on the roadway section:
  - *Curve Length in Segment:* Enter the length in miles of the horizontal curve including spiral transitions.
  - *Curve Radius:* Enter the radius in feet of the horizontal curve.

A.3.2.3 Existing Cross Section Data

Use the Existing Cross Section data entry form shown in Figure A-46 to define the following features of the roadway section:

EXISTING CROSS SECTION	
Number of Through Lanes	6
Lane Width (ft)	11.0 ft
Outside Shoulder Width (ft)	6 ft
Inside Shoulder Width (ft)	4 ft
Outside Roadside Slope	1V:6H
Median Width (ft)	15.0 ft
Median Slope	1V:3H
Median Barrier	No Median Barrier
Outside Barrier	No
Clear Zone Width (ft)	10.0 ft
Inside Shoulder Rumble Strip	Yes
Outside Shoulder Rumble Strip	Yes
% of AADT during high volume	0.0%

Figure A-46. Existing Cross Section Data Entry Form for Freeways

- **Number of Through Lanes:** Select the total number of through lanes on the freeway segment (including both directions of travel).
- **Lane Width:** Select the existing lane width of the traveled way in feet from the dropdown menu.
- **Outside Shoulder Width:** Select the existing outside shoulder width in feet from the dropdown menu.
- **Inside Shoulder Width:** Select the existing inside shoulder width in feet from the dropdown menu.
- **Outside Roadside Slope:** Select the existing roadside foreslope from the dropdown menu.
- **Median Width:** Enter the median width in feet, which is measured from the leftmost edge of the traveled way to the leftmost edge of the traveled-way in the opposite direction.
- **Median Slope:** Select the median cross slope from the dropdown menu. Select “Flat” if there is not a depressed median.

- **Median Barrier:** Select the situation that best describes the presence of barriers in the median (for more detailed discussion of these options, see HSM Chapter 18):
  - *No Median Barrier:* Absolutely no barriers exist in the median.
  - *Continuous, Centered:* A median barrier exists in the center of the median and runs the entire length of the freeway segment.
  - *Continuous, Offset:* A median barrier runs the entire length of the freeway segment, but is not centered in the median.
  - *Discontinuous:* Median barriers do exist on the freeway segment, but are not continuous.
- **Outside Barrier:** Select "Yes" from the dropdown menu if there are traffic barriers along the outside or right side of the freeway segment. Otherwise, if there are no outside barriers, select "No."
- **Clear Zone Width:** Enter the width of the clear zone on the outside or right side of the freeway section in feet.
- **Inside Shoulder Rumble Strip:** Select "Yes" from the dropdown menu if rumble strips exist on the inside shoulders of the roadway section. Otherwise, select "No."
- **Outside Shoulder Rumble Strip:** Select "Yes" from the dropdown menu if rumble strips exist on the outside shoulders of the roadway section. Otherwise, select "No."
- **% of AADT during high volume periods:** proportion of AADT during hours in which the traffic volume exceeds 1,000 veh/h/lane.

A.3.2.4 Median Barriers

If you selected "Continuous, Centered", "Continuous, Offset" or "Discontinuous" from the Median Barrier dropdown menu in the Existing Cross Section form (see Figure A-46), a Median Barrier data entry form will appear (shown in Figure A-47). Use this entry form to enter data about the median barrier, as explained below:

MEDIAN BARRIER	
Number of discontinuous median barriers	2
Inside Barrier Width (ft)	1.00 ft
W(near)	10.0 ft
Cont. Median Barrier Type	Concrete Barrier

Figure A-47. Median Barrier Data Entry Form for Freeways

- **Number of discontinuous median barriers:** Enter the total number of discontinuous (stand-alone) median barrier segments on the freeway segment. Ten (10) is the maximum value. Do not count a continuous barrier in this number.

- **Inside Barrier Width:** Enter the width in feet of the continuous median barrier. This option only appears for continuous, centered and continuous, offset median barriers.
- **W(near):** Enter the distance in feet from the inside traveled-way edge closest to the offset barrier to the barrier face.
- **Cont. Median Barrier Type:** Select the continuous median barrier type from the dropdown menu. This option only appears for continuous, centered and continuous, offset median barriers.

If discontinuous median barriers are present on the freeway segment, then a data entry form will appear (see Figure A-48). Use this data entry form to enter data about the discontinuous median barriers, as explained below:

Offset Median Barrier	Length of Inside Barrier (mi)	Horizontal Clearance (ft)	Barrier Type
1	0.275 mi	5.00 ft	Concrete Barrier
2	0.225 mi	5.00 ft	Concrete Barrier

Figure A-48. Discontinuous Median Barrier Data Entry Form for Freeways

- *Length of Inside Barrier:* Enter the length in miles of the discontinuous median barrier.
- *Horizontal Clearance:* Enter the distance in feet between the leftmost edge of the traveled-way and the discontinuous median barrier face.
- *Barrier Type:* Select the discontinuous median barrier type from the dropdown menu.

A.3.2.5 Outside Barriers

If "Yes" was selected for the presence of outside barriers, the following data entry forms will appear (see Figure A-49 and Figure A-50).

OUTSIDE BARRIER	
Number of Outside Barriers	4

Figure A-49. Outside Barrier Data Entry Form for Freeways

- **Number of Outside Barriers:** Enter the number of outside barriers present on the freeway segment.

Outside Barrier	Length of Outside Barrier (mi)	Horizontal Clearance (ft)	Barrier Type
1	0.125 mi	5.0 ft	Guardrail
2	0.400 mi	8.0 ft	Cable Barrier
3	0.100 mi	6.0 ft	Concrete Barrier
4	0.100 mi	6.0 ft	Concrete Barrier

Figure A-50. Outside Barrier Detailed Data Entry Form for Freeways

- *Length of Outside Barrier:* Enter the length in miles of the outside barrier.
- *Horizontal Clearance:* Enter the distance in feet between the right-most edge of the traveled-way and the barrier face.
- *Barrier Type:* Select the barrier type from the embedded dropdown menu.

A.3.2.6 Crash History Option

At your option, you can choose to use the existing site-specific crash history of the roadway section to assist in calculating potential crash savings with the 3R project. Otherwise, you can simply use the estimate given by the HSM crash prediction method. The choice between these options is made in the form shown in Figure A-51. The advantage of using site-specific crash history is that the benefit estimate may better reflect local conditions.

CRASH HISTORY

Consider existing crash history?

Yes ◉ No ○

Figure A-51. Crash History Option Data Entry Form for Freeways

- **Consider existing crash history?:** Select the "Yes" option if you want to use the site-specific crash history for the roadway section. Otherwise, select "No."

The *Crash Data* entry form shown in Figure A-52 will appear when "Yes" is selected for the consideration of existing crash history.

CRASH DATA	
Crash History Period (yrs)	5
Total MV-FI Crashes	2
Total MV-PDO Crashes	5
Total SV-FI Crashes	2
Total SV-PDO Crashes	5

Figure A-52. Crash Data Entry Form for Freeways

- **Crash History Period:** Enter the number of years of available crash data.
- **Total MV-FI Crashes:** Enter the total number of multiple vehicle crashes on the roadway segment that fall into the following crash severity levels:
  - Fatal crash
  - Disabling injury crash
  - Evident injury crash
  - Possible injury crash
- **Total MV-PDO Crashes:** Enter the total number of multiple vehicle crashes on the roadway segment that fall into the property-damage-only crash severity level.
- **Total SV-FI Crashes:** Enter the total number of single vehicle crashes on the roadway segment that fall into the following crash severity levels:
  - Fatal crash
  - Disabling injury crash
  - Evident injury crash
  - Possible injury crash
- **Total SV-PDO Crashes:** Enter the total number of single vehicle crashes on the roadway segment that fall into the property-damage-only crash severity level.

A.3.3 Alternatives to Consider

Near the bottom of the FWY_Project worksheet is a table in which to specify which improvement alternatives should be considered in the benefit-cost analysis (see Table A-53). Check the checkboxes for alternatives to include in the analysis.

Alternatives to Consider	Consider for Improvement/ Modification	User Selection	Value Selected
Lane Width (ft)	☐		Retain Lane Width
Outside Shoulder Width (ft)	☐		Retain Outside Shoulder Width
Inside Shoulder Width (ft)	☐		Retain Inside Shoulder Width
Median Barrier	☐	Install Continuous Centered Barrier	No Change
Outside Barrier	☐		No Outside Barriers
Inside Rumble Strip	☐		Retain Inside Rumble Strip
Outside Rumble Strip	☐		Retain Outside Rumble Strip

Figure A-53. Data Entry Form to Select Alternatives to Consider for Freeways

Each alternative is described in more detail below.

- **Lane Width:** If you have checked the Lane Width box, select the width to which the through travel lanes should be widened from the choices offered on the dropdown menu in the *User Selection* column. Only values greater than the existing lane width can be selected, up to a maximum lane width of 12 ft.
- **Outside Shoulder Width:** If you have checked the Outside Shoulder Width box, select the width to which the outside shoulders should be widened from the choices offered on the dropdown menu in the *User Selection* column. Only values greater than the existing outside shoulder width can be selected, up to a maximum lane width of 12 ft.
- **Inside Shoulder Width:** If you have checked the Inside Shoulder Width box, select the width to which the inside shoulders should be widened from the choices offered on the dropdown menu in the *User Selection* column. Only values greater than the existing outside shoulder width can be selected, up to a maximum lane width of 12 ft.
- **Median Barrier:** If you have checked the Median Barrier box, select the details of the median barrier you want to consider adding (or modifying, in the case of existing discontinuous median barriers). See the following subsection on median barrier additions and modifications for further explanation.
- **Outside Barrier:** If you have checked the Outside Barrier box, the details of the outside barrier you want to consider adding (or modifying, in the case of existing outside barriers) will be specified in a later screen (see Section A.3.3.2).
- **Inside Rumble Strip:** If you have checked the Inside Rumble Strip box, no further data entry is necessary. Installation of a shoulder rumble strip along the entire length of the inside shoulders on both roadways will be considered. Note that if an inside rumble strip already exists on the roadway section, checking the inside rumble strip box will have no effect. In this case, the cost of installing the rumble strip after repaving will automatically be added into the project cost of the 3R project.

- **Outside Rumble Strip:** If you have checked the Outside Rumble Strip box, no further data entry is necessary. Installation of a shoulder rumble strip along the entire length of the outside shoulders on both roadways will be considered. Note that if an outside rumble strip already exists on the roadway section, checking the outside rumble strip box will have no effect. In this case, the cost of installing the rumble strip after repaving will automatically be added into the project cost of the 3R project.

A.3.3.1 Adding and Modifying Median Barriers

If you check the *Median Barrier* box on the data entry form in Figure A-53, select the option from the dropdown menu that best suits your project. Note that not all these options may be available, based on existing median barriers present on the freeway section.

- **Install Continuous Centered Barrier:** Select this option to install a continuous centered median barrier. This option will only appear when there is no existing continuous median barrier along the freeway.
- **Replace Offset with Centered Continuous Barrier:** Select this option to replace an existing continuous offset median barrier with a continuous centered median barrier. This option will only appear when there is an existing continuous offset median barrier along the freeway.
- **Install Continuous Offset Barrier:** Select this option to install a continuous offset median barrier. This option will only appear when there is no existing continuous median barrier along the freeway.
- **Only Add/Edit Discontinuous Barriers:** Select this option to add and/or modify existing discontinuous median barriers. This option will only appear if no existing continuous median barrier along the freeway.
- **Keep Continuous Barrier and Add/Edit Discontinuous Barriers:** Select this option to keep the existing continuous median barrier and add and/or modify existing discontinuous median barriers. This option will only appear if there is an existing continuous median barrier.

When the Median Barrier box is selected on the data entry form in Figure A-53, one or more data entry forms will appear below the entry form. First, go to the *Median Barrier Changes* data entry form (see Figure A-54). Depending on the option selected from the median barrier improvement/modification dropdown menu in the data entry form in Figure A-53, enter all necessary data in the *Median Barrier Changes* data entry form.

MEDIAN BARRIER CHANGES	
Number of discontinuous median barriers to add	1
Cont. Med. Barrier Width (ft)	1.00 ft
W(near)	8.0 ft
Cont. Median Barrier Type	Cable Barrier

Figure A-54. Median Barrier Additions Data Entry Form for Freeways

- **Number of discontinuous median barriers to add:** Enter the total number of discontinuous (stand-alone) median barriers that will be added on the freeway segment. Ten (10) is the maximum value. Do not count a continuous barrier in this number.
- **Inside Barrier Width:** Enter the width in feet of the new continuous median barrier. This option only appears for continuous, centered and continuous, offset median barriers.
- **W(near):** Enter the distance in feet from the inside traveled-way edge closest to the offset barrier to the barrier face.
- **Cont. Median Barrier Type:** Select the continuous median barrier type from the dropdown menu. This option only appears for continuous, centered and continuous, offset median barriers.

If discontinuous median barriers currently exist on the freeway section, and the median barrier improvement/modification check box is checked in Figure A-53, you have the opportunity to make modifications to the existing discontinuous median lengths in the data entry form that will appear (see Figure A-55).

Discontinuous Median Barrier	Length of Median Barrier (mi)	Horizontal Clearance (ft)	Edit Length of Median Barrier	New Length of Median Barrier (mi)	Auto Moved
1	0.275 mi	5.00 ft	No	0.000 mi	No
2	0.225 mi	5.00 ft	Yes	0.300 mi	No

Figure A-55. Existing Discontinuous Median Barrier Modifications Data Entry Form for Freeways

If you want to modify the length of the discontinuous median barrier, select “Yes” from the dropdown menu in the Edit Length of Median Barrier column of the table shown in Figure A-55. Enter the modified barrier length in the New Length of Median Barrier column. If the discontinuous median barrier had to be moved due to lane and/or inside shoulder widening, “Yes” will appear in the Auto Moved column. The cost of moving barriers is incorporated in the project cost estimate.

If you indicate that discontinuous median barriers will be added, a data entry form shown in Figure A-56 will open. Enter all necessary data in the form.

New Discontinuous Median Barrier	Length of Median Barrier (mi)	Horizontal Clearance (ft)	Barrier Type
1	0.200 mi	6.00 ft	Guardrail

Figure A-56. New Discontinuous Median Barrier Data Entry Form for Freeways

- *Length of Median Barrier:* Enter the length in miles of the discontinuous median barrier.
- *Horizontal Clearance:* Enter the distance in feet between the leftmost edge of the traveled way and the face of the discontinuous median barrier.
- *Barrier Type:* Select the type of discontinuous median barrier to be installed from the dropdown menu.

A.3.3.2 Adding and Modifying Outside Barriers

When the *Outside Barrier* checkbox is selected in Figure A-53, one or more data forms will appear below the form. First, go to the *Outside Barrier* data entry form (see Figure A-57). Indicate the number of outside barriers that will be added to the freeway section (maximum of 10). You may only want to modify existing outside barriers, so enter "0" for this entry and move onto the next entry form below.

OUTSIDE BARRIER	
Number of Outside Barriers to Add	1

Figure A-57. Outside Barrier Additions Data Entry Form for Freeways

If outside barriers currently exist on the freeway section, and the outside barrier improvement/modification check box is selected in Figure A-53, you have the opportunity to make modifications to the existing outside barrier lengths. If you want to modify the length of the outside barrier, select "Yes" from the embedded dropdown menu in the Edit Length of Outside Barrier column of the table shown in Figure A-58. Enter the modified length in the New Length of Outside Barrier column. If the outside barrier had to be moved due to lane and/or outside shoulder widening, "Yes" will appear in the *Auto Moved* column. The cost of moving barriers will be incorporated in the project cost estimate.

Outside Barrier	Length of Outside Barrier (mi)	Horizontal Clearance (ft)	Edit Length of Outside Barrier	New Length of Outside Barrier (mi)	Auto Moved
1	0.125 mi	5.0 ft	Yes	0.200 mi	No
2	0.400 mi	8.0 ft	No		No
3	0.100 mi	6.0 ft	No		No
4	0.100 mi	6.0 ft	No		No

Figure A-58. Existing Outside Barrier Modifications Data Entry Form for Freeways

If you indicate that outside barriers will be added, enter all necessary data in the user form shown in Figure A-59.

New Outside Barrier	Length of Outside Barrier (mi)	Horizontal Clearance (ft)	Barrier Type
1	0.250 mi	8.0 ft	Guardrail

Figure A-59. New Outside Barrier Data Entry Form for Freeways

- *Length of Outside Barrier:* Enter the length in miles of the outside barrier.
- *Horizontal Clearance:* Enter the distance in feet between the rightmost edge of the traveled way and the face of the barrier.
- *Barrier Type:* Select the barrier type from the dropdown menu.

A.3.4 Results

The results of the benefit-cost analysis are shown in the Results table at the top of the FWY_Project worksheet (see Figure A-60).

RESULTS	Calculated	User Supplied	Value Used
PV MODIFIED TOTAL COST ($)*	$242,484 ◉	○	$242,484
*total cost minus milling and resurfacing cost for existing traveled way			
ANNUAL SAFETY BENEFIT ($)	$27,225	BENEFIT-COST RATIO	1.189
PRESENT VALUE OF SAFETY BENEFIT ($)	$288,421	NET BENEFIT ($)	$45,936

Figure A-60. Results of Benefit-Cost Analysis for Freeways

The Results table presents the following:

- **PV Modified Total Cost:**
  - *Calculated:* The present value of the modified total project cost is shown in this cell. The modified total cost is the total project cost not including the cost of milling and resurfacing the existing traveled way.
  - *User Supplied:* You can supply your own total project cost in this cell. Click the option button in this cell for the tool to use this user-supplied total cost in place of the value calculated by the tool.

- **Annual Safety Benefit:** This is the calculated annual crash savings due to the selected 3R project roadway improvements (other than milling and resurfacing which will be implemented whether or not the other improvements are made).
- **Present Value of Safety Benefit:** This is the present value of the annual crash savings over the service life of the roadway improvements.
- **Benefit-Cost Ratio:** The benefit-cost ratio is the ratio of the present value of safety benefit divided by the present value of the modified total cost.
- **Net Benefit:** The net benefit is the present value of safety benefit minus the present value of the modified total cost.

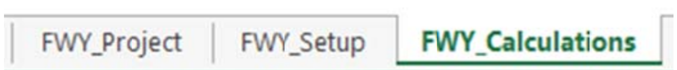
The annual number of crashes predicted before and after the 3R project, along with the annualized crash reductions, are shown to the right of the Results table (see Figure A-61).

Before FI Crashes	2.157 crashes/yr
Before PDO Crashes	4.564 crashes/yr
After FI Crashes	2.053 crashes/yr
After PDO Crashes	4.343 crashes/yr
Reduced FI Crashes	0.104 crashes/yr
Reduced PDO Crashes	0.220 crashes/yr

Figure A-61. Crash Frequencies Before and After 3R Project for Freeways

A.3.5 View Calculations

You may access the FWY_Calculations worksheet to review all of the intermediate values calculated in assessing the benefits and costs of the project. This is a read-only worksheet that enables you to review the calculations, but does not allow you to change any results.



Appendix B.
Users Guide for Spreadsheet Tool 2

Spreadsheet Tool 2 is a spreadsheet-based benefit-cost analysis tool that can be used to assess the cost-effectiveness of specific improvement alternatives for implementation in conjunction with a 3R project. The tool helps highway agencies in making the decision as to whether the 3R project should consist of pavement resurfacing only or should also include geometric design improvements. Tool 2 has the capability to assess multiple improvement alternatives as a part of a single analysis and identify the most cost effective alternative (or combination of alternatives). By contrast, Tool 1 considers only one alternative (or combination of alternatives) at a time. Tool 2 can be applied as part of the planning process for 3R projects. If a specific project site has no observed crash patterns or no traffic operational needs that would justify a design improvement, then geometric design improvements are recommended for implementation as part of a 3R project only if it is anticipated that such improvements would be cost-effective. Tool 2 provides a capability to assess all feasible improvement alternatives (or combinations of alternatives) for a given set of improvement types (see below). Like Tool 1, Tool 2 addresses candidate 3R projects on rural two-lane highways, rural four-lane undivided and divided highways (nonfreeways), and rural and urban freeways. The tool does not address 3R projects on urban and suburban arterials (nonfreeways). An example of the application of Tool 2 is presented Section 5.7.4 of this guide.

The input data for Tool 2 include a description of the existing roadway conditions and selection of the improvement(s) to be assessed. The roadway characteristics input data for Tool 2 are essentially identical to the roadway characteristics input data for Tool 1. The tool considers a single set of AADT, terrain, and cross-section geometrics for the roadway between intersections within the candidate project being assessed. Variations in cross-section geometrics at intersections or on intersection approaches do not need to be considered in using the tool. Where there are minor variations in AADT on the project or in cross-section geometrics on the roadway between intersections within the project, use the average AADT and the most common cross-section geometrics as input to the tool. Thus, the tool can be applied even where the cross section throughout the project is not entirely homogeneous. Where there are major changes in cross-section geometrics on the roadway between intersections (e.g., half the project has 6-ft paved shoulders and half has 2-ft unpaved shoulders), the project can be broken into separate sections and each section analyzed separately. Breaking the project into separate sections for analysis is only appropriate where the differences in cross-section geometrics are substantial.

Tool 2 includes logic to estimate the implementation cost of the improvement alternatives evaluated; the cost estimation logic in Tool 2 is essentially equivalent to the cost estimation logic in Tool 1. The project costs are estimated from default values of unit construction costs that are built into the tool. An option is available to change these default unit costs to match a particular agency's experience or to replace the project cost estimated by the tool with the agency's own site-specific estimate. An option is available for any given analysis as to whether the cost of right-of-way acquisition is included in the project implementation cost estimate. Right-of-way costs can also be based on default values built into the tool, user-specific unit costs for right-of-way, or site-specific cost estimates made by the agency.

The safety performance of the roadway being analyzed and the safety benefits of improvement alternatives estimated in Tool 2 are based on the crash prediction procedures presented in Part C of the AASHTO *Highway Safety Manual* (HSM) including HSM Chapters 10, 11, and 18 (*2*,*3*). The tool analyzes roadway segment (i.e., nonintersection) crashes only. The HSM crash prediction procedures are applied first to predict the crash frequencies by severity level for the existing roadway based on safety performance functions (SPFs), crash modification factors (CMFs), and local calibration factors (if available). The crash reduction effectiveness of improvements is based on the CMFs presented in Section 4.4 of this guide. The local calibration factor is set equal to 1.0 by default, but may be replaced with an agency-specific value. An option is available to provide site-specific crash history data and apply the Empirical Bayes (EB) method for converted predicted crash frequencies to expected crash frequencies, using the procedures presented in the Appendix to HSM Part C (*2*). Crash costs by severity level are set by default to values built into the tool, but may be replaced with agency-specific values.

An option is available in Tool 2 to select which improvement alternatives (or combinations of alternatives) will be considered in the benefit-cost analysis. The improvement alternatives that may be considered include:

- Lane widening
- Shoulder widening (outside shoulder only on two-lane and four-lane nonfreeways; both outside and inside shoulders on freeways)
- Shoulder paving (nonfreeways only)
- Roadside slope flattening (two-lane and four-lane nonfreeways only)
- Centerline rumble strips (undivided highways only)
- Shoulder rumble strips (outside shoulder only on undivided roads; both outside and inside shoulders on divided nonfreeways and freeways)
- Enhanced striping/delineation (nonfreeways only)
- Add median barrier (freeways only)
- Improve/restore superelevation (nonfreeways only)

The results provided by Tool 2 for the analysis of any improvement alternative (or combination of alternatives include:

- Project implementation cost ($)
- Present value of safety benefit ($)
- Benefit-cost ratio (benefit divided by cost)
- Net benefit (benefit minus cost) ($)

The most cost-effective improvement alternative (or combination of alternatives) identified by Tool 2 is the alternative (or combination of alternatives) with the highest net benefit whose implementation cost is within the highway agency's available budget.

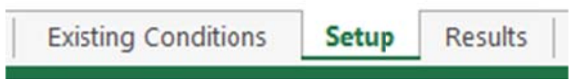
Because of its greater complexity, Tool 2 has most, but not all, of the capabilities of Tool 1 for allowing changes in default values. For example, in Tool 2, the SPF coefficients from the HSM cannot be changed.

Tool 2 has been developed in Microsoft Excel worksheets with supplementary Visual Basic programming. Since Tool 2 incorporates supplementary programming in Visual Basic, macros must be enabled on the user's computer for Tool 2 to function.

This users guide for Tool 2 in this appendix is organized differently than the users guide for Tool 1 in Appendix A because the structure of Tool 2 differs from Tool 1. This appendix begins with a guide to the setup defaults in Tool 2 for each roadway type. Then, data entry for existing roadway attributes are presented for each roadway type. Next, the selection of improvement alternatives to consider is presented for each roadway type. Finally, procedures for conducting the analysis and reviewing and interpreting the results are presented. These final procedures are the same for all roadway types.

B.1 Setup Defaults

Before preforming any benefit-cost analyses, first visit the Setup worksheet.



The purpose of the Setup worksheet is to establish default values for the assessment of 3R projects on all roadway types. The Setup worksheet contains default values for every non-site-specific data element needed by Tool 2 to perform benefit-cost calculations. You can perform analyses without changing any values in the Setup worksheet. However, you also have the option to modify any of the default values to other values that are consistent with your agency's policies, practices, or experience. You can view and edit any of the default values used in the benefit-cost analysis using the button panel at the top of the Setup worksheet, shown in Figure B-1.

Figure B-1. Button panel on Setup worksheet for Tool 2

The following subsections describe in detail how to modify default values for each roadway type, including rural two-lane highways; rural four-lane highways; and freeways.

B.1.1 Rural Two-Lane Highway Default Values

In the Setup worksheet, there is a panel of buttons at the top of the screen. Click the View/Edit Rural Two-Lane Defaults button. The window shown in Figure B-2 will then appear.

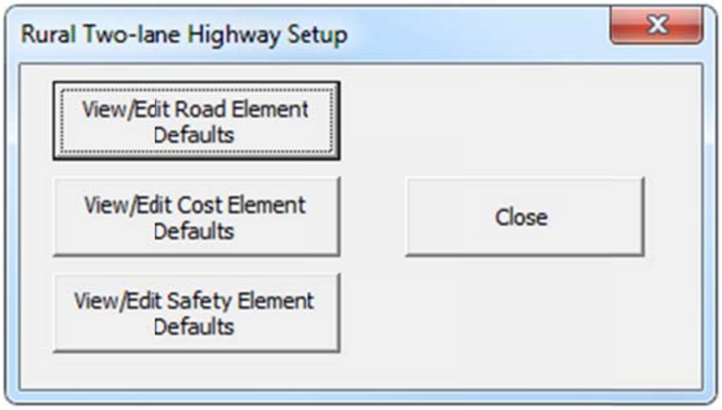


Figure B-2. Rural Two-Lane Highway Setup Window

The three buttons on the left allow you to view and edit road, cost, and safety data element defaults; these three buttons are discussed in detail in the following subsections. Click Close to exit the window and return to the Setup worksheet.

B.1.1.1 Road Elements

Click the View/Edit Road Element Defaults button in the Rural Two-lane Highway Setup window. The window shown in Figure B-3 will then appear.

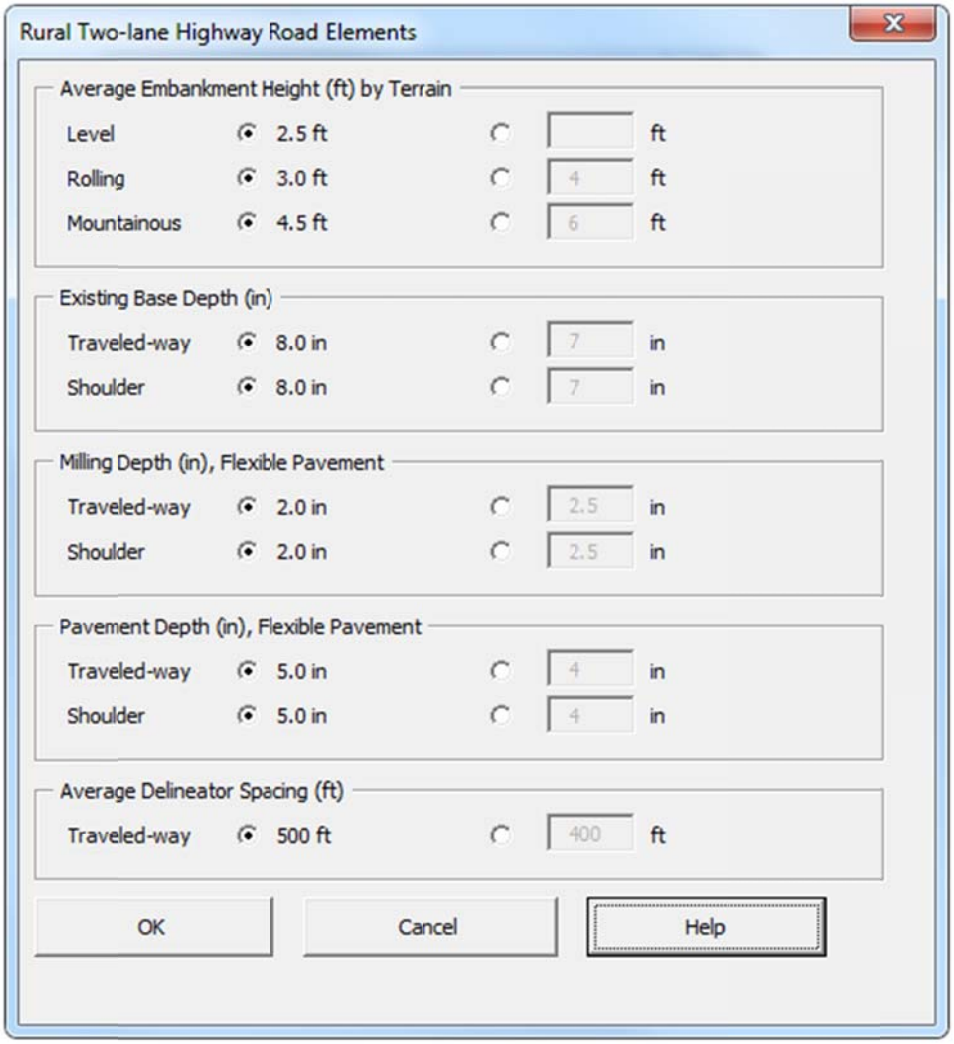


Figure B-3. Rural Two-Lane Highway Roadway Data Elements Window

Default values are provided for each element (e.g. 2.5 ft for level terrain). These defaults are always shown using the leftmost option button for each data element. You can, however, supply your own default value for any data element to be used in the analysis. To supply your own default value, click the rightmost option button for the data element of interest (see Figure B-4). Once the option button is selected, the text box adjacent to the option button will become active. Enter your revised default value in this text box. Any previous user-supplied default value will be shown in the text box for your convenience. Enter your revised default value in this text box.

Figure B-4. Typical default value selection for rural two-lane highways

Each road element is defined by the following:

- **Average Embankment Height:** Average embankment height in feet for level, rolling, and mountainous terrains.
- **Existing Base Depth:** Depth in inches of base material underneath the traveled-way and shoulder.
- **Milling Depth:** Depth in inches to which flexible pavement of traveled-way and shoulder will be milled. This data element applies only to flexible pavement.
- **Pavement Depth:** Depth of flexible pavement in inches for traveled way and shoulder. This data element applies only to flexible pavement.
- **Average Delineator Spacing:** Spacing between roadside delineators on average in feet.

Click the OK button to save any changes made to the rural two-lane highway road element defaults and return to the Rural Two-lane Highway Setup window.

Click the Close button to return to the Rural Two-lane Highway Setup window without saving any changes to the rural two-lane highway road element defaults.

B.1.1.2 Cost Elements

Click the View/Edit Cost Element Defaults button in the Rural Two-lane Highway Setup window. The window shown in Figure B-5 will appear.

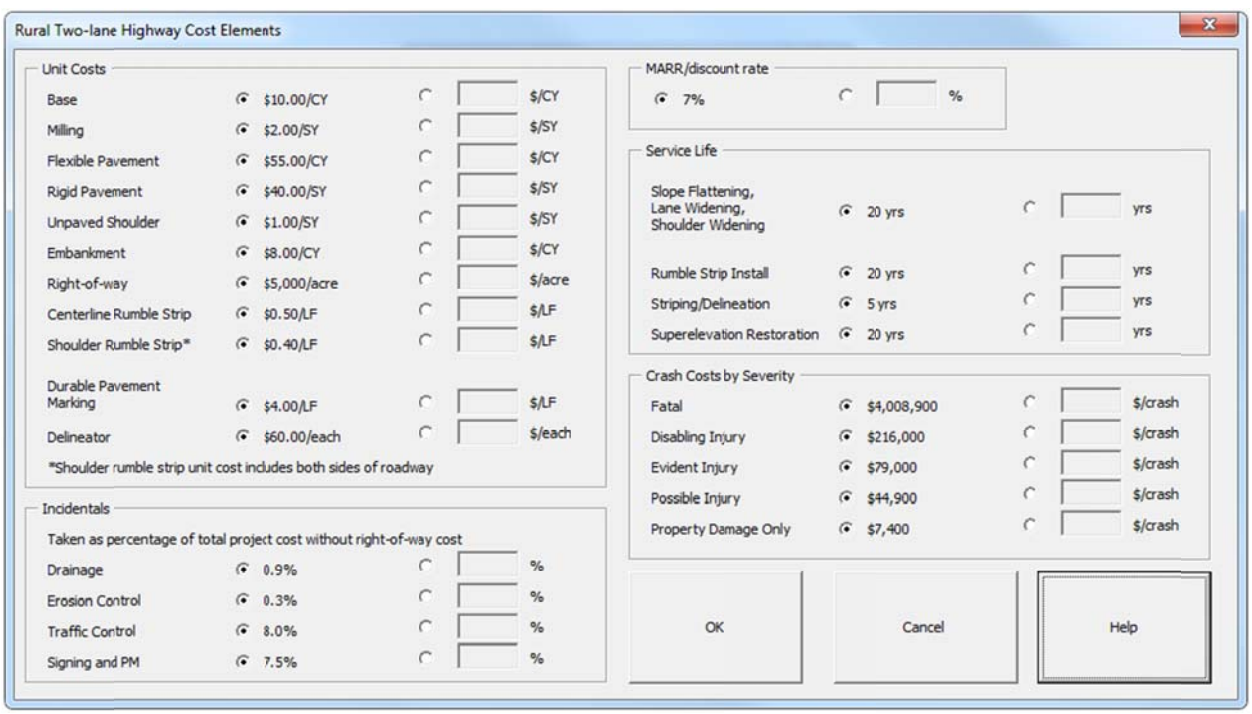


Figure B-5. Rural Two-lane Highway Cost Elements Window

Each cost data element is defined by the following:

- **Base:** Cost of base material per cubic yard.
- **Milling:** Cost of pavement milling per square yard.
- **Flexible Pavement:** Material and installation cost for flexible pavement per cubic yard.
- **Rigid Pavement:** Material and installation cost for rigid pavement per square yard.
- **Unpaved Shoulder:** Material and installation cost for unpaved shoulder per square yard.
- **Embankment:** Cost of embankment material per cubic yard.
- **Right-of-way:** Cost of acquiring right-of-way per acre.
- **Centerline Rumble Strip:** Cost per linear foot of installing a centerline rumble strip.
- **Shoulder Rumble Strip:** Cost per linear foot of installing a shoulder rumble strip.
- **Durable Pavement Marking:** Material and installation cost per linear foot for durable pavement markings.
- **Delineator:** Material and installation cost for one roadside delineator.
- **Incidentals:** Each incidental cost is calculated as a percentage of the total project cost not including the right-of-way cost.
  - *Signing and PM*: Signing and pavement markings.
- **MARR/discount rate:** Minimum attractive rate of return (MARR) for analysis of 3R project investments. Federal guidelines suggest an MARR value at 7 percent. The MARR is also referred to as discount rate.
- **Service Life (yr):** Expected lifetime of roadway improvement.
  - *Slope Flattening:* Service life of slope flattening, including flattening the roadside foreslope only.
  - *Lane Widening:* Service life for widening of the traveled-way.
  - *Shoulder Widening:* Service life for widening of the shoulder adjacent to the traveled-way.
    - *NOTE:* Slope Flattening, Lane Widening, and Shoulder Widening should always be assigned identical service lives.
  - *Rumble Strip Installation:* Service life of centerline and shoulder rumble strips.
  - *Striping/Delineation:* Service life of roadway striping and roadside delineators.
  - *Superelevation Restoration:* Service life of restoring or changing horizontal curve superelevation.

- **Crash Cost by Severity:** Societal crash costs by crash severity level. Crash severity levels are defined in a manner consistent with the HSM.
  - *Fatal:* Cost of a fatal crash.
  - *Disabling Injury:* Cost of a disabling injury crash.
  - *Evident Injury:* Cost of an evident injury crash.
  - *Possible Injury:* Cost of a possible injury crash.
  - *Property Damage Only:* Cost of a property damage only crash.

Click the OK button to save any changes made to the rural two-lane highway cost data element defaults and return to the Rural Two-Lane Highway Setup window.

Click the Close button to return to the Rural Two-Lane Highway Setup window without saving any changes to the rural two-lane highway cost data element defaults.

B.1.1.3 Safety Elements

Click the View/Edit Safety Element Defaults button in the Rural Two-Lane Highway Setup window. The window shown in Figure B-6 will appear.

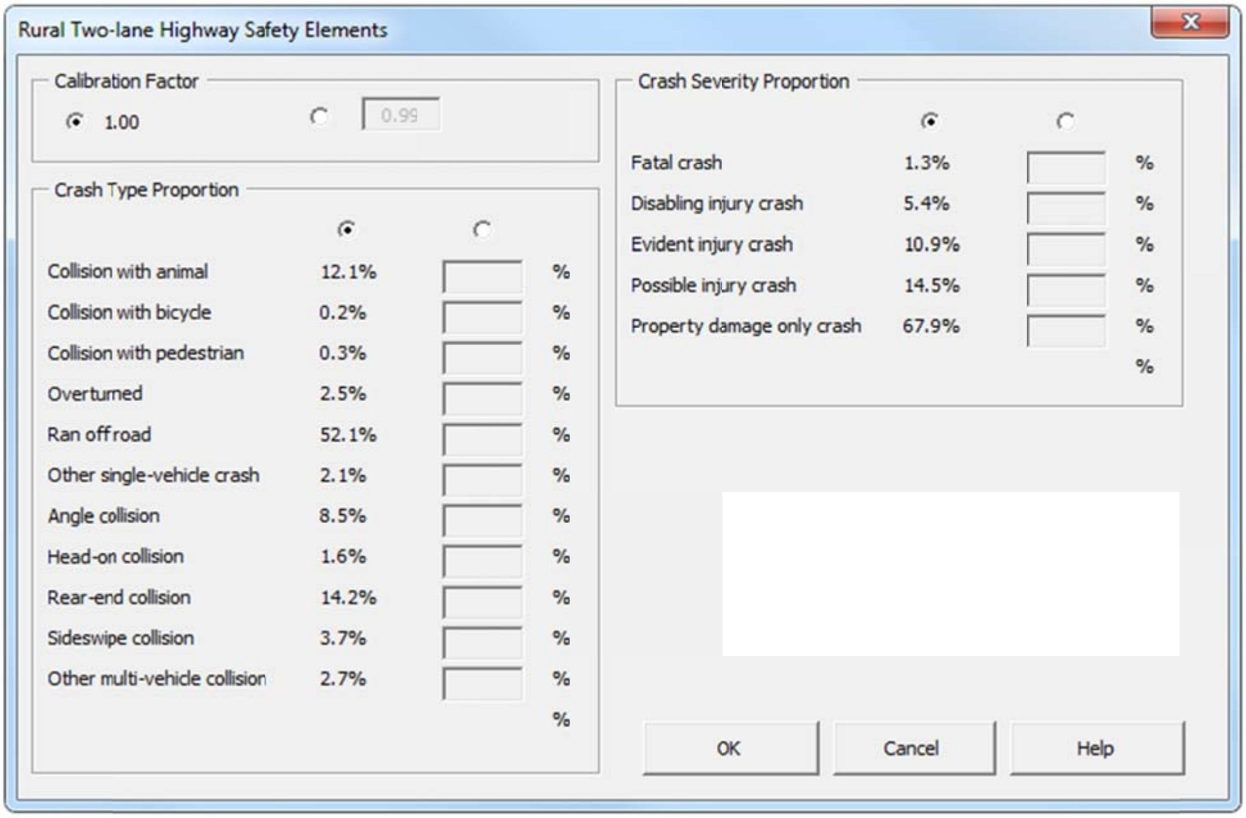


Figure B-6. Rural Two-Lane Highway Safety Elements Window

Each safety data element is defined by the following:

- **Calibration Factor:** This is a factor to adjust crash frequency estimates produced from the safety prediction procedure to approximate your local conditions. A default value of 1.0 is built into the tool.
- **Crash Type Proportions:** These are the percentage of all crashes for each crash type shown. Default values of these percentages from HSM Chapter 10 are built into the tool. You may also enter agency-specific values. All percentages must add to 100 percent. If the sum of all percentages is not equal to 100 percent, then an error message will be displayed. To assist the user, a sum is shown at the bottom of the window as you type in percentages (see Figure B-7).
- **Crash Severity Proportions:** These are the percentage of all crashes for each crash severity level. Default values of these percentages from HSM Chapter 10 are built into the tool. You may also enter agency-specific values. All percentages must add to 100 percent. If the sum of all percentages is not equal to 100 percent an error message will be displayed. While no figure is shown, the entry of crash severity proportions functions similarly to the crash type proportions illustrated in Figure B-7.

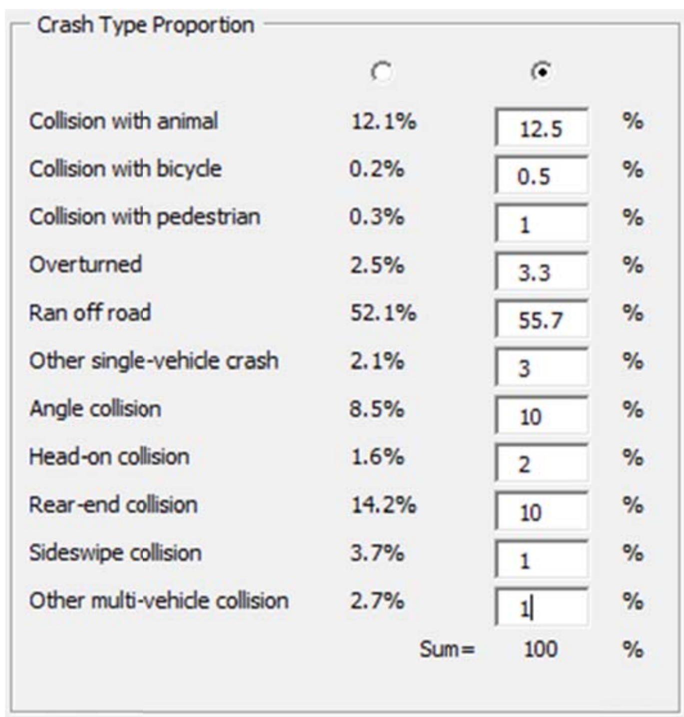


Figure B-7. Entering user-supplied proportions

There is no capability for changing the coefficients of the rural two-lane highway SPFs in Tool 2.

Click the OK button to save any changes made to the rural two-lane highway safety data element defaults and return to the Rural Two-Lane Highway Setup window.

Click the Close button to return to the Rural Two-Lane Highway Setup window without saving any changes to the rural two-lane highway safety data element defaults.

B.1.2 Rural Multilane Highway Defaults

All of the rural multilane highways considered in Tool 2 have four lanes, two-lanes in each direction of travel.

In the Setup worksheet, there is a panel of buttons at the top of the screen (see Figure B-1). Click the View/Edit Rural Multilane Defaults button. The window shown in Figure B-8 will appear.

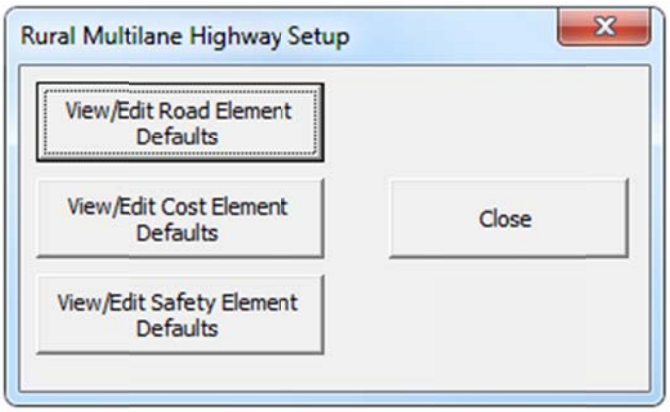


Figure B-8. Rural Multilane Highway Setup Window

The three buttons on the left allow you to view and edit road, cost, and safety data element defaults; these three buttons are discussed in detail in the following subsections. Click Close to exit the window and return to the Setup worksheet.

B.1.2.1 Road Elements

Click the View/Edit Road Element Defaults button in the Rural Multilane Highway Setup window. The window shown in Figure B-9 will appear.

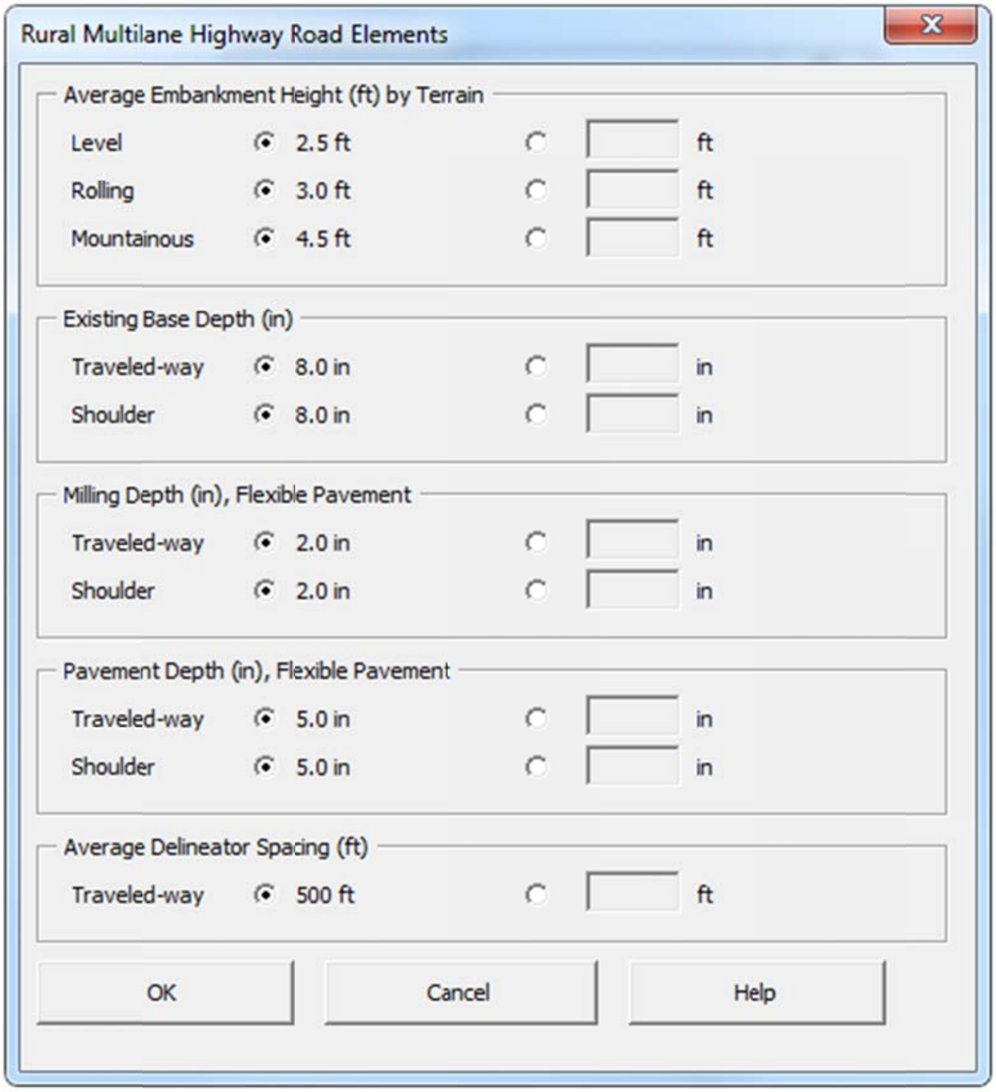


Figure B-9. Rural Multilane Highway Roadway Data Elements Window

Each road element is defined by the following:

- **Average Embankment Height:** Average embankment height in feet for level, rolling, and mountainous terrains.
- **Existing Base Depth:** Depth in inches of base material underneath the traveled way and shoulder.
- **Milling Depth:** Depth in inches to which flexible pavement of traveled way and shoulder will be milled. This data element applies only to flexible pavement.
- **Pavement Depth:** Depth in inches of flexible pavement for traveled way and shoulder. This data element applies only to flexible pavement.
- **Average Delineator Spacing:** Average spacing in feet between roadside delineators.

Click the OK button to save any changes made to the rural multilane highway road element defaults and return to the Rural Multilane Highway Setup window.

Click the Close button to return to the Rural Multilane Highway Setup window without saving any changes to the rural multilane highway road element defaults.

B.1.2.2 Cost Elements

Click the View/Edit Cost Element Defaults button in the Rural Multilane Highway Setup window. The window shown in Figure B-10 will appear.

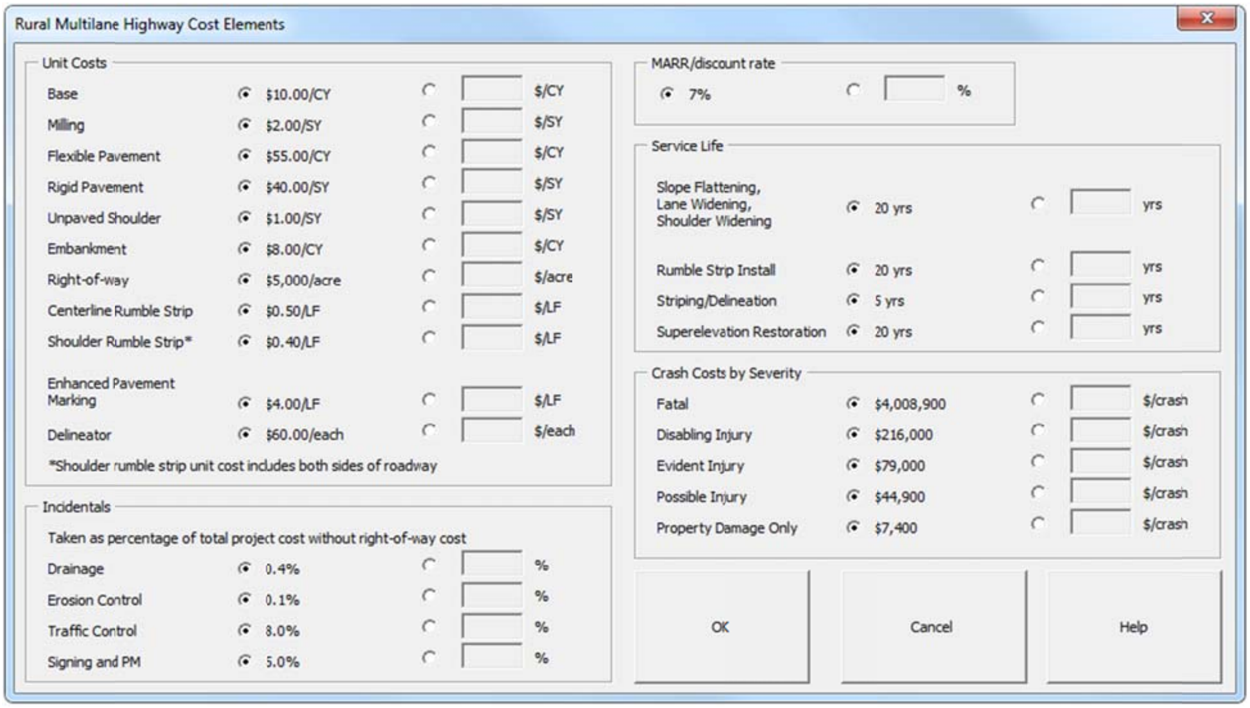


Figure B-10. Rural Multilane Highway Cost Elements Window

Each cost data element is defined by the following:

- **Base Unit Cost:** Cost of base material per cubic yard.
- **Milling Unit Cost:** Cost of pavement milling per square yard.
- **Flexible Pavement Unit Cost:** Material and installation cost of flexible pavement per cubic yard.
- **Rigid Pavement Unit Cost:** Material and installation cost of rigid pavement per square yard.
- **Unpaved Shoulder Unit Cost:** Material and installation cost of unpaved shoulder per square yard.
- **Embankment Unit Cost:** Cost of embankment material per cubic yard.

- **Right-of-way Unit Cost:** Cost of acquiring right-of-way per acre.
- **Centerline Rumble Strip Unit Cost:** Cost of installing a centerline rumble strip per linear foot. This value only applies to undivided rural multilane highways.
- **Shoulder Rumble Strip Unit Cost:** Cost per linear foot for installing a shoulder rumble strip.
- **Durable Pavement Marking Unit Cost:** Material and installation cost per linear foot for durable pavement markings.
- **Delineator Cost:** Material and installation cost for one roadside delineator.
- **Incidentals:** Each incidental cost is calculated as a percentage of the project total cost, not including the right-of-way cost.
    - *Signing and PM*: Signing and pavement markings.
- **MARR/discount rate:** Minimum attractive rate of return (MARR) for analysis of 3R project investments. Federal guidelines suggest an MARR value at 7 percent. The MARR is also referred to as discount rate.
- **Service Life:** Expected lifetime of roadway improvement.
    - *Slope Flattening:* Service life of slope flattening, including flattening the roadside foreslope only.
    - *Lane Widening:* Service life for widening of the traveled-way.
    - *Shoulder Widening:* Service life for widening of the shoulder adjacent to the traveled-way.
        - *NOTE:* Slope Flattening, Lane Widening, and Shoulder Widening should always be assigned identical service lives.
    - *Rumble Strip Installation:* Service life of centerline and shoulder rumble strips.
    - *Striping/Delineation:* Service life of roadway striping and roadside delineators.
    - *Superelevation Restoration:* Service life of restoring or changing horizontal curve superelevation.
- **Crash Cost by Severity:** Societal crash costs by crash severity level. Crash severity levels are defined in a manner consistent with the HSM.
    - *Fatal:* Cost of a fatal crash.
    - *Disabling Injury:* Cost of a disabling injury crash.
    - *Evident Injury:* Cost of an evident injury crash.
    - *Possible Injury:* Cost of a possible injury crash.
    - *Property Damage Only:* Cost of a property damage only crash.

Click the OK button to save any changes made to the rural multilane highway cost data element defaults and return to the Rural Multilane Highway Setup window.

Click the Close button to return to the Rural Multilane Highway Setup window without saving any changes to the rural multilane highway cost data element defaults.

B.1.2.3 Safety Elements

Click the View/Edit Safety Element Defaults button in the Rural Multilane Highway Setup window. The window shown in Figure B-11 will appear.

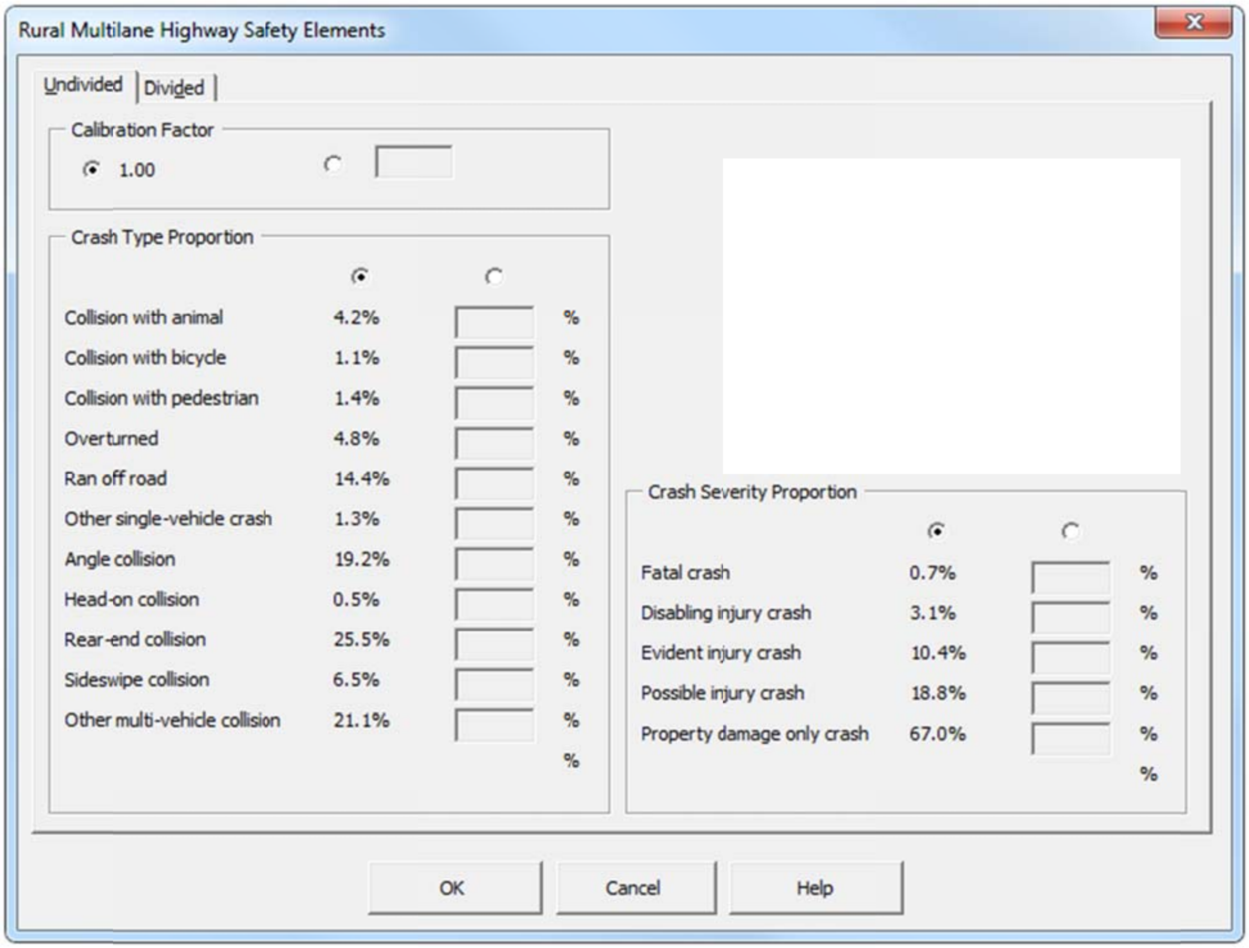


Figure B-11. Rural Multilane Highway Safety Elements Window

The safety data element defaults need to be selected for both undivided and divided multilane highways as shown in Figure B-12. Use the tabs at the top of the window to switch between undivided and divided multilane safety data element defaults.

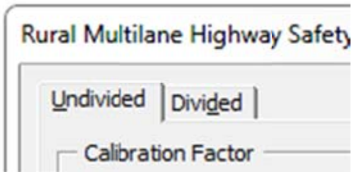


Figure B-12. Undivided and divided tabs for rural multilane highways

Each safety data element is defined by the following:

- **Calibration Factor:** This is a factor to adjust crash frequency estimates produced from the safety prediction procedure to approximate your local conditions. A default value of 1.0 is built into the tool.
- **Crash Type Proportions:** These are the percentage of all crashes for each crash type shown. Default values of these percentages from HSM Chapter 11 are built into the tool. You may also enter agency-specific values. All percentages must add to 100 percent. If the sum of all percentages is not equal to 100 percent, then an error message will be displayed. To assist the user, a sum is shown at the bottom of the window as you type in percentages (see Figure B-13).
- **Crash Severity Proportions:** These are the percentage of all crashes for each crash severity level. Default values of these percentages from HSM Chapter 11 are built into the tool. You may also enter agency-specific values. All percentages must add to 100 percent. If the sum of all percentages is not equal to 100 percent an error message will be displayed. While no figure is shown, the entry of crash severity proportions functions similarly to the crash type proportions illustrated in Figure B-13.

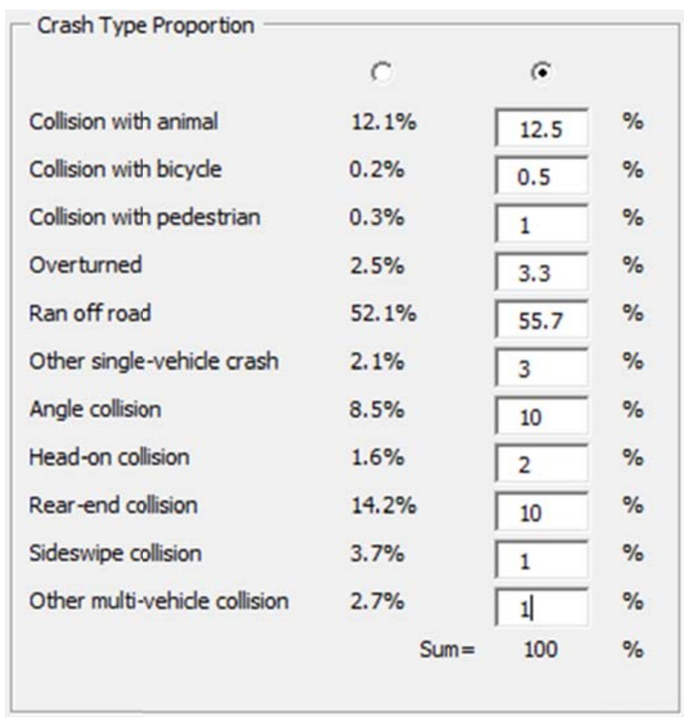


Figure B-13. Entering user-supplied proportions for rural multilane highways

There is no capability for changing the coefficients of rural multilane highway SPFs in Tool 2.

Click the OK button to save any changes made to the rural multilane highway safety data element defaults and return to the Rural Multilane Highway Setup window.

Click the Close button to return to the Rural Multilane Highway Setup window without saving any changes to the rural multilane highway safety data element defaults.

B.1.3 Freeway Defaults

In the Setup worksheet, there is a panel of buttons at the top of the screen (see Figure B-1). Click the View/Edit Freeway Defaults button. The window shown in Figure B-14 will appear.

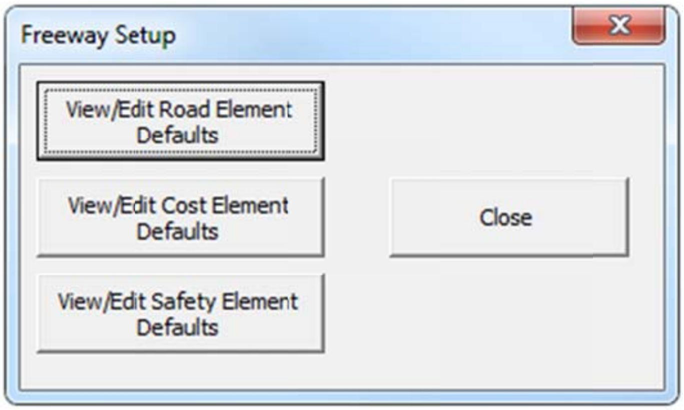


Figure B-14. Freeway Setup Window

The three buttons on the left allow you to view and edit road, cost, and safety data element defaults; these three buttons are discussed in detail in the following subsections. Click Close to exit the window and return to the Setup worksheet.

B.1.3.1 Road Elements

Click the View/Edit Road Element Defaults button in the Freeway Setup window. The window shown in Figure B-15 will appear.

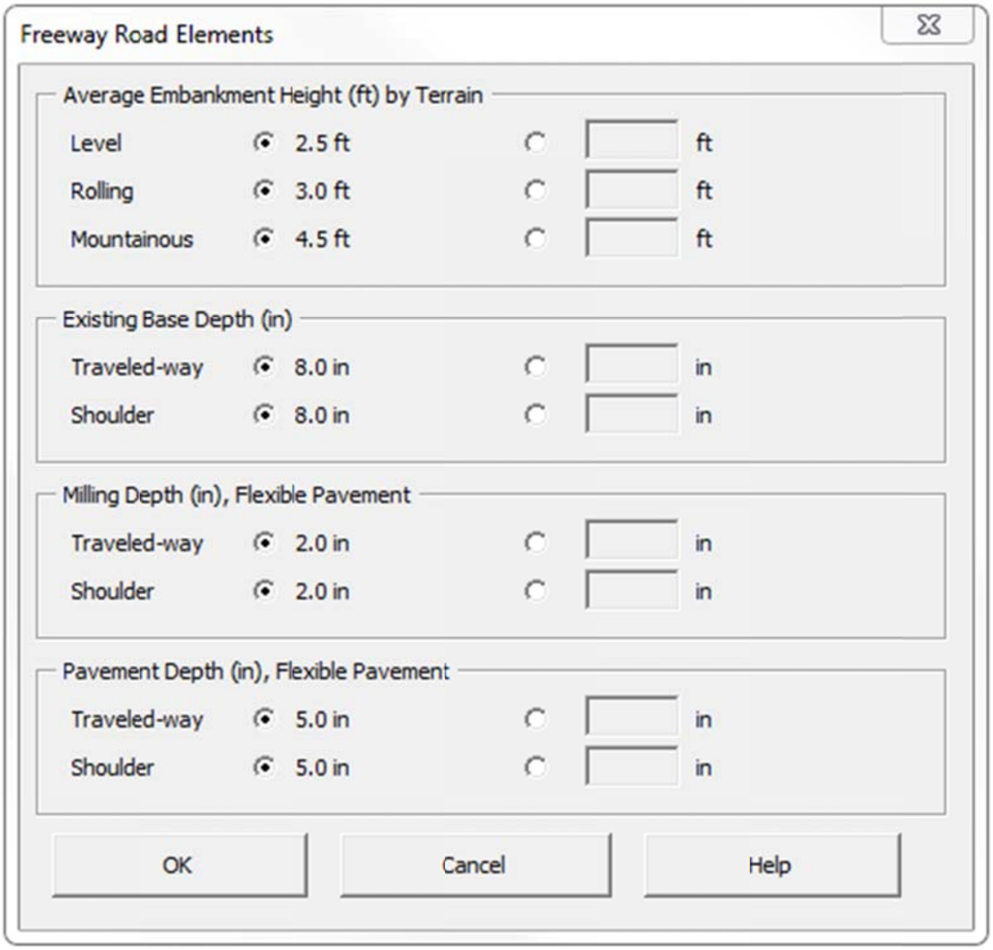


Figure B-15. Freeway Road Elements window

Each road element is defined by the following:

- **Average Embankment Height:** Average embankment height in feet for level, rolling, and mountainous terrains.
- **Existing Base Depth:** Depth of base material in inches underneath the traveled way and shoulder.
- **Milling Depth:** Depth in inches to which flexible pavement of traveled way and shoulder will be milled. This data element applies only to flexible pavement.
- **Pavement Depth:** Depth in inches of flexible pavement for traveled-way and shoulder. This data element applies only to flexible pavement.

Click the OK button to save any changes made to the freeway road element defaults and return to the Freeway Setup window.

Click the Close button to return to the Freeway Setup window without saving any changes to the freeway road element defaults.

B.1.3.2 Cost Elements

Click the View/Edit Cost Element Defaults button in the Freeway Setup window. The window shown in Figure B-16 will appear.

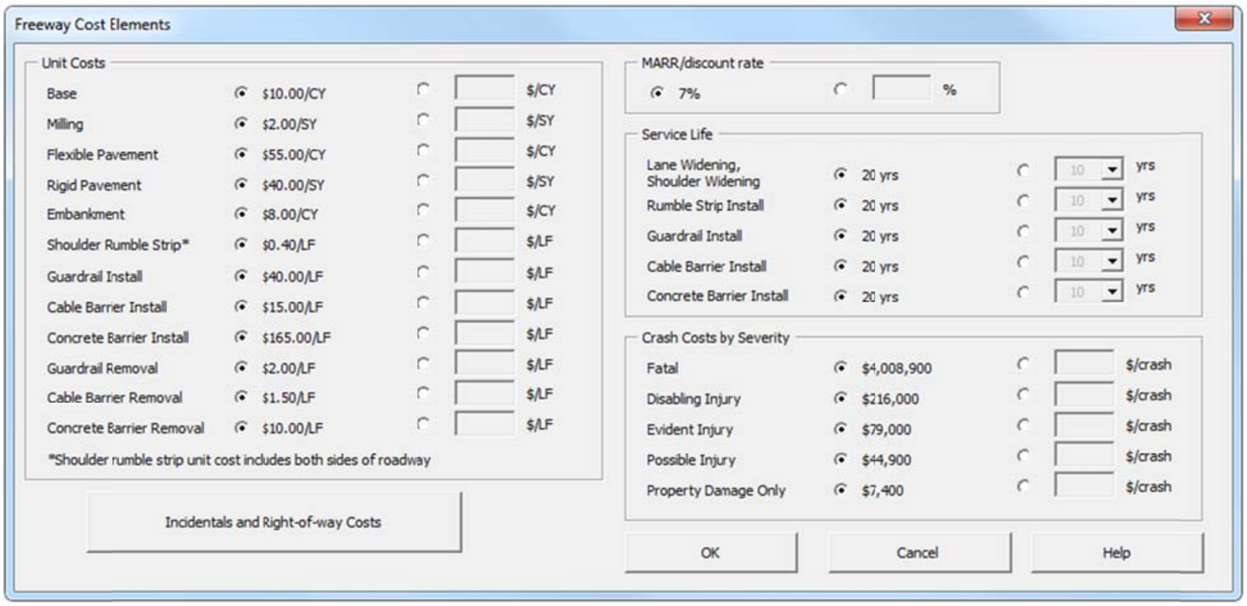


Figure B-16. Freeway Cost Elements window

Each cost data element is defined by the following:

- **Base Unit Cost:** Cost of base material per cubic yard.
- **Milling Unit Cost:** Cost of pavement milling per square yard.
- **Flexible Pavement Unit Cost:** Material and installation cost of flexible pavement per cubic yard.
- **Rigid Pavement Unit Cost:** Material and installation cost of rigid pavement per square yard.
- **Embankment Unit Cost:** Cost of embankment material per cubic yard.
- **Right-of-way Unit Cost:** Cost of acquiring right-of-way per acre for each freeway type.
- **Shoulder Rumble Strip Unit Cost:** Cost per linear foot for installing a shoulder rumble strip.
- **Guardrail Unit Cost:** Cost per linear foot for installing a W-shaped guardrail.
- **Cable Barrier Unit Cost:** Cost per linear foot for installing a cable barrier.
- **Concrete Barrier Unit Cost:** Cost per linear foot for installing a concrete barrier.
- **Guardrail Removal Unit Cost:** Cost per linear foot for removing a guardrail.

- **Cable Barrier Removal Unit Cost:** Cost per linear foot for removing a cable barrier.
- **Concrete Barrier Removal Unit Cost:** Cost per linear foot for removing a concrete barrier.
- **MARR/discount rate:** Minimum attractive rate of return (MARR) for analysis of 3R project investments. Federal guidelines suggest an MARR value at 7 percent. The MARR is also referred to as discount rate.
- **Service Life:** Expected lifetime of roadway improvement.
    - *Slope Flattening:* Service life of slope flattening, including flattening the roadside foreslope only.
    - *Lane Widening:* Service life for widening of the traveled-way.
    - *Shoulder Widening:* Service life for widening of the shoulder adjacent to the traveled-way.
        - *NOTE:* Slope Flattening, Lane Widening, and Shoulder Widening should always be assigned identical service lives.
    - *Rumble Strip Installation:* Service life of shoulder rumble strips.
    - *Guardrail Installation*: Service life of guardrails.
    - *Cable Barrier Installation*: Service life of cable barriers.
    - *Concrete Barrier Installation*: Service life of concrete barriers.
- **Crash Cost by Severity:** Societal crash costs by crash severity level. Crash severity levels are defined in a manner consistent with the HSM.
    - *Fatal:* Cost of a fatal crash.
    - *Disabling Injury:* Cost of a disabling injury crash.
    - *Evident Injury:* Cost of an evident injury crash.
    - *Possible Injury:* Cost of a possible injury crash.
    - *Property Damage Only:* Cost of a property damage only crash.

To set defaults for incidentals and right-of-way costs for freeways, click the Incidentals and Right-of-way Costs button in the Freeway Cost Elements window. The window shown in Figure B-17 will appear.

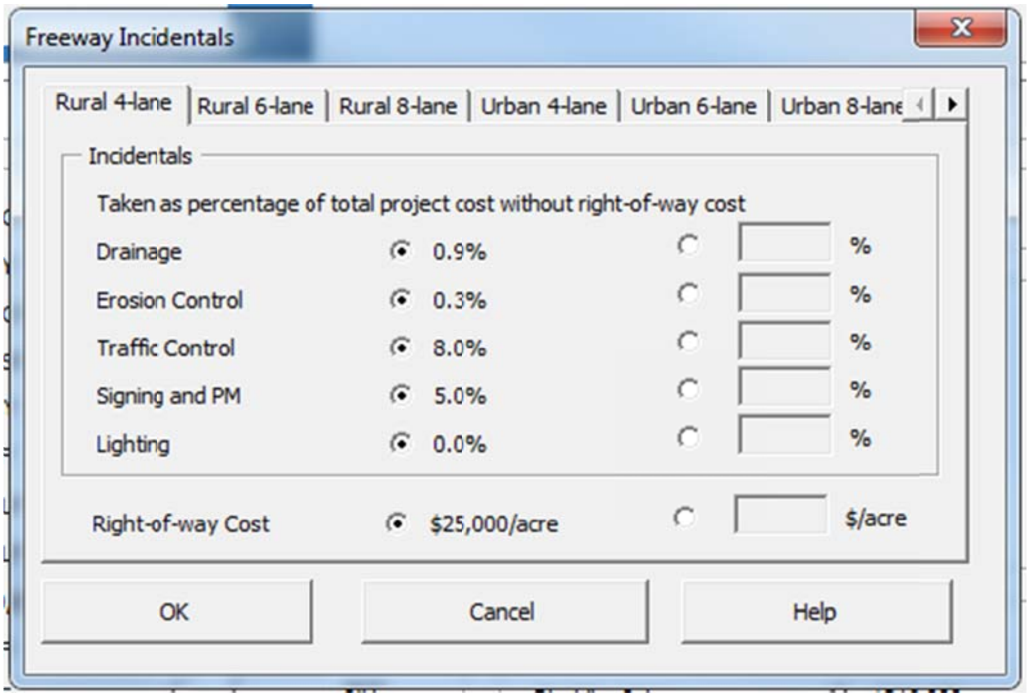


Figure B-17. Freeway Incidentals window

Freeway incidentals and right-of-way costs are defined for each freeway type. Use the tabs at the top of the window to toggle between different freeway types. These elements are defined below:

- **Incidentals:** Each incidental is calculated as a percentage of the project total cost not including the right-of-way cost for each freeway type.
  - *Signing and PM:* Signing and pavement markings.
- **Right-of-Way Unit Cost:** Cost of acquiring right-of-way per acre for each freeway type.

Click the OK button to save any changes made to the freeway cost data element defaults and return to the Freeway Setup window.

Click the Close button to return to the Freeway Setup window without saving any changes to freeway cost data element defaults.

B.1.3.3 Safety Elements

Click the View/Edit Safety Element Defaults button in the Freeway Setup window. The window shown in Figure B-18 will appear.

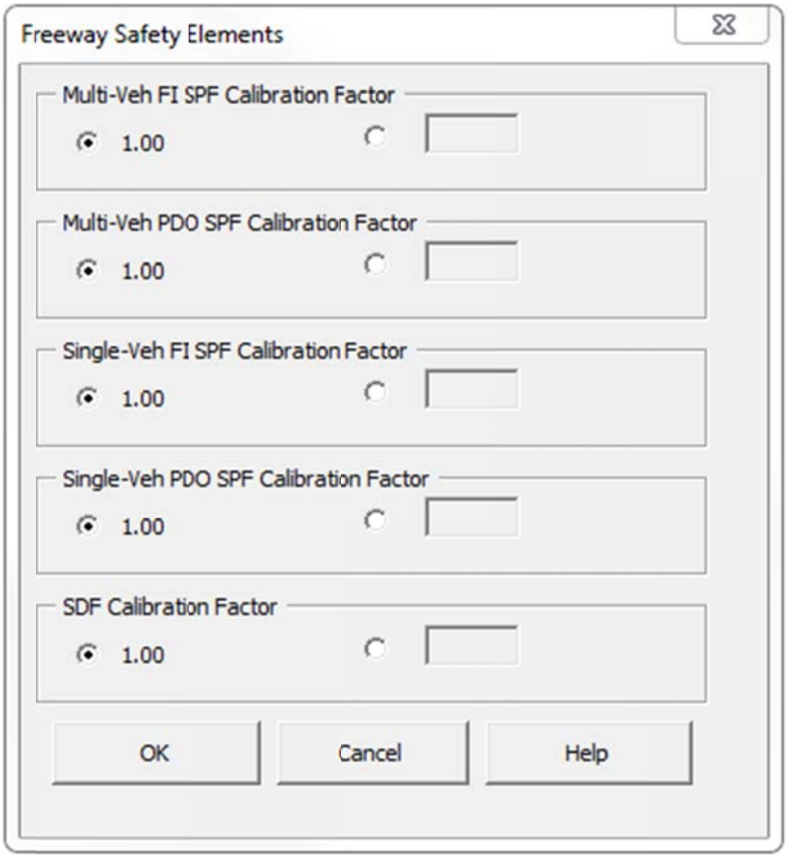


Figure B-18. Freeway Safety Elements window

Each safety data element is defined by the following:

- **Calibration Factor:** This is a factor to adjust crash frequency estimates produced from the safety prediction procedure to approximate your local conditions. A default value of 1.0 is built into the tool.

Click the OK button to save any changes made to the freeway safety data element defaults and return to the Freeway Setup window.

Click the Close button to return to the Freeway Setup window without saving any changes to the freeway safety data element defaults.

B.2 Existing Roadway Attributes

After the setup defaults have been either retained or modified, as you wish, the tool is ready to perform benefit-cost analyses. Proceed to the Existing Conditions worksheet.

There is a panel of buttons at the top of the Existing Conditions worksheet, shown in Figure B-19.

Figure B-19. Button Panel on Existing Conditions Worksheet for Tool 2

The following subsections discuss the function of these buttons in detail.

B.2.1 Start New Analysis

To start entering roadway data for a new analysis, click the Start New button. The window shown in Figure B-20 will appear.

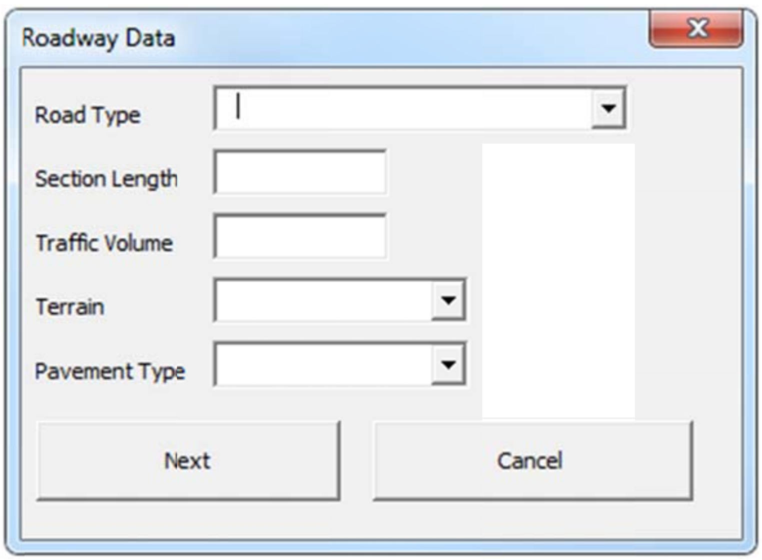


Figure B-20. Roadway Data entry form

- **Road Type:** Select rural two-lane highway, rural four-lane undivided highway, rural four-lane divided highway, rural freeway, or urban freeway to identify the area type and roadway type for the candidate 3R project site.
- **Section Length:** Enter the length of the roadway section in miles.
- **Traffic Volume:** Enter the average annual daily traffic on the roadway section in vehicles per day.

- **Terrain:** Select the terrain type in which the roadway section is located.
- **Pavement Type:** Select the type of pavement for the roadway section, either flexible or rigid.

Click Next when you are finished filling out all fields in the Roadway Data window.

Click Cancel to exit without saving.

When you click Next, a window will appear in which you should enter all applicable roadway segment attributes needed for the benefit-cost analysis. The windows that appear will differ for each roadway type. The following subsections explain the data entry for each roadway type.

B.2.1.1 Rural Two-Lane Highway Project Data

Enter all attributes about the roadway segment using the Rural Two-Lane Highway Project Data window. The window is composed of four different pages. Navigate between these pages by clicking on the tabs at the top of the window. Each page is discussed below.

First navigate to the Existing Cross Section tab shown in Figure B-21.

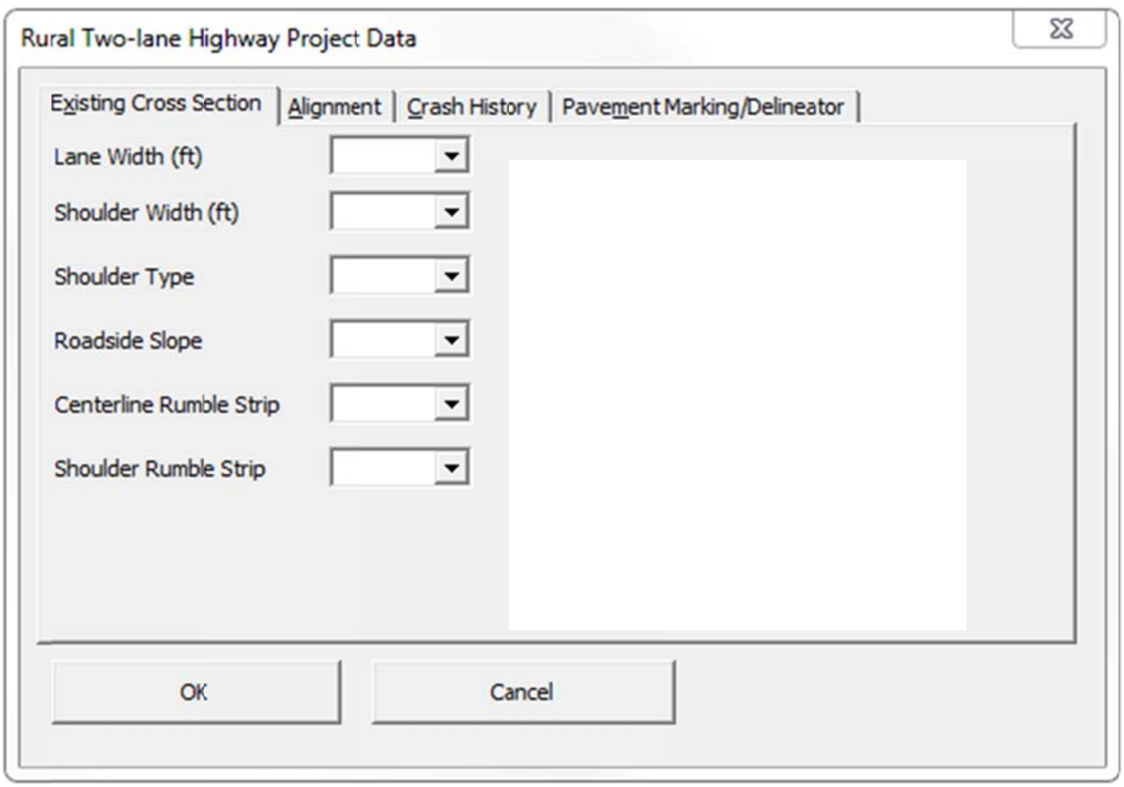


Figure B-21. Rural Two-lane Highway Project Data Window: Existing Cross Section Tab

- **Lane Width:** Select the existing lane width of the traveled way in feet.
- **Shoulder Width:** Select the existing shoulder width in feet.
- **Shoulder Type:** Select the existing shoulder type.
- **Roadside Slope:** Select the existing roadside foreslope.
- **Centerline Rumble Strip:** Select Yes from the dropdown menu if centerline rumble strips are present on the roadway section. Otherwise, select No.
- **Shoulder Rumble Strip:** Select Yes from the dropdown menu if shoulder rumble strips are present on the roadway section. Otherwise, select No.

Next, click on the Alignment tab.

Use the option buttons in Figure B-22 to select either entry of average curve data or entry of specific curve data. Depending on which option button you select, different text boxes and dropdown menus will appear in the window. Note that if you plan on considering superelevation improvement as part of your 3R project, you must enter specific curve data.

The window in Figure B-22 shows all data entry needed to use the average curve data entry option.

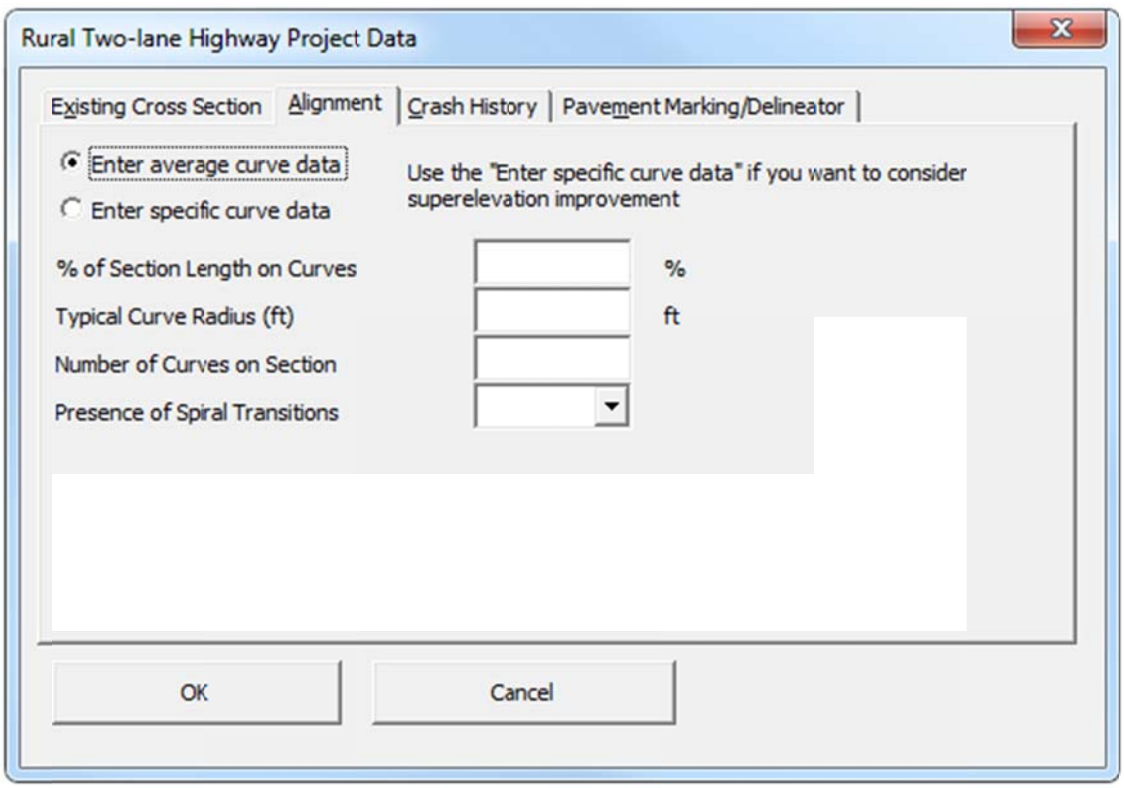


Figure B-22. Rural Two-Lane Highway Project Data window: Alignment tab, average curve data

- **% of Section Length on Curves:** Enter the percentage of the roadway section that is located on horizontal curves. Include any spiral transitions that may be present in the percentage.
- **Typical Curve Radius:** Enter the average horizontal curve radius for the roadway section.
- **Number of Curves on Section:** Enter the number of horizontal curves on the roadway section.
- **Presence of Spiral Transitions:** If spiral transitions are present with the horizontal curves, use the dropdown menu to select Yes. Otherwise, select No.

The window in Figure B-23 shows all data entry needed to use the specific curve data entry option.

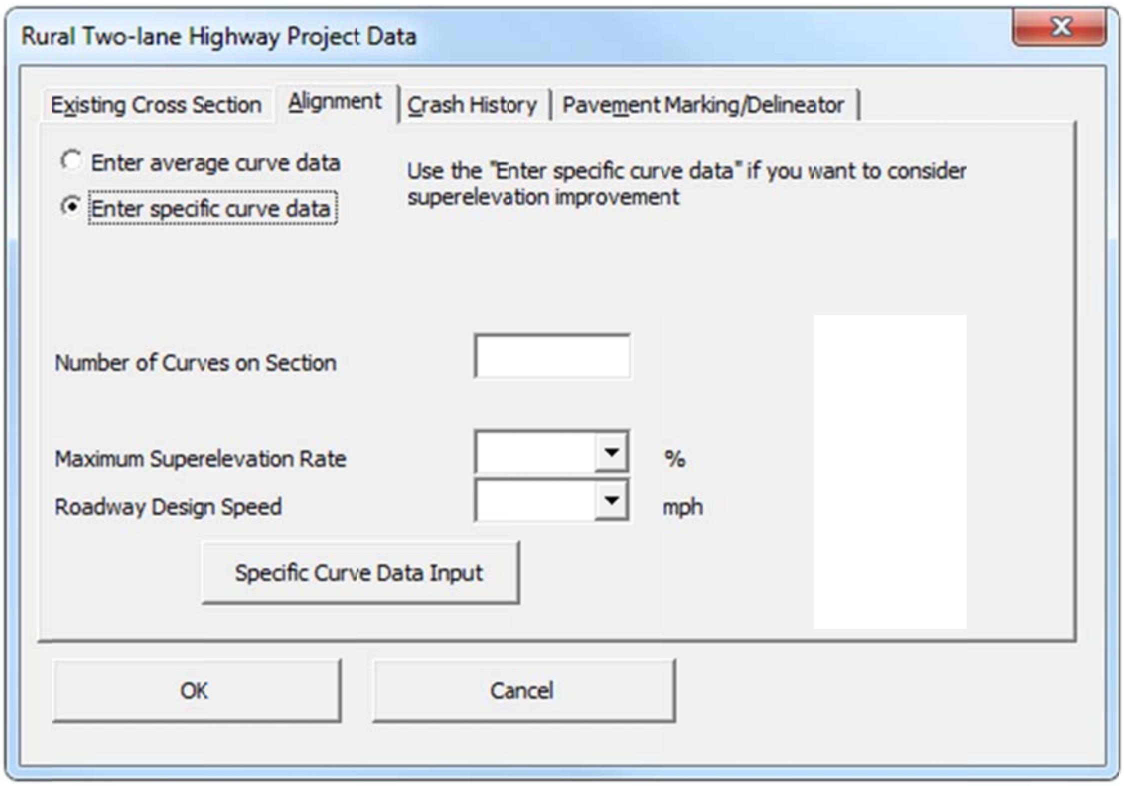


Figure B-23. Rural Two-lane Highway Project Data window: Alignment tab, specific curve data

- **Number of Curves in Roadway Section:** Enter the number of horizontal curves that are present on the roadway section.
- **Maximum Superelevation Rate (e_{max}):** Enter your agency's maximum superelevation rate for horizontal curves on rural two-lane highways.
- **Design Speed:** Enter the design speed of the roadway section in miles per hour.

Next, you will need to click the Specific Curve Data Input button to enter details about each horizontal curve on the roadway segment.

The window shown in Figure B-24 will appear when the Specific Curve Data Input button is clicked.

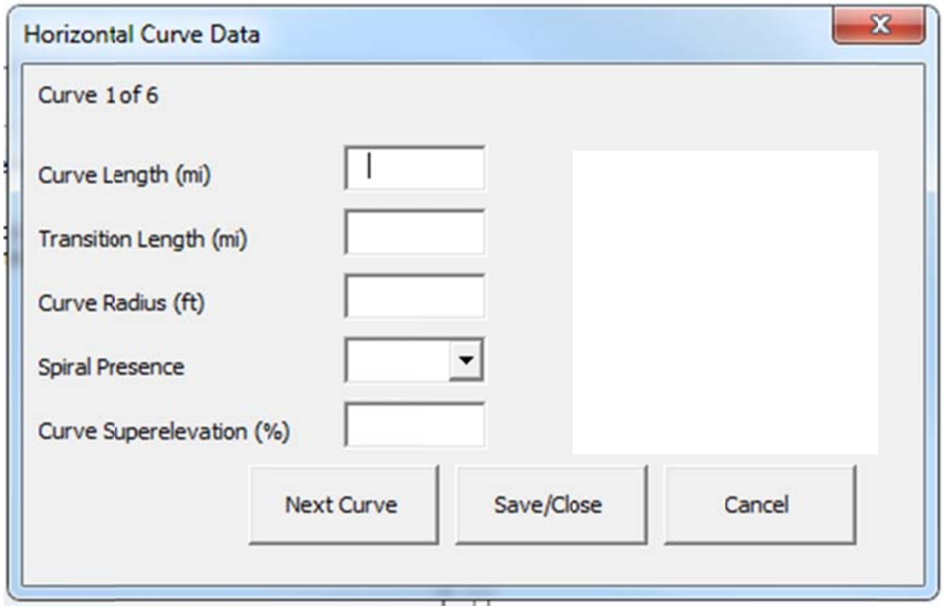


Figure B-24. Specific curve data entry window: First curve on rural two-lane highway

At the top of the Horizontal Curve Data window is a label that indicates which horizontal curve you are entering data for. For each individual horizontal curve:

- **Curve Length:** Enter the length in miles of horizontal curve, not including spiral transitions.
- **Transition Length:** Enter the length in miles of any spiral transition that may be present for one side of the horizontal curve.
- **Curve Radius:** Enter the radius of the horizontal curve in feet.
- **Spiral Presence:** Select Yes from the dropdown menu if spiral curves are present. Otherwise, select No.
- **Curve Superelevation:** Enter the existing superelevation rate for the horizontal curve as a percent.

Click the Next Curve button to save the data entered for the curve and proceed to data entry for the next curve on the roadway segment.

Click the Save/Close button to save the data entered for the curve and exit the Horizontal Curve Data window.

Click the Cancel button to exit the Horizontal Curve Data window without saving changes to the curve currently shown in the window.

The window for data entry on the last curve on the roadway section is shown in Figure B-25.

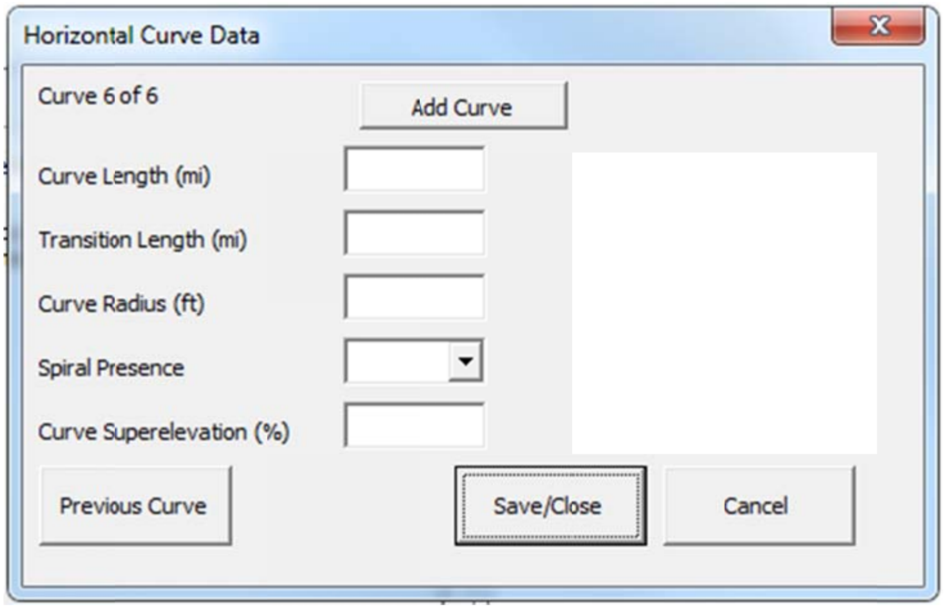


Figure B-25. Specific curve data entry window: Last curve on rural two-lane highway

All data entry for the last curve on the roadway section is the same as previously defined, however there is a button (the Add Curve button) that allows you to add more curves to the roadway section in case more are needed.

Click the Previous Curve button to save data entered for the curve and return to data entry for the previous curve on the roadway section.

All other buttons are the same as previously defined for the Horizontal Curve Data window.

Next, proceed to the Crash History tab, as shown in Figure B-26.

At your option, you can choose to use the existing site-specific crash history of the roadway section to assist in calculating potential crash savings with the 3R project. Otherwise, you can simply use the estimate given by the HSM crash prediction method. The choice between these options is made in the window shown in Figure B-26. The advantage of using site-specific crash history is that the benefit estimate may better reflect local conditions.

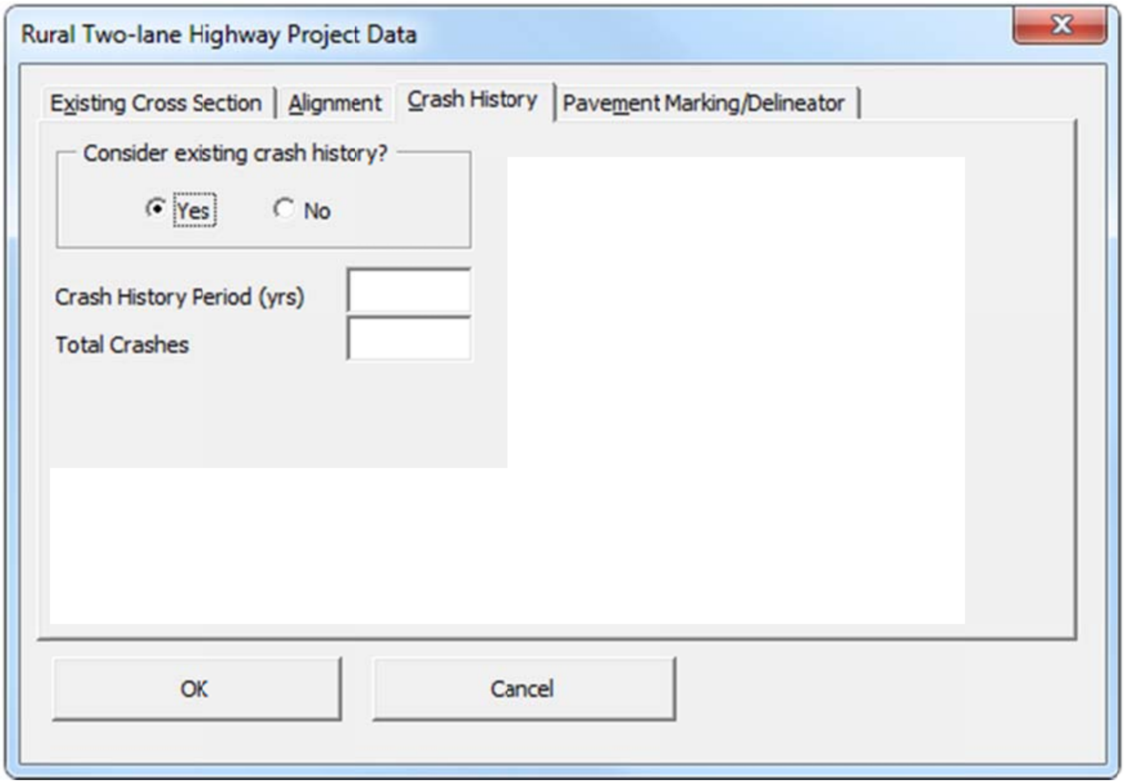


Figure B-26. Rural Two-lane Highway Project Data window: Crash History tab

If the Yes option is chosen for considering existing site-specific crash history, enter the following data:

- **Crash History Period:** Enter the number of years of available crash data.
- **Total Crashes:** Enter the total number of crashes that have occurred during this time period.

Next, proceed to the Pavement Marking/Delineator tab, as shown in Figure B-27.

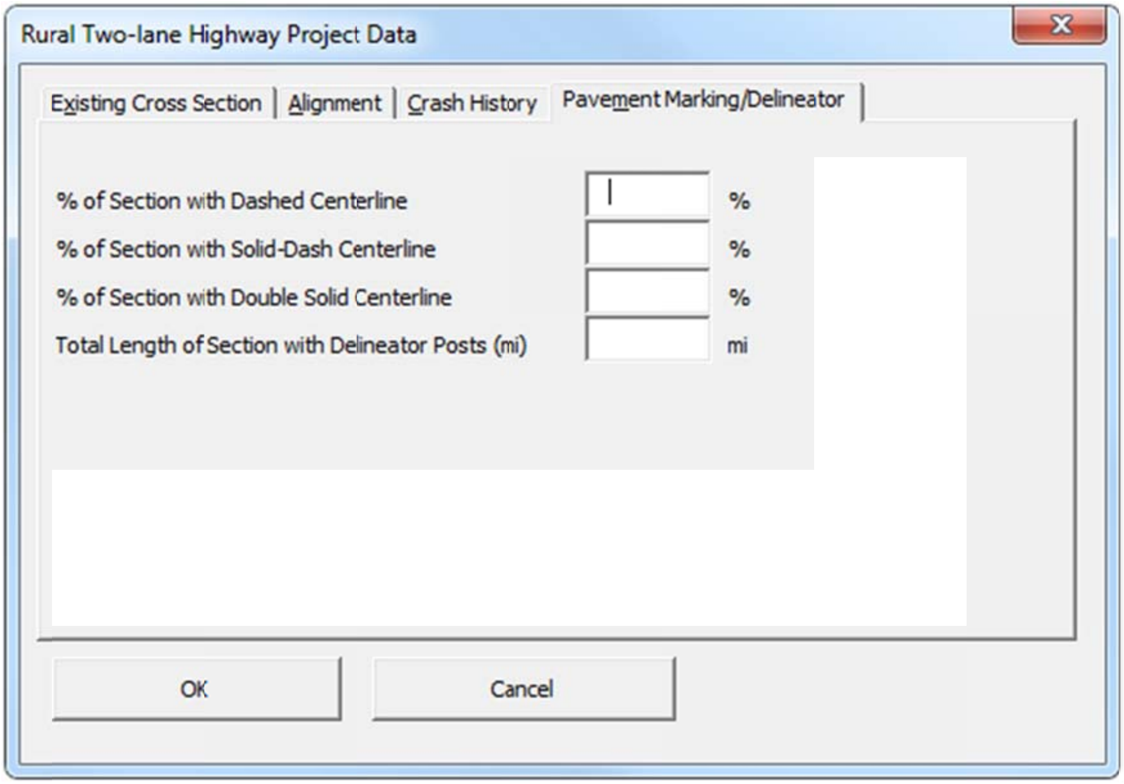


Figure B-27. Rural Two-lane Highway Project Data window: Pavement Marking/Delineator tab

- **% of Section with Dashed Centerline:** Enter the percentage of the roadway section for which the centerline striping is dashed only.
- **% of Section with Solid-Dash Centerline:** Enter the percentage of the roadway section for which the centerline striping is a solid-dash combination.
- **% of Section with Double Solid Centerline:** Enter the percentage of the roadway section for which the centerline striping is double-solid.
- **Total Length of Section with Delineator Posts:** Enter the length in miles for the portion of the roadway section that will have roadside delineator posts. Include both sides of the roadway separately (i.e. enter 2 mi if a 1-mi roadway section has roadside delineators on both sides of the roadway.

B.2.1.2 Rural Multilane Undivided and Divided Highway Project Data

Enter all attributes about the roadway segment using the Rural Multilane Highway Project Data window. The window is composed of four different pages. Navigate between these pages by clicking on the tabs at the top of the window. Each page is discussed below.

First navigate to the Existing Cross Section tab shown in Figure B-28.

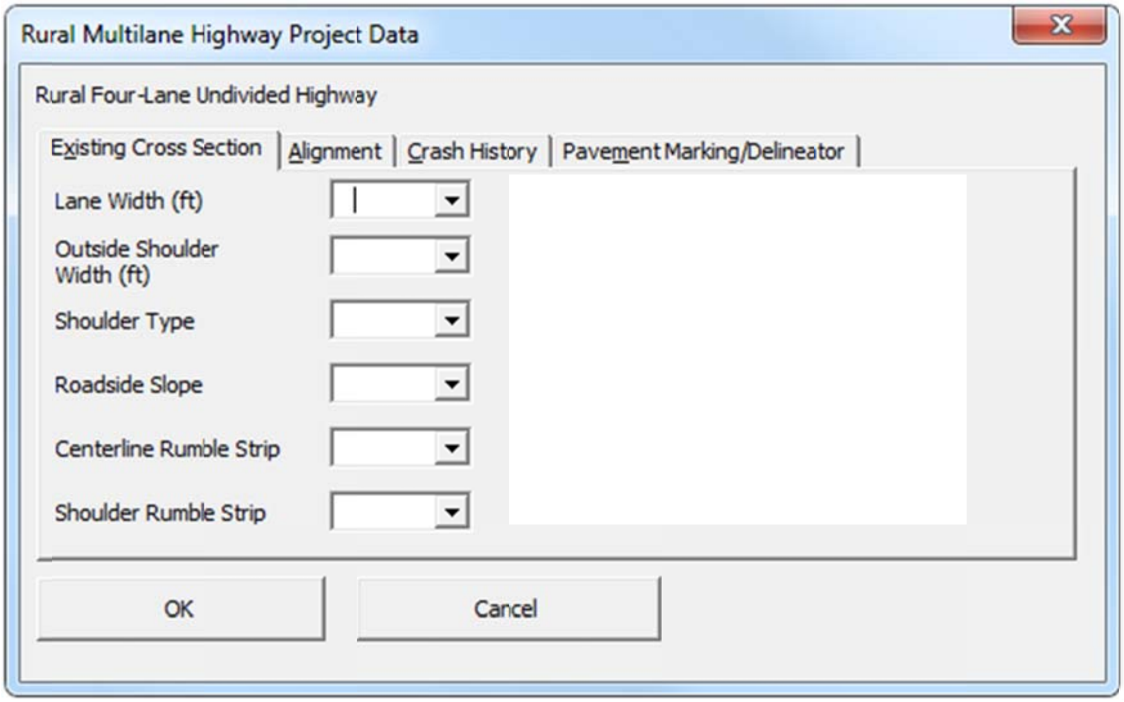


Figure B-28. Rural Multilane Highway Project Data window: Existing Cross Section tab

Figure B-28 shows the window that will appear for rural multilane undivided highways. The data entered in this window are as follows:

- **Lane Width:** Select the existing lane width of the traveled way in feet.
- **Shoulder Width:** Select the existing shoulder width in feet.
- **Shoulder Type:** Select the existing shoulder type.
- **Roadside Slope:** Select the existing roadside foreslope.
- **Centerline Rumble Strip:** Select Yes from the dropdown menu if centerline rumble strips are present on the roadway section. Otherwise, select No.
- **Shoulder Rumble Strip:** Select Yes from the dropdown menu if shoulder rumble strips are present on the roadway section. Otherwise, select No.

For rural multilane divided highways, Centerline Rumble Strips will not appear in the window in Figure B-28.

Next, click on the Alignment tab.

If you plan on considering superelevation improvement as part of your 3R project, you must enter specific curve data. Otherwise, you can enter 0 for number of curves, and skip the specific curve data entry.

The window in Figure B-29 shows all alignment data entry required.

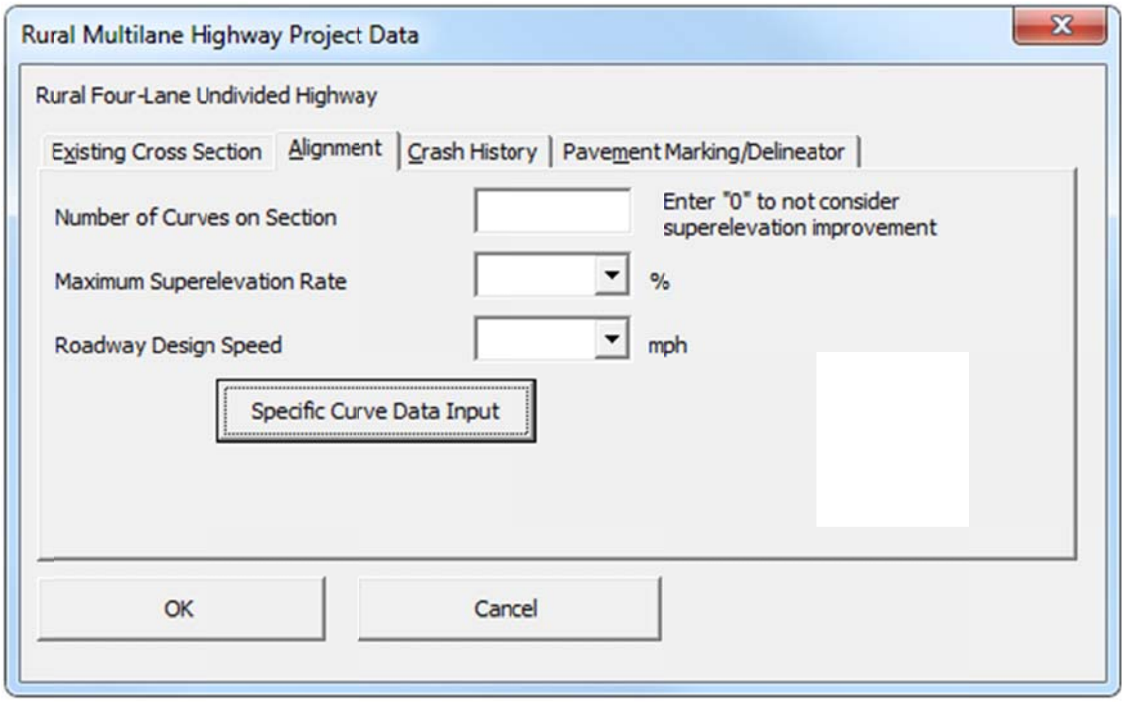


Figure B-29. Rural Multilane Highway Project Data window: Alignment tab

- **Number of Curves in Roadway Section:** Enter the number of horizontal curves that are present on the roadway section.
- **Maximum Superelevation Rate (e_{max}):** Enter your agency's maximum superelevation rate for horizontal curves on rural two-lane highways.
- **Design Speed:** Enter the design speed of the roadway section in miles per hour.

Next, if you entered a value greater than 0 for the Number of Curves in Roadway Section, you will need to click the Specific Curve Data Input button to enter details about each horizontal curve on the roadway segment.

The window shown in Figure B-30 will appear when the Specific Curve Data Input button is clicked

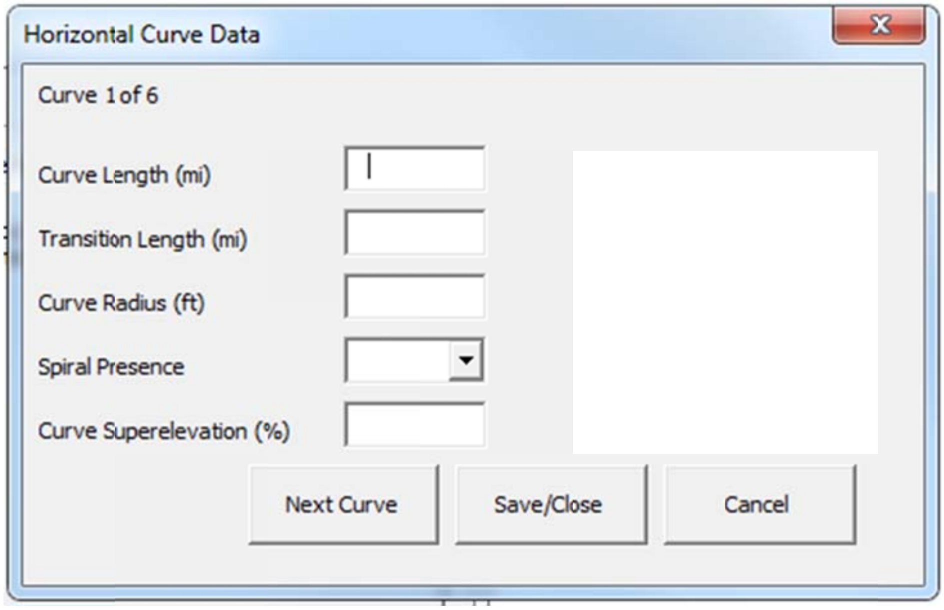


Figure B-30. Specific curve data entry: first curve on rural multilane highway

At the top of the Horizontal Curve Data window is a label that indicates which horizontal curve you are entering data for. The following data are entered for each curve:

- **Curve Length:** Enter the length in miles of horizontal curve, not including spiral transitions.
- **Transition Length:** Enter the length in miles of any spiral transition that may be present for one side of the horizontal curve.
- **Curve Radius:** Enter the radius of the horizontal curve in feet.
- **Spiral Presence:** Select Yes from the dropdown menu if spiral curves are present. Otherwise, select No.
- **Curve Superelevation:** Enter the existing superelevation rate for the horizontal curve as a percent.

Click the Next Curve button to save the data entered for the curve and proceed to data entry for the next curve on the roadway segment.

Click the Save/Close button to save the data entered for the curve and exit the Horizontal Curve Data window.

Click the Cancel button to exit the Horizontal Curve Data window without saving changes to the curve currently shown in the window.

The window for data entry on the last curve on the roadway section is shown in Figure B-31.

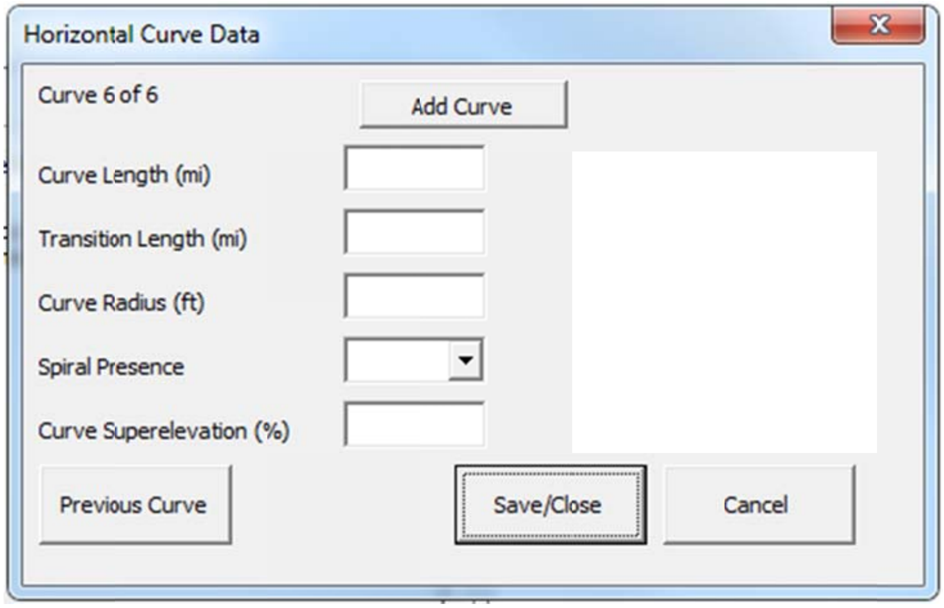


Figure B-31. Specific curve data entry: last curve on rural multilane highway

All data entry for the last curve on the roadway section is the same as previously defined; however there is a button (the Add Curve button) that allows you to add more curves to the roadway section in case you need to add more.

Click the Previous Curve button to save data entered for the curve and return to data entry for the previous curve on the roadway section.

All other buttons are the same as previously defined for the Horizontal Curve Data window.

Next, proceed to the Crash History tab, shown in Figure B-32.

At your option, you can choose to use the existing site-specific crash history of the roadway section to assist in calculating potential crash savings with the 3R project. Otherwise, you can simply use the estimate given by the HSM crash prediction method. The choice between these options is made in the window shown in Figure B-32. The advantage of using site-specific crash history is that the benefit estimate may better reflect local conditions.

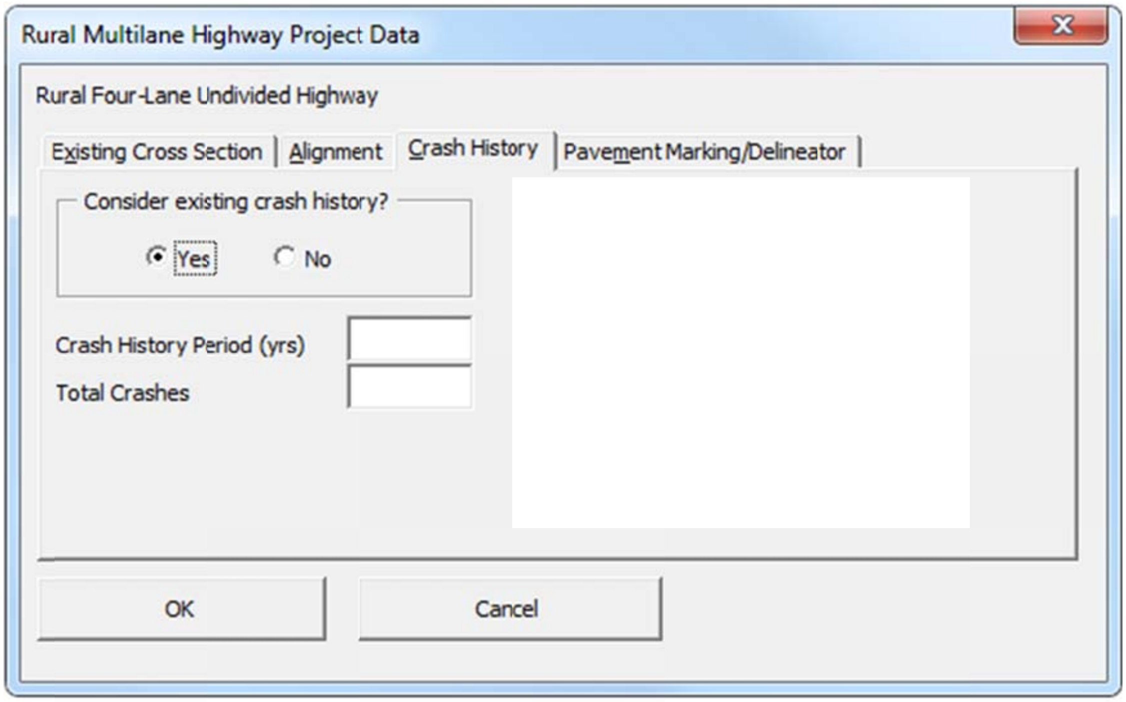


Figure B-32. Rural Multilane Highway Project Data window: Crash History tab

If the Yes option is chosen for considering existing crash history, enter the following data:

- **Crash History Period:** Enter the number of years of available crash data.
- **Total Crashes:** Enter the total number of crashes that have occurred during this time period.

Next, proceed to the Pavement Marking/Delineator tab, shown in Figure B-33.

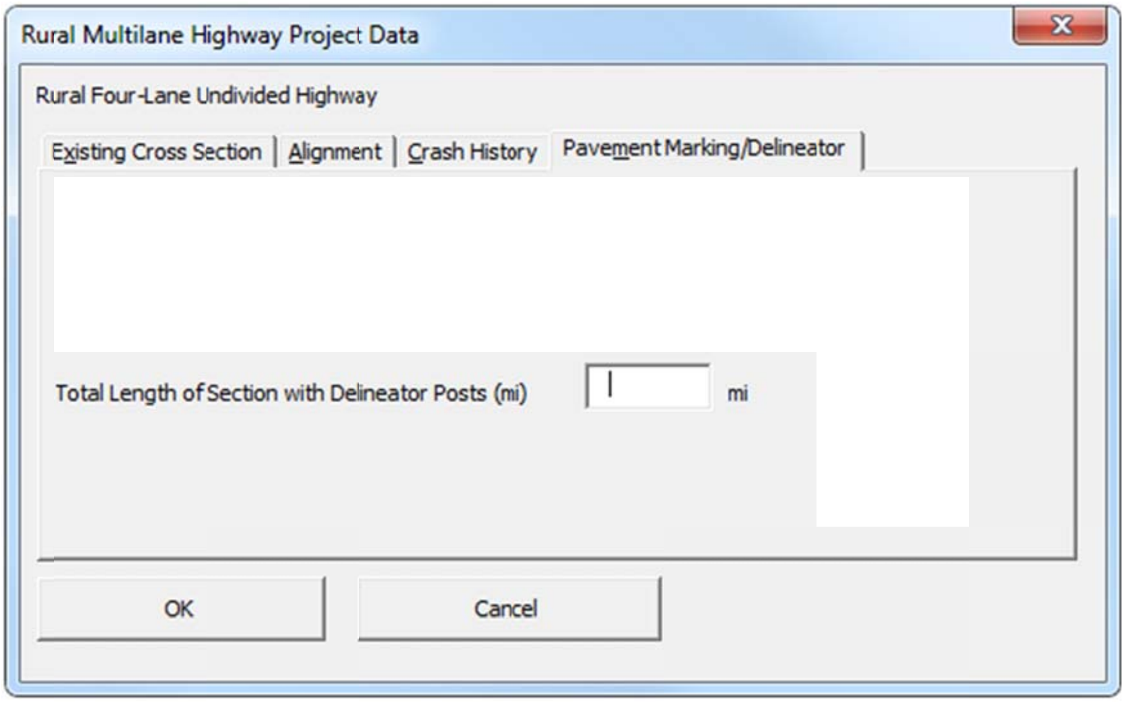


Figure B-33. Rural Multilane Highway Project Data window: Pavement Marking/Delineator tab

- **Total Length of Section with Delineator Posts:** Enter the length in miles of the roadway section that will have [OR that has] roadside delineator posts. Include both sides of the roadway separately (i.e. enter 2 mi if a 1-mi roadway section has roadside delineators on both sides of the roadway.

B.2.1.3 Rural and Urban Freeway Project Data

Enter all attributes about the roadway segment using the Freeway Project Data window. The window is composed of five different pages. Navigate between these pages by clicking on the tabs at the top of the window. Each page is discussed below.

First navigate to the Existing Cross Section tab shown in Figure B-34

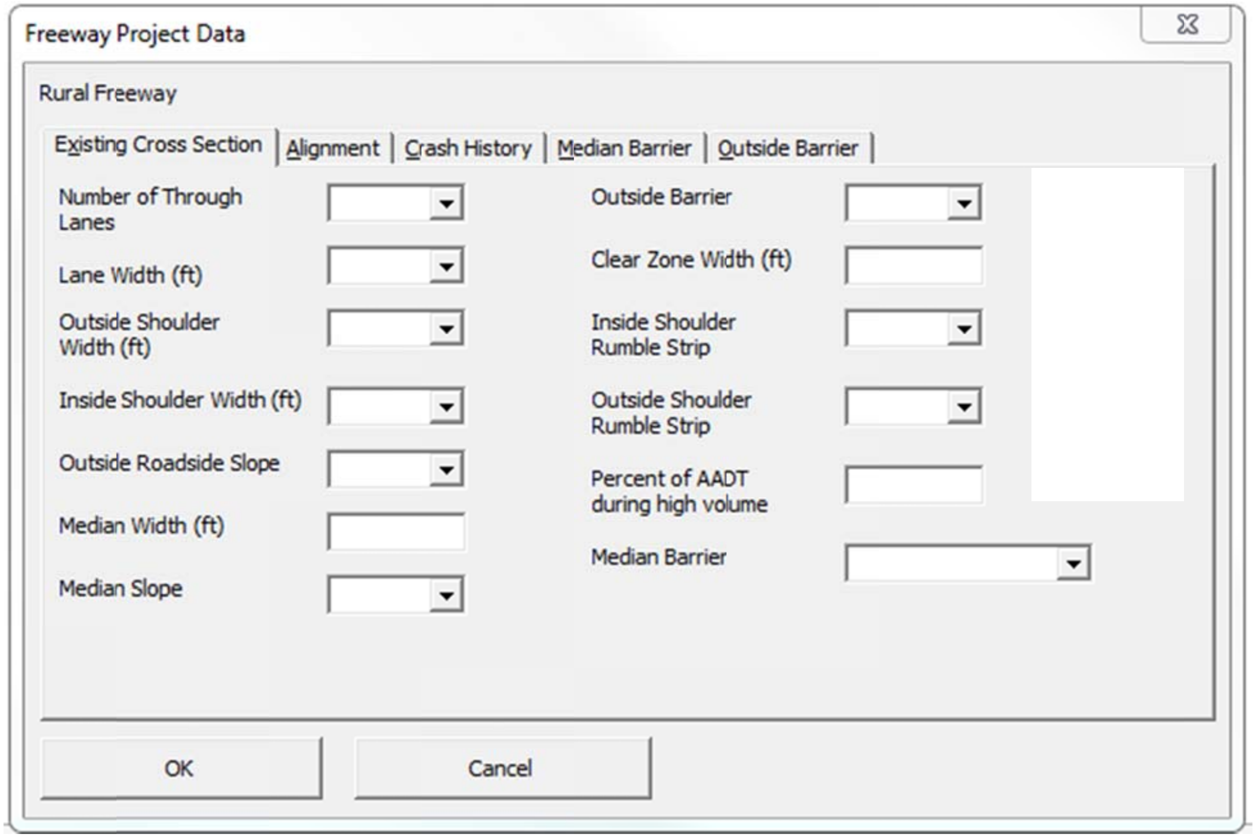


Figure B-34. Freeway Project Data window: Existing Cross Section tab

- **Number of Through Lanes:** Select the total number of through lanes on the freeway segment from the dropdown menu.
- **Lane Width:** Select the existing lane width of the traveled way in feet from the dropdown menu.
- **Outside Shoulder Width:** Select the existing outside shoulder width in feet from the dropdown menu.
- **Inside Shoulder Width:** Select the existing inside shoulder width in feet from the dropdown menu.
- **Outside Roadside Slope:** Select the existing roadside foreslope from the dropdown menu.
- **Median Width:** Enter the median width in feet, measured from the left-most edge of the traveled-way to the left-most edge of the traveled way of the opposite direction.
- **Median Slope:** Select the median cross slope from the dropdown menu. Select Flat if there is not a depressed median.
- **Outside Barrier:** Select Yes from the dropdown menu if there are outside barriers that are present along the freeway segment. Otherwise, if there are no outside barriers, select No.
- **Clear Zone Width:** Enter the width of the clear zone in feet.

- **Inside Shoulder Rumble Strip:** Select Yes from the dropdown menu if rumble strips are present on the inside shoulders of the roadway section. Otherwise, select No.
- **Outside Shoulder Rumble Strip:** Select Yes from the dropdown menu if rumble strips are present on the outside shoulders of the roadway section. Otherwise, select No.
- **% of AADT during high volume periods:** proportion of AADT during hours in which the traffic volume exceeds 1,000 veh/h/lane.
- **Median Barrier:** Select Yes from the dropdown menu if there are median barriers that are present along the freeway segment. Otherwise, if there are no median barriers, select No.

Next, click on the Alignment tab.

Use the option buttons in Figure B-35 to select either entry of average curve data or entry of specific curve data. Depending on which option button you select, different text boxes and dropdown menus will appear in the window.

The window in Figure B-35 shows all data entry required for using the average curve data entry option.

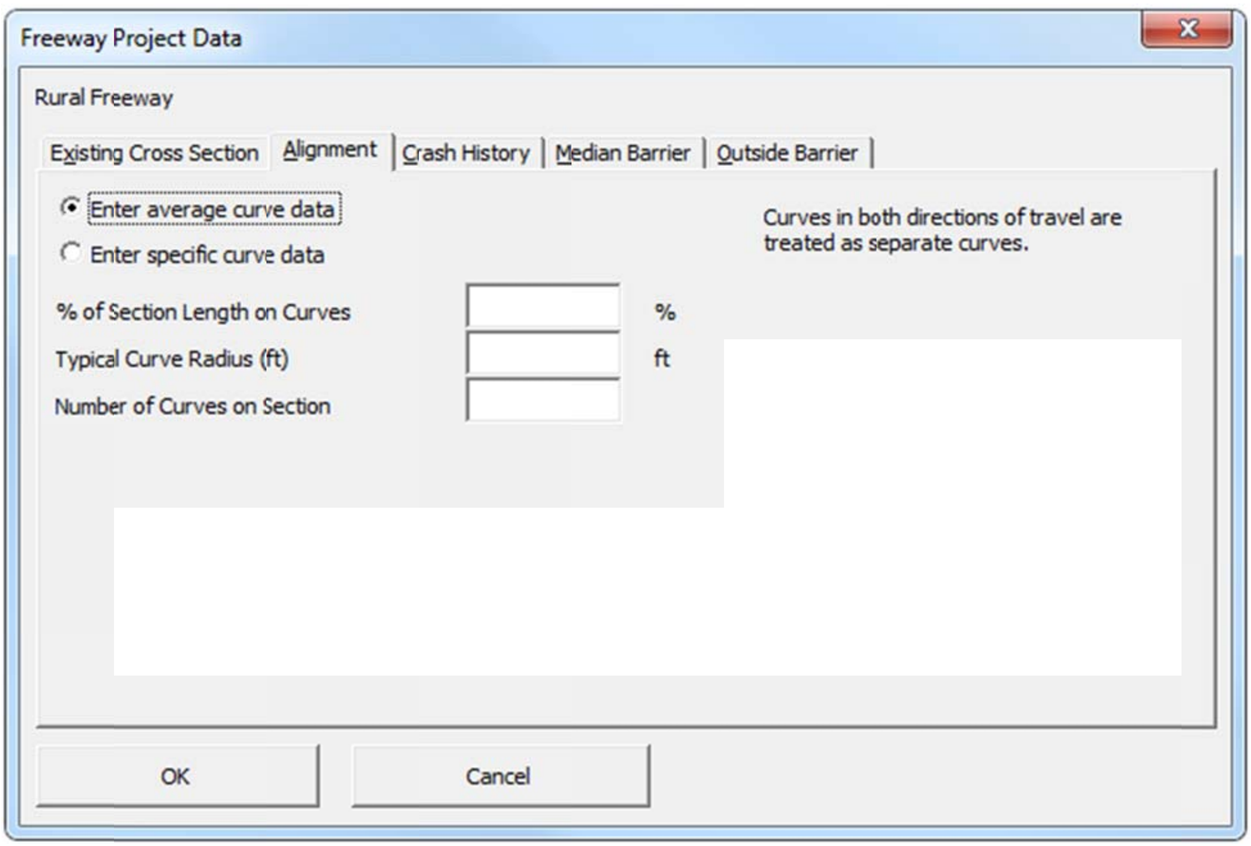


Figure B-35. Freeway Project Data window: Alignment tab, average curve data entry

- **% of Section Length on Curves:** Enter the percentage of the roadway section that is located on horizontal curves. Include spiral transitions in the percentage if present.
- **Typical Curve Radius:** Enter the average horizontal curve radius for the roadway section.
- **Number of Curves on Section:** Enter the number of horizontal curves on the roadway section.

The window in Figure B-36 shows all data entry required for using the specific curve data entry option.

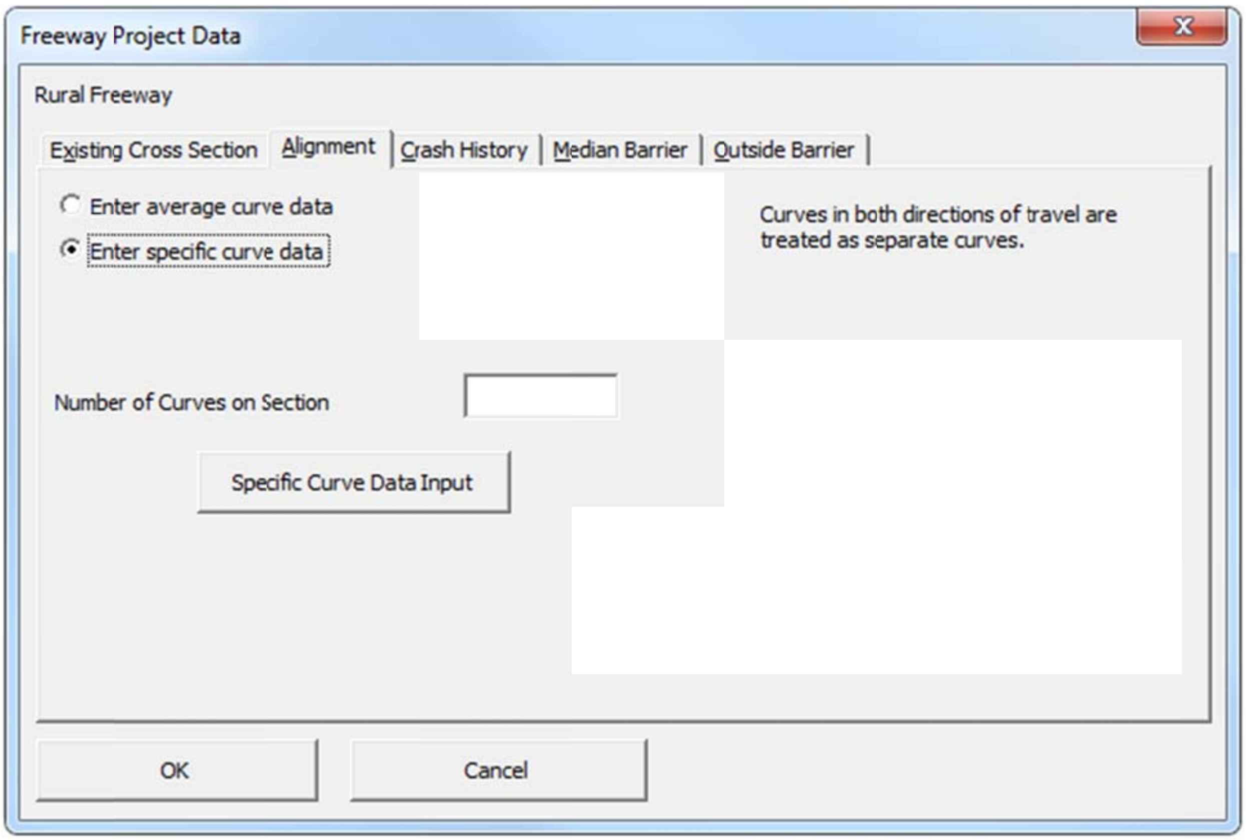


Figure B-36. Freeway Project Data window: Alignment tab, specific curve data entry

- **Number of Curves in Roadway Section:** Enter the number of horizontal curves that are present on the roadway section. Count curves in each direction of travel separately.

Next, you will need to click the Specific Curve Data Input button to enter details about each horizontal curve on the roadway segment.

The window shown in Figure B-37 will appear when the Specific Curve Data Input button is clicked.

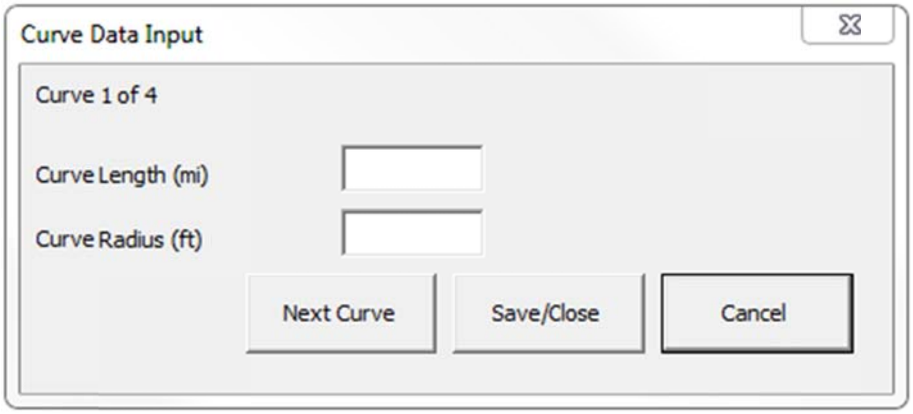


Figure B-37. Specific curve data entry: first curve on freeway

At the top of the Horizontal Curve Data window is a label that indicates which horizontal curve you are entering data for.

- **Curve Length:** Enter the length in miles of the horizontal curve not including spiral transitions in miles.
- **Curve Radius:** Enter the radius of the horizontal curve in feet.

Click the Next Curve button to save the data entered for the curve and proceed to data entry for the next curve on the roadway segment.

Click the Save/Close button to save the data entered for the curve and exit the Horizontal Curve Data window.

Click the Cancel button to exit the Horizontal Curve Data window without saving changes to the curve currently shown in the window.

The window for data entry on the last curve on the roadway section is shown in Figure B-38.

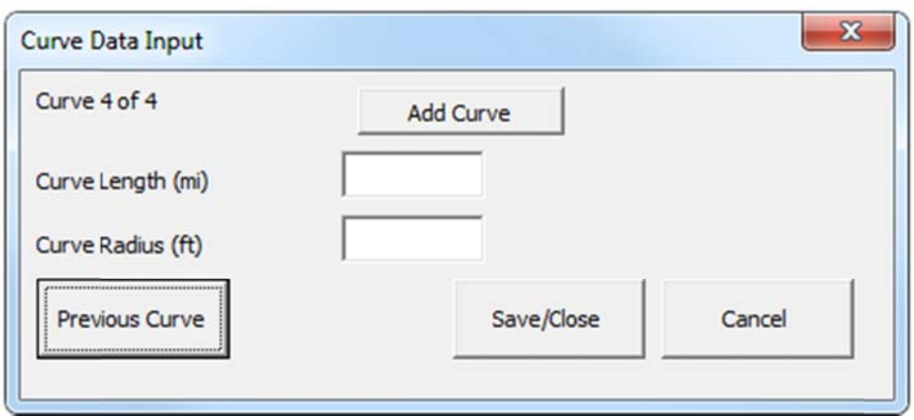


Figure B-38. Specific curve data entry: last curve on freeway

All data entry for the last curve on the roadway section is the same as previously defined; however, there is a button (the Add Curve button) that allows you to add more curves to the roadway section in case you need add more.

Click the Previous Curve button to save data entered for the curve and return to data entry for the previous curve on the roadway section.

All other buttons are the same as previously defined for the Horizontal Curve Data window.

Next, proceed to the Crash History tab, shown in Figure B-39.

At your option, you can choose to use the existing site-specific crash history of the roadway section to assist in calculating potential crash savings with the 3R project. Otherwise, you can simply use the estimate given by the HSM crash prediction method. The choice between these options is made in the window shown in Figure B-39. The advantage of using site-specific crash history is that the benefit estimate may better reflect local conditions.

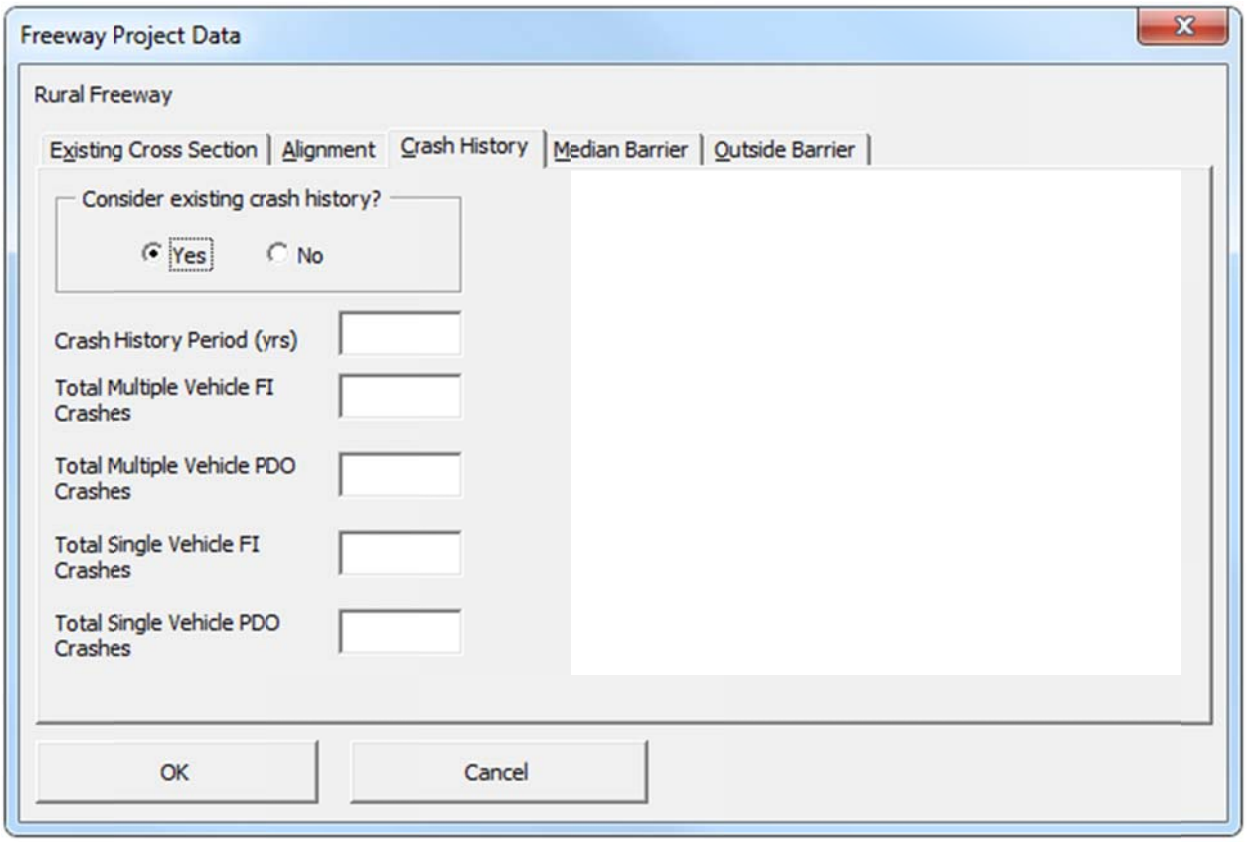


Figure B-39. Freeway Project Data window: Crash History tab

If the Yes option is chosen for considering existing crash history, enter the following data:

- **Crash History Period:** Enter the number of years of available crash data.
- **Total MV-FI Crashes:** Enter the total number of multiple vehicle crashes on the roadway segment that fall into the following crash severity levels combined:
  - Fatal crash
  - Disabling injury crash
  - Evident injury crash
  - Possible injury crash
- **Total MV-PDO Crashes:** Enter the total number of multiple vehicle crashes on the roadway segment that fall into the property-damage-only crash severity level.
- **Total SV-FI Crashes:** Enter the total number of single vehicle crashes on the roadway segment that fall into the following crash severity levels combined:
  - Fatal crash
  - Disabling injury crash
  - Evident injury crash
  - Possible injury crash
- **Total SV-PDO Crashes:** Enter the total number of single vehicle crashes on the roadway segment that fall into the property-damage-only crash severity level.

The last two tabs in the Freeway Project Data window are for entering data describing the median barriers and outside barriers on the freeway section. These two tabs will appear only if you selected Yes for the presence of either type of barrier.

If you selected Yes for median barrier presence in the Existing Cross Section tab, then proceed to the Median Barrier tab, shown in Figure B-40. Otherwise skip to data entry for outside barriers shown in Figure B-43.

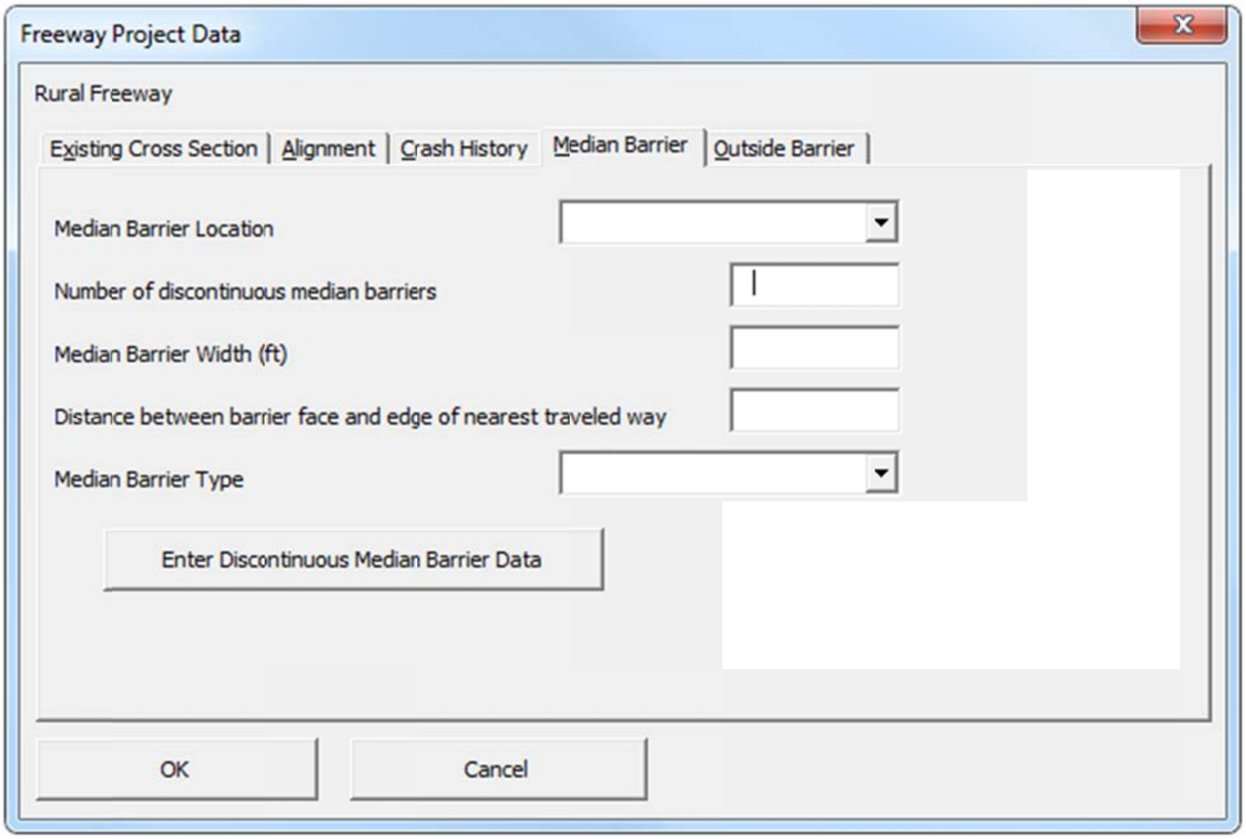


Figure B-40. Freeway Project Data window: Median Barrier tab

The first dropdown menu in the Median Barrier tab is for the Median Barrier Location. The following defines each option of the dropdown menu. Select the option that describes your situation.

- *Continuous, Centered*: A median barrier is present in the center of the median and runs the entire length of the freeway segment.
- *Continuous, Offset*: A median barrier runs the entire length of the freeway segment, but is not centered in the median.
- *Discontinuous*: Median barriers are present on the freeway segment, but are not continuous.

Based on your entry in the Median Barrier Location dropdown menu, the remaining data entry fields in the Median Barrier tab may remain or disappear. The following defines each attribute.

- **Number of discontinuous median barriers:** Enter the total number of discontinuous (stand-alone) median barriers on the freeway section. Do not count a continuous barrier in this number.
- **Inside Barrier Width:** Enter the width of the continuous median barrier in feet. This option appears only for continuous, centered and continuous, offset median barriers.

- **Distance between barrier face and edge of nearest traveled way:** Enter the distance in feet from the inside traveled-way edge closest to the offset barrier to the barrier face. This option appears only for continuous, offset median barriers.
- **Cont. Median Barrier Type:** Select the continuous median barrier type from the embedded dropdown menu. This option appears only for continuous, centered and continuous, offset median barriers.

Next, if there are discontinuous median barriers present, you will need to click the Enter Discontinuous Median Barrier Data button to enter details about each discontinuous barrier on the roadway segment.

The window in Figure B-41 will appear when the Enter Discontinuous Median Barrier Data button is clicked.

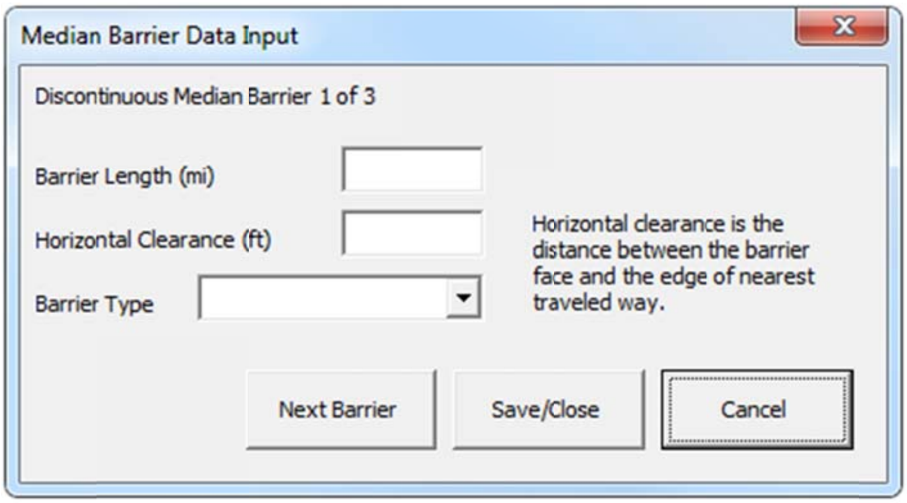


Figure B-41. Discontinuous median barrier data entry: first barrier on freeway

At the top of the Median Barrier Data Input window is a label that indicates which median barrier you are entering data for.

- **Barrier Length:** Enter the length in miles of the discontinuous median barrier.
- **Horizontal Clearance:** Enter the distance in feet between the leftmost edge of the traveled way and the face of the discontinuous median barrier.
- **Barrier Type:** Select the discontinuous median barrier type from the dropdown menu.

Click the Next Barrier button to save the data entered for the median barrier and proceed to data entry for the next median barrier on the roadway segment.

Click the Save/Close button to save the data entered for the median barrier and exit the Median Barrier Data Input window.

Click the Cancel button to exit the Median Barrier Data Input window without saving changes to the median barrier currently shown in the window.

The window for data entry on the last median barrier on the roadway section is shown in Figure B-42.

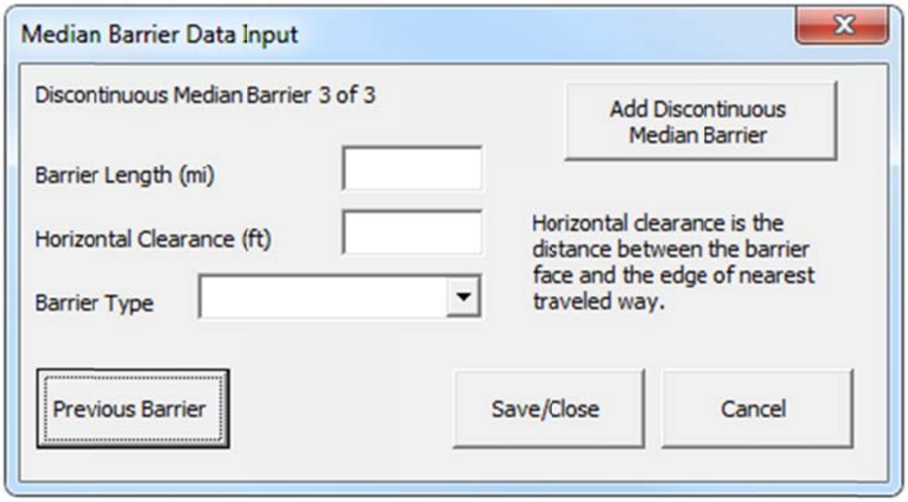


Figure B-42. Discontinuous median barrier data entry: last barrier on freeway

All data entry for the last median barrier on the roadway section is the same as previously defined, however there is a button (the Add Discontinuous Median Barrier button) that allows you to add more median barriers to the roadway section in case you need to add more.

Click the Previous Barrier button to save data entered for the median barrier and return to data entry for the previous median barrier on the roadway section.

All other buttons are the same as previously defined for the Median Barrier Data Input window.

If you selected Yes for outside barrier presence in the Existing Cross Section tab, then proceed to the Outside Barrier tab, shown in Figure B-43. Otherwise skip to the next section.

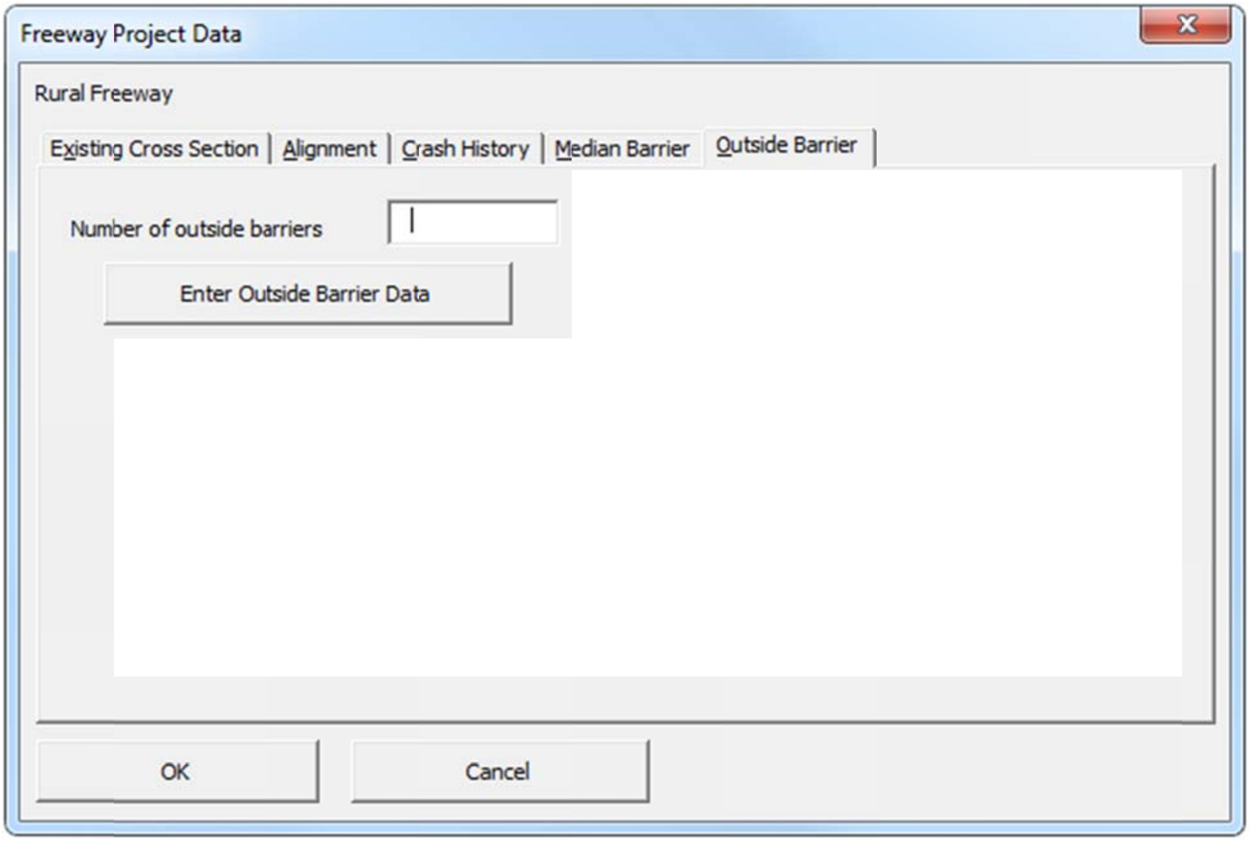


Figure B-43. Freeway Project Data window: Outside Barrier tab

- **Number of Outside Barriers:** Enter the number of outside barriers that are present on the freeway segment.

Next, you will need to click the Enter Outside Barrier Data button to enter details about each outside barrier on the roadway segment.

The window in Figure B-44 will appear when the Enter Outside Barrier Data button is clicked.

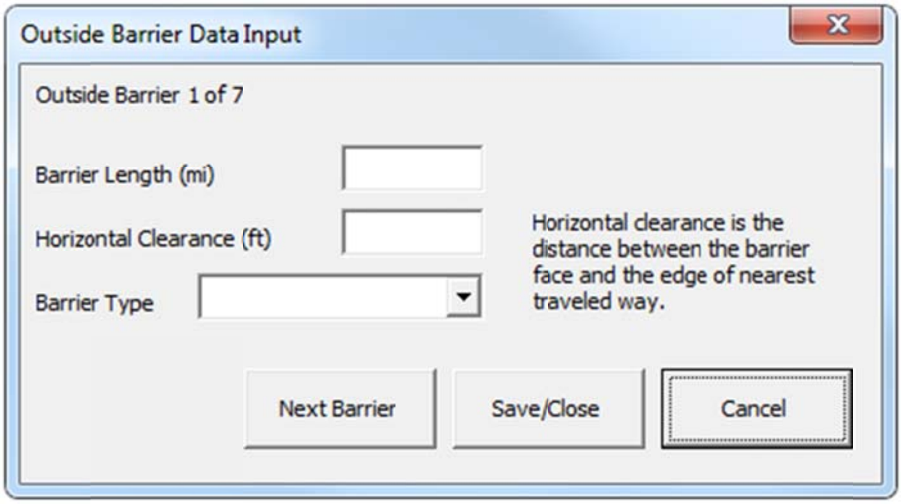


Figure B-44. Outside barrier data entry: first barrier on freeway

At the top of the Outside Barrier Data Input window is a label that indicates which outside barrier you are entering data for.

- **Barrier Length:** Enter the length in miles of the outside barrier.
- **Horizontal Clearance:** Enter the distance in feet between the rightmost edge of the traveled way and the barrier face.
- **Barrier Type:** Select the barrier type from the dropdown menu.

Click the Next Barrier button to save the data entered for the curve and proceed to data entry for the next outside barrier on the roadway segment.

Click the Save/Close button to save the data entered for the outside barrier and exit the Outside Barrier Data Input window.

Click the Cancel button to exit the Outside Barrier Data Input window without saving changes to the outside barrier currently shown in the window.

The window for data entry on the last median barrier on the roadway section is shown in Figure B-45.

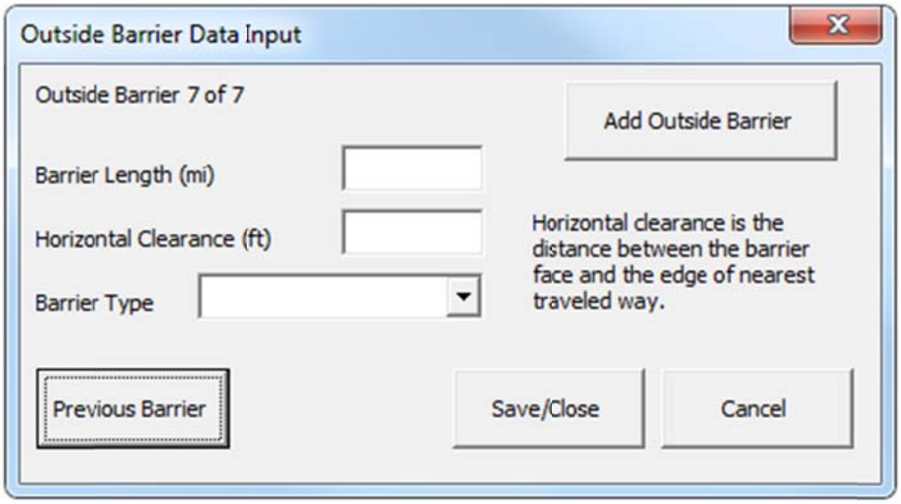


Figure B-45. Outside barrier data entry: last barrier on freeway

All data entry for the last outside barrier on the roadway section is the same as previously defined, however there is a button (the Add Outside Barrier button) that allows you to add more outside barriers to the roadway section in case you need to add more.

Click the Previous Barrier button to save data entered for the outside barrier and return to data entry for the previous outside barrier on the roadway section.

All other buttons are the same as previously defined for the Outside Barrier Data Input window.

You have now finished entering all necessary roadway segment data for the economic analysis.

B.2.2 Edit Analysis Data Already Entered

With the procedures presented above, you entered all roadway segment data needed for a specific benefit-cost analysis. However, if you need to go back and edit any of the roadway segment attributes already entered, click the Edit Roadway Data or Edit Project Data buttons at the top of the Existing Conditions worksheet (see Figure B-19).

B.3 Alternatives to Consider

The next step is to select which roadway improvements you want to consider for potential inclusion in the 3R project. Click the Alternatives to Consider button at the top of the Existing Conditions worksheet. Roadway improvements available for inclusion in the analysis depend on the roadway type being examined. The following subsections present the window that will appear for each roadway type.

B.3.1 Rural Two-lane Highway

The window shown in Figure B-46 will appear when the Alternatives to Consider button is clicked for rural two-lane highways.

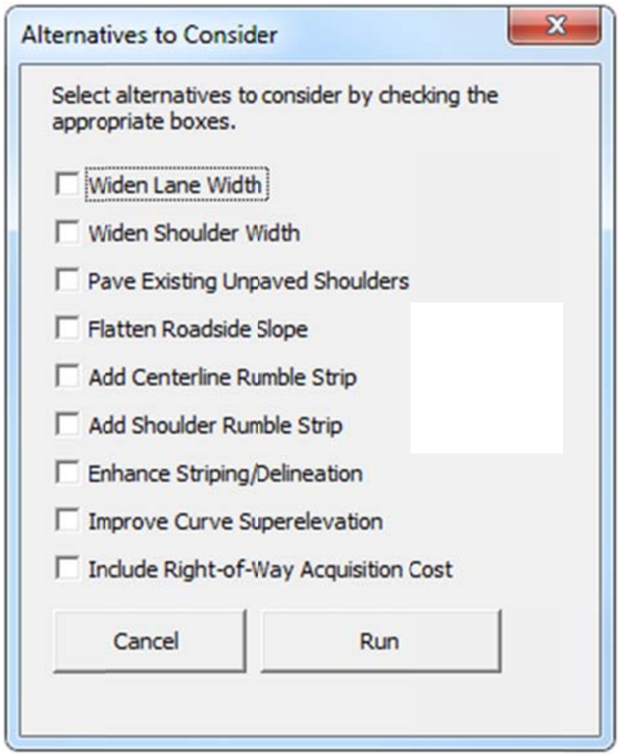


Figure B-46. Alternatives to consider for rural two-lane highways

Place a check mark next to all alternatives you want to consider for potential improvement.

- **Widen Lane Width:** This option will appear only if the existing lane width is less than 12 ft. Selecting lane widening will result in consideration of all lane width options from the existing lane width to 12 ft, in 0.5-ft intervals.
- **Widen Shoulder Width:** This option will appear only if the existing shoulder width is less than 8 ft. Selecting shoulder widening will result in consideration of all shoulder width options from the existing shoulder width to 8 ft, in 1-ft intervals.
- **Pave Existing Unpaved Shoulders:** This option will appear only if the existing shoulder type is unpaved.
- **Flatten Roadside Slope:** This option will appear only if the existing roadside foreslope is steeper than 1V:6H. If the existing roadside foreslope is 1V:2H, then options of 1V:2H, 1V:3H, 1V:4H, and 1V:6H will be considered. If the existing roadside foreslope is 1V:3H, then options of 1V:3H, 1V:4H, and 1V:6H will be considered. If the existing roadside foreslope is 1V:4H, then options of 1V:4H, and 1V:6H will be considered.
- **Add Centerline Rumble Strip:** This option will appear only if no centerline rumble strip is currently present.

- **Add Shoulder Rumble Strip:** This option will appear only if no shoulder rumble strip is currently present.
- **Enhance Striping/Delineation:** Select enhanced striping/delineation if you want to consider installing durable pavement markings for both centerline and edge striping as well as installing roadside delineators.
- **Improve Curve Superelevation:** Select improve curve superelevation if you want the tool to consider improving the curve superelevation, where needed. Superelevation improvements will only be considered for curves on which HSM procedures indicate that a crash reduction would be likely to result from the superelevation improvement.
- **Include Right-of-Way Acquisition Cost:** Select this option if you want to include the cost of acquiring right-of-way in the benefit-cost analysis. The tool assumes right-of-way acquisition is needed for all lane and shoulder widening as well as roadside slope flattening.

B.3.2 Rural Multilane Highway

The window in Figure B-47 will appear when the Alternatives to Consider button is clicked for rural multilane undivided and divided highways.

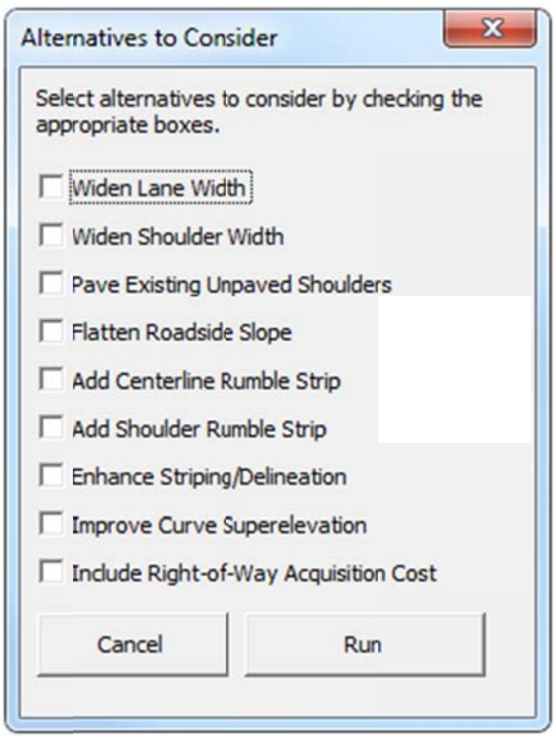


Figure B-47. Alternatives to consider for rural multilane highways

Place a check mark next to all alternatives you want to consider for improvement.

- **Widen Lane Width:** This option will appear only if the existing lane width is less than 12 ft. Selecting lane widening will result in consideration of all lane width options from the existing lane width to 12 ft, in 0.5-ft intervals.
- **Widen Shoulder Width:** This option will appear only if the existing shoulder width is less than 8 ft. Selecting shoulder widening will result in consideration of all shoulder width options from the existing shoulder width to 8 ft, in 1-ft intervals. On divided highways, only widening of the outside shoulders is considered.
- **Pave Existing Unpaved Shoulders:** This option will appear only if the existing shoulder type is unpaved.
- **Flatten Roadside Slope:** This option will appear only if the existing roadside foreslope is steeper than 1V:6H. If the existing roadside foreslope is 1V:2H, then options of 1V:2H, 1V:3H, 1V:4H, and 1V:6H will be considered. If the existing roadside foreslope is 1V:3H, then options of 1V:3H, 1V:4H, and 1V:6H will be considered. If the existing roadside foreslope is 1V:4H, then options of 1V:4H, and 1V:6H will be considered.
- **Add Centerline Rumble Strip:** This option will appear only if no centerline rumble strip is currently present. This option only applies to undivided roadways.
- **Add Shoulder Rumble Strip:** This option will appear only if no shoulder rumble strip is currently present.
- **Enhance Striping/Delineation:** Select enhanced striping/delineation if you want to consider installing durable pavement markings for both centerline and edge striping as well as installing roadside delineators.
- **Improve Curve Superelevation:** Select improve curve superelevation if you want the tool to consider improving the curve superelevation, where needed. Superelevation improvements will only be considered for curves on which HSM procedures indicate that a crash reduction would be likely to result from the superelevation improvement.
- **Include Right-of-Way Acquisition Cost:** Select this option if you want to include the cost of acquiring right-of-way in the benefit-cost analysis. The tool assumes right-of-way acquisition is needed for all lane and shoulder widening as well as roadside slope flattening.

B.3.3 Freeway

The window shown in Figure B-48 will appear when the Alternatives to Consider button is clicked for rural and urban freeways.

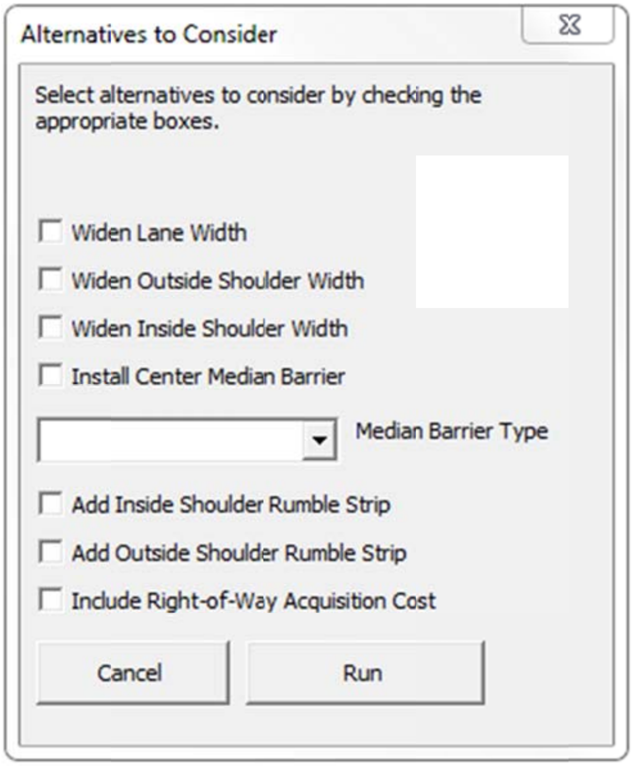


Figure B-48. Alternatives to consider for freeways

Place a check mark next to all alternatives you want to consider for improvement.

- **Widen Lane Width:** This option will appear only if the existing lane width is less than 12 ft. Selecting lane widening will result in consideration of all lane width options from the existing lane width to 12 ft in 0.5-ft intervals. If lane widening option is selected, the tool will automatically consider both widening lanes by adding width on the median side of the roadway and widening lanes by adding width toward the outside of the roadway. These scenarios may differ in cost; the benefits may differ as well, because a change in median width affects the benefits. Both widening scenarios are considered through the entire analysis process and both will be included in the results table.
- **Widen Outside Shoulder Width:** This option will appear only if the existing outside shoulder width is less than 12 ft. Selecting outside shoulder widening will result in consideration of all outside shoulder width options from the existing shoulder width to 12 ft, in 1-ft intervals.
- **Widen Inside Shoulder Width:** This option will appear only if the existing inside shoulder width is less than 12 ft. Selecting inside shoulder widening will result in consideration of all inside shoulder width options from the existing shoulder width to 12 ft, in 1-ft intervals.
- **Install Center Median Barrier:** This option will appear only if no continuous barriers (either centered or offset) are present. Select the barrier type or all barrier types that you want to consider in the analysis.

- **Add Inside Shoulder Rumble Strip:** This option will appear only if no inside shoulder rumble strip is currently present.
- **Add Outside Shoulder Rumble Strip:** This option will appear only if no outside shoulder rumble strip is currently present.
- **Include Right-of-Way Acquisition Cost:** Select this option if you want to include the cost of acquiring right-of-way in the economic analysis. If right-of-way acquisition costs are selected for consideration, the tool assumes that right-of-way acquisition is needed for all lane and shoulder widening towards the outside of the freeway.

B.4 Run the Analysis

Click the Run button in the Alternatives to Consider window to start the benefit-cost analysis.

The window shown in Figure B-49 will appear indicating the number of possible design alternatives based on your alternatives to consider input. Most analyses are completed within seconds, however there is a possibility of longer computing times if there are a very large number of design alternatives.

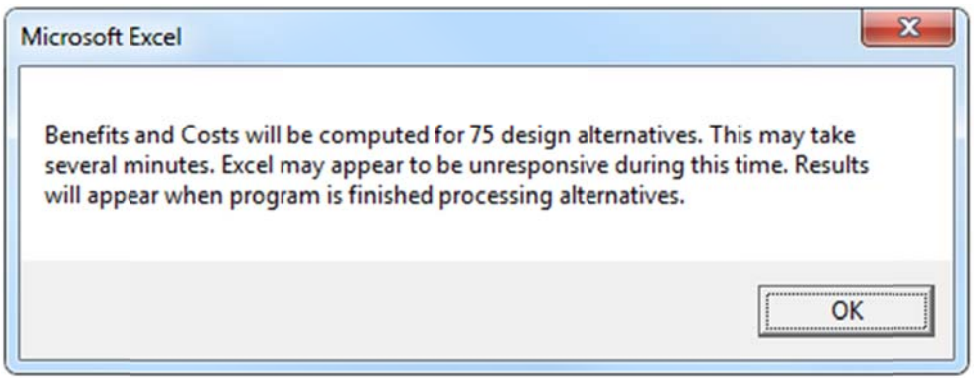
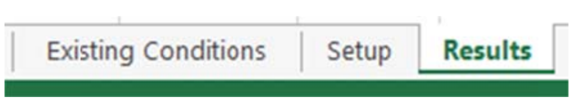


Figure B-49. Message prior to running the analysis

Click the OK button to proceed with the analysis.

B.5 Results

When the tool is finished computing benefits and costs for all possible alternatives, the results will be displayed in the Results worksheet. This worksheet will appear automatically.



The results of the analysis are presented in a table with each design alternative sorted by net benefits in descending order. For each alternative considered, the results table includes the improvement benefits, improvement costs, benefit-cost ratio, net benefits, and the "after project" condition for each roadway attribute that was considered for improvement.

For rural two-lane and multilane highways, any superelevation improvements to curves will be shown in the last column of the results table.

For freeway sections, the last column in the results table will indicate any changes that had to be made to median and outside barriers due to widening of lanes and shoulders. The cost of moving barriers is considered in the benefit-cost analysis.

The preferred alternative is generally the alternative with the highest net benefits whose improvement cost falls within the available budget for the project. However, the user is not constrained to select the preferred alternative indicated by the tool. The final decision on which alternative(s) to implement for a project always involves an assessment by the highway agency of a broad range of factors, safety cost-effectiveness being only one of those many factors.

Appendix C.
Updated Crash Cost Estimates

Crash costs are used in benefit-cost analyses to represent the benefits of reducing crashes. The crash cost values, by crash severity level, currently used in the examples presented in this document are as follows:

- Fatality (K) $4,008,900
- Disabling injury (A) $216,600
- Evident injury (B) $79,000
- Possible injury (C) $44,900
- Property damage only (O) $7,400

These crash cost values represent the comprehensive societal costs of crashes, and are currently used by a number of highway agencies in benefit-cost analyses. These values of crash costs are accepted and used by a number of highway agencies because they are presented in Chapter 7 of the AASHTO *Highway Safety Manual* (HSM) (*2*), and the HSM is generally considered an authoritative source. However, many highway agencies use crash costs that differ from these values. The crash cost values in current use by highway agencies range from approximately $1 million per fatality to over $9 million per fatality.

On looking further into the HSM crash cost values, however, it is evident that they are in need of updating. The HSM crash cost values are taken from a 2005 FHWA report (*31*), which it presents crash costs based on 2001 data. The FHWA report also provides a methodology for updating these crash costs to future years. The crash costs used as default values in these guidelines are based on the FHWA report values updated to 2015 levels. The recommended methodology for updating the crash cost values, based on the FHWA report is presented below. This updating procedure is in current use by both the New Hampshire and Ohio Departments of Transportation.

Table C-1 shows that the comprehensive societal costs of crashes by severity level for 2001 can be broken down into two components:

- human capital cost component
- other societal cost component

Table C-1. Separation of Comprehensive Societal Costs of Crashes for 2001 into Human Capital Cost and Other Societal Cost Components

Crash severity level	Comprehensive societal cost ($) 2001	Human capital cost component ($) 2001	Other societal cost component ($) 2001
Fatal (K)	4,008,900	1,245,600	2,763,300
Disabling injury (A)	216,600	111,400	104,600
Evident injury (B)	79,000	41,900	37,100
Possible injury (C)	44,900	28,400	16,500
Property damage only (O)	7,400	6,400	1,000

The human-capital costs for 2001 are updated to future years with the consumer price index (CPI) as published by the Bureau of Labor Statistics of the U.S. Department of Labor (*32*). The values of the CPI are 177.1 for 2001 and 237.9 for September 2015, so an update factor for human-capital costs can be computed as:

$$CPI_{2001\rightarrow 2015} = \frac{237.9}{177.1} = 1.344 \qquad \textbf{(C-1)}$$

Table C-2 shows how the human capital costs component of crash costs can be updated from 2001 levels to 2015 levels.

Table C-2. Updating of the Human Capital Cost Component of Comprehensive Societal Crash Costs from 2001 to 2015 Levels

Crash severity level	Human capital cost component ($) 2001	CPI update factor 2001→2015	Human capital cost component ($) 2015
Fatal (K)	1,245,600	1.344	1,674,100
Disabling injury (A)	111,400	1.344	149,700
Evident injury (B)	41,900	1.344	56,3000
Possible injury (C)	28,400	1.344	38,200
Property damage only (O)	6,400	1.344	8,600

The other costs for 2001 are updated to future years with the employment cost index (ECI) representing total compensation for all private industry workers, not seasonally adjusted, as published by the Bureau of Labor Statistics of the U.S. Department of Labor (*33*). The values of the ECI are 85.0 for 2001 and 124.5 for September 2015, so an update factor for human-capital costs can be computed as:

$$ECI_{2001\rightarrow 2015} = \frac{124.5}{85.0} = 1.465 \qquad \textbf{(C-2)}$$

Table C-3 shows how the other societal costs component of crash costs can be updated from 2001 levels to 2015 levels.

Table C-3. Updating of the Other Societal Cost Component of Comprehensive Societal Crash Costs from 2001 to 2015 Levels

Crash severity level	Other societal cost component ($) 2001	CPI update factor 2001→2015	Other societal cost component ($) 2015
Fatal (K)	2,763,300	1.465	4,048,200
Disabling injury (A)	104,600	1.465	153,200
Evident injury (B)	37,100	1.465	54,400
Possible injury (C)	16,500	1.465	24,200
Property damage only (O)	1,000	1.465	1,500

Table C-4 shows that the updated crash costs for 2015 are determined as the sum on the human-capital component and the other-costs component of crash costs, each updated from 2001 to 2015.

Table C-4. Combining the Human Capital Cost and Other Societal Crash Cost Components for 2015 into Comprehensive Societal Crash Costs

Crash severity level	Human capital cost component ($) 2015	Other societal cost component ($) 2015	Comprehensive societal cost ($) 2015
Fatal (K)	1,674,100	4,048,200	5,722,300
Disabling injury (A)	149,700	153,200	302,900
Evident injury (B)	56,3000	54,400	110,700
Possible injury (C)	38,200	24,200	62,400
Property damage only (O)	8,600	1,500	10,100

The updated crash costs in the final column of Table C-4 have been used in these guidelines in place of the HSM values, based on 2001 data, shown in the first column of Table C-1.