

***SafetyAnalyst*: Software Tools for
Safety Management of Specific
Highway Sites**

Task K

**White Paper for
Module 3—Economic Appraisal and
Priority Ranking**

**For
Federal Highway Administration**

**GSA Contract No. GS-23F-0379K
Task No. DTFH61-01-F-00096**

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Module 3—Economic Appraisal and
Priority Ranking**

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Preface

This white paper presents a plan for developing functional specifications for *SafetyAnalyst* software Module 3, the economic appraisal and priority-ranking tools, and was prepared for the Federal Highway Administration (FHWA) under the requirements of GSA Contract No. GS-23F-0379K, Task No. DTFH61-01-F-00096. This paper, prepared as part of Task K, summarizes the technical approach to development of the *SafetyAnalyst* economic appraisal and priority-ranking tools. Preparers of this paper include Mr. Douglas W. Harwood and Dr. Emilia Kohlman Rabbani, Midwest Research Institute (MRI), and other members of the *SafetyAnalyst* team.

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SAFETYANALYST WHITE PAPER FOR MODULE 3—ECONOMIC APPRAISAL AND PRIORITY RANKING

Section 1 Introduction

In April 2001, the Federal Highway Administration (FHWA) entered into a contract with Midwest Research Institute (MRI) to plan and develop a set of software tools for safety management of specific highway sites, known as *SafetyAnalyst*. The *SafetyAnalyst* team also includes iTRANS Consulting, Inc.; Human Factors North, Inc.; Ryerson Polytechnic University; Woodward Communications, Inc.; and Dr. Ezra Hauer. *SafetyAnalyst* will incorporate computerized analytical tools that correspond to the main steps in highway safety management for site-specific improvements. The *SafetyAnalyst* team will first plan and then develop detailed functional specifications for the *SafetyAnalyst* software tools. Under a separate contract, computer software to implement each tool will be developed by a yet-to-be-selected FHWA contractor from the functional specifications.

This white paper, prepared as part of Task J, summarizes the technical approach to development of *SafetyAnalyst* software Module 3, the economic appraisal, and priority-ranking tools. *SafetyAnalyst* will be comprised of four modules, which when packaged together, incorporate the six main steps for highway safety management:

- Module 1. Network screening
- Module 2. Diagnosis and countermeasure selection
- Module 3. Economic appraisal and priority ranking
- Module 4. Evaluation

Thus, this white paper addresses the technical approach to the third of the four *SafetyAnalyst* modules.

This white paper expands on the material documented in the *SafetyAnalyst* Work Plan (May 2002) and incorporates changes in response to comments from the September 2002 meeting of the Technical Working Group (TWG), providing detailed explanations of the general approach to be followed during *SafetyAnalyst* development, and the actual economic appraisal and priority-ranking processes to be implemented. It serves as a planning document as well as an overview of the module for the software development contractor. This will assure that the most appropriate economic appraisal and priority-ranking methodologies will be incorporated in the functional specifications provided to the software development contractor. The general approach to Module 3 utilizes many of the research results from NCHRP Project 3-56 (Harwood et al., 2002) and the work in

formulating the Interactive Highway Safety Design Model (IHSDM) Crash Prediction Model (Harwood et al., 2000).

This white paper provides a technical overview of the economic appraisal and priority-ranking tools, but it does not constitute a functional specification. The *SafetyAnalyst* team will develop a draft of a detailed functional specification for the economic appraisal and priority-ranking tools in Task L. That draft will be refined in response to FHWA and TWG comments in Task M. The detailed functional specification will then be provided to the software development contractor so that software development work can begin. It is expected that several key aspects of the economic appraisal and priority-ranking tools will remain to be resolved, even when the detailed functional specifications are complete. Thus, some pieces of logic may be incomplete in the functional specifications and some parameters may have values that are not yet quantified. Research to resolve these issues will be undertaken in Task E, in parallel with the software development effort.

This document is organized as follows. Following this introduction there is a general overview of the purpose of economic appraisal and priority-ranking tools. The third section discusses the planned capabilities of the economic appraisal and priority-ranking tools. The fourth section describes the functionality of the main components of the tools, namely those in which inputs are requested, required data are imported and processed, analyses are performed, and output is organized and delivered. The paper concludes with a section on planned development activities followed by two appendices. Appendix A provides a list of accident modification factors (AMFs) that have been developed and a list of those that will need to be developed. Appendix B presents a simplified example of safety benefit estimation using the Empirical Bayes (EB) approach.

Section 2

Purpose and Use of Economic Appraisal and Priority Ranking Tools

The purpose of the economic appraisal and priority-ranking tools is to provide the user with a means to conduct an economic analysis of implementing a countermeasure or combination of countermeasures at a site and for programming of safety countermeasures across a network. The extent of the economic appraisal performed by these tools is dependent upon the needs of the user. Several different scenarios exist for how a *SafetyAnalyst* user might utilize these tools. For example, for a particular roadway segment, intersection, or interchange ramp, a user might have already selected a countermeasure, either based upon output from the countermeasure selection tool or through personal experience/knowledge, for which the user would like to know the safety benefits in terms of the expected number of accidents to be reduced and in economic terms. In this situation, the economic appraisal tool will perform an economic analysis for that particular countermeasure at that specific site, based upon the economic criterion selected by the user. In another scenario, a user might have selected several countermeasures or combinations of countermeasures for possible implementation at a specific site. The user would be able to use the economic appraisal tool to evaluate the cost-effectiveness of each countermeasure and combination of countermeasures, based upon an economic criterion selected by the user, to determine which countermeasure(s) should receive top priority. In a final scenario, a user might have selected candidate countermeasures (or combinations of countermeasures) at multiple sites throughout the highway network and would like to know which countermeasures should be implemented to maximize the safety benefits, given budgetary constraints. The priority-ranking tool would be used in this final scenario.

Essentially, the economic appraisal tool will provide a means for estimating the safety effectiveness of countermeasures at a specific site within the highway network, expressing this effectiveness estimate in economic terms. The priority-ranking tool will provide the means to consider which countermeasure(s) should be implemented at a specific site using the safety effectiveness estimates, and provide a priority ranking of countermeasures across numerous sites given certain budget constraints.

Economic appraisal of candidate improvements and priority rankings for candidate improvements are very closely related. The primary distinction between the two tools concerns the number of sites considered in the analyses. The economic appraisal tool is intended for analysis of an individual site. This tool will be used to perform an economic analysis for a particular countermeasure or combinations of countermeasures at the specific site in question. The priority-ranking tool will be used to conduct economic analyses, which compare proposed countermeasures at multiple sites or at all sites within a jurisdiction.

The economic appraisal and priority ranking procedures will be developed for compatibility with the requirements for hazard elimination projects as part of FHWA's

Highway Safety Improvement Program (HSIP). *SafetyAnalyst* will be capable of providing economic analysis and priority ranking results in a form that will be accepted by FHWA as justification for a safety project. This will be accomplished, in part, by providing capabilities that meet FHWA's current HSIP guidelines and, in part, by providing new capabilities developed in consultation with FHWA based on the assumption that these new capabilities will be accepted by FHWA for use by state and local agencies to justify safety improvements.

Section 3

Capabilities Planned for the Tools

This section identifies the capabilities planned for the economic appraisal and priority-ranking tools. Details on how the tools will function to achieve these capabilities are provided in Section 4. Several of these capabilities will require results of previous tasks. Users may need the option to customize the tool, and omit some capabilities, if they do not have the data needed to support them.

3.1 Overview

The economic appraisal and priority-ranking tools will perform the following sequence of steps:

1. *Request the user to identify sites and countermeasures to be evaluated.*

The user will identify sites and countermeasures for which economic appraisals should be performed. The user will be able to obtain or create lists of sites and countermeasures in several ways:

- Import a list of selected sites and countermeasures directly from Module 2
- Open a saved file from Module 2 that displays selected sites and countermeasures
- Input a list of selected sites and countermeasures directly into Module 3

The user will then be able to choose from the lists the specific sites and countermeasures to be considered in economical appraisal and priority ranking.

2. *Request the user to select the economic criterion (or criteria) to be used in the economic appraisal.*

In this step, the user will select one or more economic criteria by which the economic appraisal will be performed:

- Cost-effectiveness
- Benefit-cost ratio
- Net benefits

- 3. Perform economic appraisal for the particular sites and countermeasures (or combinations of countermeasures) selected by the user.*

The tool will perform the economic evaluation based on the economic criterion (or criteria) of the user's choice for each of the sites and countermeasures (or combinations of countermeasures) selected in Step 1. The benefits would be calculated by determining the expected number of accidents per year for the existing site condition, using the same procedures developed for the *SafetyAnalyst* network screening tool, and then determining the expected number of accidents reduced per year using AMFs for the selected countermeasure(s). The construction cost will, whenever possible, be estimated from default values of unit cost incorporated in the program. These default values can be changed by the user when site specific data are available or the user can substitute an available site-specific estimate for the total project cost.

- 4. Display economic appraisal results to the user.*

In this step, the economic appraisal results will be displayed to the user. The user will have the option to review these results on the screen, print them, or save them to a file.

- 5. Rank alternatives based on criteria selected by the user.*

For a given site, the user will be able to display the results for all countermeasures evaluated in priority rank order based on one or more user-selected ranking criteria. When economic appraisals have been conducted for multiple sites, the user will be able to choose either to display rankings for all selected countermeasures (or combinations of countermeasures) or only the highest ranked countermeasures for each site based on the specific ranking criteria selected by the user. The user will also be able to request the order by which the countermeasures should be displayed (e.g., ascending order based on cost or cost effectiveness; or descending order based on expected number of accidents reduced, benefit-cost ratio, or net benefits).

- 6. Determine the improvement alternatives that should be implemented to maximize safety benefits given a budgetary constraint.*

The ranking tool should be able to determine the optimum mix of countermeasures for all sites selected that maximizes the systemwide safety benefits, given a budgetary constraint. The tool will use integer programming to perform the optimization process.

It is also expected that the tools will have a help function that will provide assistance and explanation of the use of the tool to users.

Section 4

Functional Approach to Each Capability

This section outlines the anticipated functional details for each capability of the economic appraisal and priority-ranking tools. The level of detail should provide an idea of the logical framework of the software and facilitate its application.

4.1 Request the User to Identify Sites and Countermeasures to Be Evaluated

The user will have several means available to identify sites and countermeasures for economic evaluation. One option will enable the user to directly access from Module 2 the list of sites and potential countermeasures for each site that were selected by the user with the countermeasure selection tool. With the first option, the user will typically be utilizing all of the *SafetyAnalyst* tools in sequential fashion beginning with network screening and culminating with economic appraisal and priority-ranking. A second option will enable the user to open a saved file from Module 2 with the same information. With this second option, the user will be returning to *SafetyAnalyst* to complete an analysis that was begun earlier. A third option will enable the user to directly input a list of new, or additional, sites and potential countermeasures for which economic evaluations should be performed. In this case, the user will be taken, by a command button, to the countermeasure selection tool input screen (Module 2) and will be able to identify the locations and potential improvement alternatives that he/she wants available for consideration in the economic appraisal and priority-ranking tools. In doing so, the user will be using logic from the countermeasure selection tool without realizing it.

Once the list of potential sites and countermeasures is identified, the user will be able to select the sites and countermeasures for the economic analysis. The user may include in the analysis any particular site or all sites. In addition, for any given site, the user may select certain countermeasures from the list or may include the entire list of potential countermeasures.

4.2 Request the User to Select the Economic Criterion (or Criteria) to Be Used in the Economic Appraisal

Several different scenarios are available for use in appraising or ranking sites. The scenarios range from performing an economic appraisal of one proposed countermeasure improvement at a specific site to performing an economic appraisal and ranking of multiple countermeasure improvements at multiple sites. Once a countermeasure or combinations of countermeasures has been selected for further consideration, the user will have the option within the economic appraisal tool to select the type(s) of economic criteria by which to evaluate the countermeasures:

- Cost-effectiveness (dollars spent per accident reduced)
- Benefit-cost ratio (ratio of the present value of future safety benefits of a project to the construction costs)
- Net benefits (present value of future safety benefits minus the construction costs)

The user will be able to select more than one criterion for evaluation, which will allow the user to compare the results of the different approaches. The advantages and disadvantages of each criterion, presented in more detail in the following section, may help the user decide which criterion or criteria are the most appropriate for his/her analysis.

After selection of the economic criteria the user will have the option to modify default values used in the economic analysis and priority ranking process. These default values include:

- monetary estimate of cost for specific accident severity levels
- AMFs
- construction costs for improvement projects
- service lives for improvement projects

These variables and their use in the economic analyses are explained in more detail in later sections of this report, but it is important to note that the user will have the option to adjust these variables to account for local conditions.

4.3 Perform Economic Analysis for a Particular Countermeasure (or Combination of Countermeasures) Selected by the User

Based on the type of economic criteria selected by the user, the economic appraisal tool will perform different calculations.

In evaluating a candidate improvement based upon the cost-effectiveness criterion, the cost-effectiveness of the candidate improvement is generally expressed in terms of the dollars spent per accident reduced. Projects with lower cost per accident reduced are more likely to maximize the benefits of an improvement program than projects with higher cost per accident reduced.

$$\text{Cost-effectiveness} = \text{Total Cost/Expected Number of Accidents Reduced} \quad (1)$$

This approach has the advantage of simplicity and may be more accepted than alternative approaches because it does not incorporate any estimates of accident reduction benefits in monetary terms. The primary disadvantages of this approach are it does not explicitly consider the severity of the accidents reduced, it is not well suited for deciding

among alternative candidate improvements for a given site, and it does not explicitly provide a recommended program that maximizes safety benefits. Severity weighting schemes can be incorporated into cost-effectiveness analyses to overcome one of the disadvantages of this approach, but the arbitrary nature of the weights may introduce some of the same concerns as assigning monetary values to accidents of different severity levels. The possible use of a severity weighting scheme to estimate equivalent property-damage-only (EPDO) accidents is addressed below.

The second approach to economic evaluation of candidate improvements is by benefit-cost ratio. The benefit-cost ratio is the ratio of the present benefit of a project to the construction costs. For a candidate improvement to be economically justified, its benefit-cost ratio should be greater than 1.0. The most desirable improvements are those with the highest benefit-cost ratios:

$$\text{B/C Ratio} = \text{Benefit/Cost} \quad (2)$$

Unlike the cost-effectiveness approach, benefit-cost ratios give explicit consideration to accident severity because accident cost estimates differ by severity level. FHWA uses a benefit-cost ratio approach for economic justification of safety improvements funded through the Highway Safety Improvement Program (HSIP). Therefore, it will be important that the economic appraisal and priority-ranking tools have the capability to conduct an evaluation that is compatible with the HSIP requirements so any project found to be justified by *SafetyAnalyst* would be acceptable for federal funding. A disadvantage of the benefit-cost ratio approach is that if there are multiple benefit and cost terms, it is not always clear whether specific terms belong in the numerator or the denominator of the benefit-cost ratio. For example, it is not always clear whether some maintenance costs should be treated as a decrease in the annual safety benefit or should be converted to a present value and treated as an increase in the project cost.

The third approach to economic appraisal of candidate improvements is by net benefits. The net project benefit approach assesses projects by benefits minus costs. Several sources, including Winfrey (1969) and AASHTO (1977), consider this approach to be superior to evaluation by a benefit-cost ratio because it eliminates the issue of whether particular cost items should appear in the numerator or denominator of the benefit-cost ratio. For this approach, the most desirable improvements are those with the highest net benefit:

$$\text{Net Benefit} = \text{Benefit} - \text{Costs} \quad (3)$$

The cost-effectiveness approach shown in Equation (1) is intended for application by users who do not wish to attribute monetary costs to accidents. The last two approaches [benefit-cost ratio and net benefit as shown in Equations (2) and (3)] require a monetary estimate of the costs and benefits for each countermeasure. Typically, all costs and benefits are expressed in monetary terms, which requires estimates of the dollar value of each accident reduced. All benefits and costs must be expressed consistently on either an annual or present-value basis. Conversion of costs or benefits between an annualized and

present value basis requires an estimate of the service life of the improvement and a specified minimum attractive rate of return (also known as the discount rate). A challenge in these approaches is deciding the monetary estimates of accident reduction benefits.

Both the benefit-cost ratio and net benefit approaches, treat accident reduction as an economic benefit. As noted above, the principles of economic analysis require that all benefits and costs must be expressed consistently on either an annual or present-value basis. The specific procedures presented below recommend the use of a present-value basis: the amount of future accident savings is converted to a present value and compared to the countermeasure construction cost which, by its nature is a present value. The use of a consistent basis for comparison, such as the present value, is necessary for:

- Comparing countermeasures with different service lives
- Comparing countermeasures in which the accident reduction benefits are not uniform over time

The argument can be made that a life saved 20 years in the future is worth no less than a life saved next year. This is correct, but the use of the present worth factor to convert future accident reduction benefits to their present value is not a moral judgment about the value of accident savings, but only an economic convention to allow appropriate comparisons of present expenditures and future benefits. Consider, for example, an alternative evaluation procedure that turns the issue around and performs the economic analysis on an annualized basis, rather than a net present value basis. The annual accident cost savings would be unchanged and the construction cost would be annualized using the capital recovery factor. The net annual benefits would be computed as the annual accident cost savings minus the annualized construction cost. This approach involves no moral dilemma, because the accident cost savings are constant, but it produces results that will provide *exactly* the same project rankings as the net present value approach.

The cost-effectiveness approach has been provided for any user who rejects the notion that accidents have costs that can be expressed in economic terms.

Inherent within the various types of economic analyses that Module 3 will be capable of performing is the estimation of benefits and/or costs of specific proposed improvements. The following sections discuss and exemplify the estimation of expected benefits and costs of proposed improvements and the formulation of the three economic criteria.

4.3.1 Expected Benefits of Improvements

The first step in estimating the expected safety benefit of an improvement is calculating the expected number of accidents reduced per year. The anticipated benefits of improvements are evaluated from “before-after” accident predictions. The two main

aspects to this process are:

- An estimate of the number, severity, and types of accidents that would occur *without the improvement(s) or modification(s)*
- An estimate of the reduction in the number, severity, and types of accidents that would occur *after the improvement(s) or modification(s) are implemented*

A large number of research studies have attempted to quantify the benefits of highway engineering improvements aimed at reducing the number and/or severity of accidents. From the before-after evaluations two approaches have been utilized for quantitatively estimating the safety benefits of improvements. One approach is estimating an AMF. An AMF represents the expected percent decrease (or increase) in a particular type of accident (target accident) for a given improvement. The second, and more recent, approach uses SPFs in an EB framework to predict the expected number of accidents reduced per year. SPFs are mathematical relationships between crash occurrence and traffic and other characteristics for a particular location type. In some cases, it may be appropriate to use SPFs to derive an AMF for a particular improvement type.

At present, AMFs are available only for a limited number of improvement types. This knowledge void results from the difficulty of evaluating the effects on crashes affected by a measure. Hauer has prepared for IHSDM a series of reports documenting what is known about AMFs for various design elements. Information on these and other AMFs is provided in IHSDM documents including the FHWA report by Harwood et al. (2000) entitled, *Prediction of the Expected Safety Performance of Rural Two-Lane Highways*. A list of design elements for which AMFs are available and another for which AMFs should be developed are presented in Appendix A.

SPFs for several facility types, including rural two-lane highways, rural multilane highways, urban arterials, and rural and urban freeways, will be needed for *SafetyAnalyst*. A consistent set of SPFs for a wide range of facility and accident types will be developed for *SafetyAnalyst*. It is not yet known whether these SPFs will be useful in estimating AMFs for particular countermeasures. This will be approached cautiously, however, because it has been established that, while regression models like the SPFs are good predictors of overall accident experience, the individual coefficients are not always good predictors of the incremental effects of particular geometric design or traffic control variables.

A procedure combining base models, like the SPFs anticipated for use in *SafetyAnalyst*, with AMFs for specific geometric design and traffic control features, has been formulated in the FHWA report mentioned above (Harwood et al., 2000) for use in the IHSDM Crash Prediction Module for rural two-lane highways. This module includes a procedure to calibrate the SPFs for application to other jurisdictions or other points in time than those used in their development. Appendix B presents a simplified illustration of the approach to safety benefit estimation using the EB procedure developed for the IHSDM crash prediction module. This example illustrates one approach that may be applied to safety benefit estimation in *SafetyAnalyst*.

When the effectiveness of given countermeasures is known or can be estimated in quantitative terms from AMFs/SPFs, these quantitative estimates will be incorporated into the economic appraisal and priority-ranking tools to calculate the expected number of accidents reduced per year. These AMFs/SPFs will serve as default values or estimates of the safety effectiveness for the given countermeasures. *SafetyAnalyst* users will also have the capability to calibrate and/or modify these AMFs for local conditions.

Any AMFs that are included in *SafetyAnalyst* will be treated as default values that users will have the capability to change as new research and evaluation results become available. In particular, Module 4 of *SafetyAnalyst* will be an evaluation tool that will allow users to evaluate countermeasures after their implementation to quantify their safety effectiveness. The results of such evaluations, when found to be reliable, should be used in future economic appraisals performed with Module 3.

It should also be noted that efforts are underway to develop a *Highway Safety Manual*. Just as the *Highway Capacity Manual* provides quantitative procedures to assess the traffic operational effects of proposed improvements, the *Highway Safety Manual* will provide quantitative procedures to assess the traffic safety effects of proposed improvements. The timing of *Highway Safety Manual* development relative to *SafetyAnalyst* development is uncertain, but it would be desirable for the *Highway Safety Manual* and *SafetyAnalyst* to use a consistent approach to safety benefit estimation.

SafetyAnalyst users need to be aware, however, that quantitative AMFs are not likely to be available for all potential countermeasures. When no default AMF for a countermeasure is included in *SafetyAnalyst*, the economic appraisal and priority-ranking tools will not be able to include the respective countermeasures in the analyses unless the user can provide an estimated AMF. When no default estimate of the safety effectiveness of particular countermeasures exists, the user will have the capability to input an estimate of the safety effectiveness (i.e., an AMF), based upon local experience. When such information is provided by the user, the economic appraisal and priority-ranking tools will include the respective countermeasures in the analyses.

When evaluating a potential countermeasure in terms of the project cost-effectiveness, estimating the expected safety benefit of an improvement ends with calculating the expected number of accidents reduced per year because project cost-effectiveness of a candidate improvement is generally expressed as cost per accident reduced. However, with the other types of economic analyses, it is common to express the expected safety benefits of an improvement in monetary terms. Not all analysts are comfortable with assigning monetary values to human lives or injuries, but in fact such estimates are inherent in all economic decisions to implement some highway improvement projects and not implement others. The following cost estimates for use in safety evaluation of highway improvements are FHWA's most recent accident cost estimates:

- Fatal accident \$3,000,000

- Incapacitating injury accident \$208,000
- Serious injury accident \$42,000
- Minor injury accident \$22,000
- Property-damage-only accident \$2,300

These estimates are based on a 1994 FHWA technical advisory and have been updated to 2002 cost levels. These estimates may serve as default cost estimates for use in safety evaluation, but the user will be able to adjust these cost estimates for local conditions. It is our understanding that FHWA is considering the adoption of accident cost estimates that incorporate the full economic and societal costs of accidents. The *SafetyAnalyst* team will monitor these efforts. It is our intention that *SafetyAnalyst* should incorporate, as default values, whatever set of accident costs are recommended by FHWA at the time of its release. However, users will be able to modify these default values so that analysis can be conducted in a manner consistent with the practices of individual highway agencies.

To compare the safety benefits of improvements that occur over a number of years to the construction costs which are incurred before the benefits begin to be realized, the safety benefits expressed in monetary terms must be reduced to their present value. This is accomplished by multiplying the annual benefits by the following factor:

$$(P/A, i, n) = \frac{(1+i)^n - 1}{i(1+i)^n} \quad (4)$$

- where:
- (P/A, i, n) = uniform series present worth factor to convert a series of uniform annual amounts to its present value
 - i = minimum attractive rate of return expressed as a decimal fraction (i.e., for a 4% minimum attractive rate of return, i = 0.04)
 - n = number of years that amounts are paid or received (i.e., service life of improvement)

The minimum attractive rate of return (i) represents the return that could be made on other projects or investments (i.e., the opportunity cost) if the funds were not invested on a highway safety improvement. A typical value for the minimum attractive rate of return is 4%, which corresponds to the average long-term cost of capital in real terms (i.e., adjusted for inflation); this value is recommended in the *AASHTO Manual on User Benefit Analysis of Highway and Bus Transit Improvements* (1977).

Based on the concept presented above, an equation was formulated in NCHRP Project 3-56 (Harwood et al., 2002) to determine the safety benefits. The equation and its main components are introduced below, followed by an example.

4.3.1.1 Safety Benefit Formulation

The benefits due to accidents reduced by a geometric or traffic control improvement can be estimated using a safety benefit equation that takes into account the following variables: expected number of annual accidents for location type m at site j (N_{jm}), accident modification factor for countermeasure k at location type m (AMF_{mk}), proportion of total accidents to which AMF_{mk} applies expressed as a decimal fraction and based on severity levels (RF_{ms}), and accident reduction cost by severity level (AC_s). The present value of the safety benefits for each countermeasure (or combinations of countermeasures) can be quantified as:

$$PSB_{jk} = \left[\sum_{m=1}^2 \sum_{s=1}^2 N_{jm} (1 - AMF_{mk}) RF_{ms} AC_s \right] (P/A, i, n) \quad (5)$$

where:

- PSB_{jk} = present value of safety benefits of countermeasure k at site j
- N_{jm} = expected annual accident frequency for location type m at site j
- AMF_{mk} = accident modification factor applied to total accidents for countermeasure k at location type m
- RF_{ms} = proportion of total accidents in severity level s to which AMF_{mk} applies, expressed as a decimal fraction
- AC_s = cost savings per accident reduced for accident severity level s
- $(P/A, i, n)$ = uniform series present worth factor to convert a series of uniform annual amounts to its present value

These variables and subscripts are described below in slightly more detail.

4.3.1.2 Subscripts

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

- nonintersection locations ($m = 1$)
- intersections ($m = 2$)

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

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

The index variable k represents the countermeasure (or combinations of countermeasures) considered (e.g., a combination of countermeasures may be a 1 ft increase in lane width, a 2 ft increase in shoulder width, and paving the shoulder).

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

4.3.1.3 Accident Modification Factors for Specific Improvement Types (AMF_{mk})

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

The ratio of the AMF after the improvement to the AMF before the improvement represents the AMF for the improvement itself. An improvement with an AMF of 0.95 would be expected to decrease accident frequency by 5 percent, while an improvement with an AMF of 1.05 would be expected to increase accident frequency by 5 percent.

A key issue to be addressed is the determination of appropriate AMFs for combinations of countermeasures. It is well established that accident reduction percentages should not be combined in additive fashion. If one countermeasure reduces accidents by 20 percent and another by 10 percent, their combined effort will not be 30 percent, but would be expected to be less than 30 percent. Current practice in the IHSDM crash predication module is to combine AMFs in multiplicative fashion. For the above example, the AMFs of 0.80 and 0.90 would be multiplied together to obtain an AMF of 0.72, corresponding to a 28 percent accident reduction. The multiplicative approach assumes that the safety effects of the two countermeasures are independent—that implementation of one does not influence the effectiveness of the other; this is a hypothesis that is probably incorrect, but the interactions between countermeasures are not enough understood to disprove it.

Some highway agencies which consider that the multiplicative approach presented above is too optimistic make a conservative assumption is that combinations of countermeasures have the same effectiveness as the more effective of the countermeasures being combined. In this approach, the combined effectiveness of a countermeasure with 20 percent effectiveness and one with 10 percent effectiveness would be 20 percent. This approach may be too pessimistic because it implies that it would *never* be justified to spend additional funds to implement both countermeasures because the same effect can be obtained by implementing just one.

The range of approaches to the effectiveness of combined countermeasures presented above results from a general lack of understanding of the interactions among the safety effects of combined countermeasures. In fact, the true effectiveness of combined countermeasures is probably within the range between the multiplicative result and the more effective of the individual countermeasures (i.e., between 20 and 28 percent in the preceding example).

SafetyAnalyst will need a consistent approach to dealing with the effectiveness of combined countermeasures. This approach will need to be developed as part of Task E. However, the dilemma concerning the effectiveness of combined countermeasures is indicative of the larger dilemma of uncertainty about the values of available AMFs. Our plan is to include the best available AMFs in *SafetyAnalyst*, but to allow users to replace those AMFs with values based on local experience and, as the *SafetyAnalyst* evaluation tool (Module 4) comes into wider use, with the results of evaluations performed within *SafetyAnalyst*.

4.3.1.4 Accident Severity Distribution (RF_{ms})

In most cases, AMFs for various countermeasures will be applied equally to accidents of all severity levels. Knowledge of the safety effects of geometric improvements has not yet progressed to the point that it is possible to reliably estimate such effects separately for each accident severity level. However, *SafetyAnalyst* will have the capability to incorporate AMFs that differ by severity level should these become available in the future. *SafetyAnalyst* will incorporate default levels of the accident severity distribution for roadway segments and intersections to estimate the reduction in accident frequency separately for each of two accident severity levels:

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

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

Table 1 provides the estimates of the accident severity distribution for nonintersection locations and at-grade intersections on two-lane highways based on data from the FHWA Highway Safety Information System (HSIS) for Illinois, Michigan, Minnesota, and North Carolina (Harwood et al., 2000). These estimates are examples of types of default values for the accident severity distribution that could be used in developing the software for Module 3.

Table 1. Default Distribution for Accident Severity Level for Two-Lane Highways (Harwood et al., 2000)

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

4.3.1.5 Expected Annual Accident Frequency (N_{jm})

The number of expected annual accidents for nonintersection locations, N_{j1} , and for at-grade intersections, N_{j2} , can be user-input values based on previous accident histories,

or determined through regression models, specific accident modification factors, and calibration factors (see Harwood et al., 2000).

4.3.1.6 Accident Reduction Cost (AC_s)

The safety benefits of specific countermeasures can be expressed in monetary terms using accident cost estimates such as the ones published by FHWA and presented earlier in the section. For analysis purposes, all of the fatal and injury accident levels can be combined into a single accident cost level. It is generally inappropriate to treat fatal accident costs separately when analyzing specific sites because the occurrence of a fatal accident at any particular site may be simply random. The A, B, and C injury levels can be combined because not all potential users of *SafetyAnalyst* have accident record systems that classify accident severity in this way. The accident cost estimates that would be used as default values based on the most recent FHWA data are:

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

SafetyAnalyst will allow users to replace the accident cost estimates with alternative values used by their agency.

A simplified example of safety benefit calculations is presented below. The AMF and RF values used in the example are based on those used in the IHSDM Crash Prediction Module (Harwood et al., 2000).

Example: *Given a 5-mi two-lane roadway segment with 10-ft lane widths and 2-ft paved shoulders, calculate the estimated safety benefit of widening the lanes to 11 ft.*

Assume that the safety prediction model for a typical base roadway segment is:

$$\text{Accidents/year} = ADT \times L \times 365 \times 10^{-6} \times \exp(-0.4865)$$

where: ADT = average daily traffic volume
 L = length of roadway segment (mi)

AMFs assembled by a team of experts are then used to adjust the base model prediction to account for the effects of lane width, shoulder width and type, roadside conditions, driveway density, horizontal curvature, vertical curvature, and grade.

The base condition considers:

Lane width (LW)	=	12 ft
Shoulder width (SW)	=	6 ft
Shoulder type (ST)	=	Paved
Roadside hazard rating (RHR)	=	3

Driveway density (DD)	=	5 driveways per mi
Horizontal curve	=	none
Vertical curve	=	none
Grade	=	level (0 percent)

For example, assuming a major road ADT of 12,000 veh/day the predicted safety performance for the base condition would be:

$$\text{Accidents/year} = 12,000 \times 5 \times 365 \times 10^{-6} \times \exp(-0.4865) = 13.46$$

In this example the roadway section differs from the base condition as follows: lane width is 10 ft, and shoulder width is 2 ft. For this the prescribed AMFs applied to total accidents are both 1.105 that is, accidents are increased 10.5% because the lane is 2 ft narrower than the base condition and another 10.5% because the shoulder is 4 ft narrower than the base condition. All other characteristics are in accordance with the base conditions. The predicted safety performance for the actual conditions is obtained by multiplying the base condition estimate by the two AMFs.

$$\text{Accidents/year} = 13.46 \times 1.105 \times 1.105 = 16.44$$

This would be our best estimate of the safety performance of this roadway segment in the absence of any crash history data. If we had such data, we could do better by using the EB procedure (see Appendix B for an EB example). The next step is to determine the AMF due to the improvement option. According to research conducted in IHSDM Crash Prediction Module (Harwood et al., 2000), for a 11 ft lane width the AMF applied to total accidents is 1.0175. Because the only improvement was to increase the lane width from 10 ft to 11 ft, the AMF applied to total accidents for the given improvement can be calculated by dividing the AMF after the improvement by the AMF before:

$$\text{AMF due to improvement} = 1.0175/1.105 = 0.92$$

This means that by increasing the lane width from 11 ft to 10 ft we can expect an 8% decrease in accidents. Thus, the safety benefit (expected decrease in number of accidents) of widening the lane from 10 to 11 ft can be estimated as:

$$16.44 \times (1-0.92) = 1.32 \text{ accidents per year}$$

If other improvements were made, the AMFs would be combined in a multiplicative fashion in order to get a final AMF.

The benefit of increasing the lane width from 10 to 11 ft can be expressed in monetary terms using Equation (5):

$$\text{PSB} = \{[16.44 \times (1-0.92) \times 0.321 \times 103,000] + [16.44 \times (1-0.92) \times 0.679 \times 2,300]\} \times \{[(1+0.04)^{20} - 1]/[0.04 \times (1+0.04)^{20}]\} = 45,538 \times 13.59 = \$618,867$$

Notice that the first term of the equation proportions the number of accidents reduced into fatal and injury accidents and property-damage-only accidents based on Table 1 values (0.321 and 0.679, respectively) and accident cost values (103,000 and 2,300, respectively). The second term converts the annual safety benefits to present value assuming a minimum attractive rate of return 4% and service life of 20 years for the improvements made.

For this example, the safety benefit would be equal to \$618,867.

4.3.2 Costs of Implementing Improvements

Estimating the construction cost of candidate countermeasures is more straightforward than estimating the benefits of candidate improvements, and highway agencies have extensive experience in estimating construction costs. The question arises, though, as to whether the economic appraisal and priority-ranking tools should provide default construction costs for candidate countermeasures, or should the user be prompted to input an estimate of the construction costs of each proposed countermeasure. Clearly, construction costs vary among highway agencies, so locally derived costs will provide more reliable analysis results than national average costs. There is also some concern that if the tools provide default construction costs, *SafetyAnalyst* users might simply accept the default cost estimates without considering whether those default values are appropriate for their own agency or for the site in question. However, based upon input from the TWG, it is recommended that, whenever possible, the economic appraisal and priority-ranking tools provide default construction cost estimates for candidate improvements, and that *SafetyAnalyst* users have the capability to modify the default estimates, as appropriate, on a site-specific basis. The construction cost would be determined based on site and countermeasure characteristics and unit construction cost values. An example of a construction cost calculation using unit constructions costs is presented below. The equation and default unit costs used in the example are based on the results of NCHRP Project 3-56 (Harwood et al., 2002).

Example: Given a 5-mi two-lane roadway segment with 10-ft lane width and 2-ft paved shoulder; calculate the construction cost of widening the lanes to 11 ft.

Since the segment has 2-ft paved shoulder before and after the improvement, there is a need to calculate the cost of shoulder widening in order to replace 1 ft of shoulder that will now be part of the lane width. According to NCHRP Project 3-56 (Harwood et al., 2002), the unit cost for lane widening is \$3.93/ft², for resurfacing the travel lane is \$1.07, for shoulder widening is \$5.32/ft² (includes roadside earth work costs), and for shoulder paving is \$0.47/ft². The construction cost can be calculated as follows:

$$CC = (LWcost + Rescost) \times L \times 5280 \times Nlanes \times (LW2 - LW1) + (SWcost + Srescot) \times L \times 5280 \times 2 \times \{[(LW2 - LW1) \times (Nlanes/2)] + (SW2 - SW1)\}$$

where: CC = construction cost

L	=	<i>total length of the site under analysis (miles)</i>
LW_{cost}	=	<i>lane widening cost (\$/ft²)</i>
SW_{cost}	=	<i>shoulder widening cost (\$/ft²)</i>
Res_{cost}	=	<i>pavement resurfacing cost (\$/ft²)</i>
$Sres_{cost}$	=	<i>shoulder paving cost (\$/ft²)</i>
$LW1$	=	<i>lane width before improvement</i>
$LW2$	=	<i>lane width after improvement</i>
$SW1$	=	<i>shoulder width before improvement</i>
$SW2$	=	<i>shoulder width after improvement</i>
N_{lanes}	=	<i>number of lanes</i>

For this example the construction cost would be equal to:

$$CC = (3.93+1.07) \times 5 \times 5280 \times 2 \times (11-10) + (5.32+0.47) \times 5 \times 5280 \times 2 \times [(11-10) \times 2/2 + (2-2)] = \$569,712$$

4.3.3 Costs-Effectiveness Formulation

Based on the definition of cost-effectiveness presented earlier, the cost-effectiveness formula can be written as follows:

$$CE_{jk} = CC_{jk} / AR_{jk} \quad (6)$$

where: CE_{jk} = cost-effectiveness of countermeasure k at site j
 AR_{jk} = number of accidents reduced for countermeasure k at site j
 CC_{jk} = construction cost for countermeasure k at site j

The number of accidents reduced by a geometric or traffic control improvement can be estimated using the expected number of annual accidents for location type m at site j (N_{jm}), accident modification factor for countermeasure k at location type m (AMF_{mk}), and the service life of the countermeasure (n). The accident reduction formula can be written as follows:

$$AR_{jk} = \sum_{m=1}^2 N_{jm} (1 - AMF_{mk}) n \quad (7)$$

where: AR_{jk} = number of accidents reduced for countermeasure k at site j
 N_{jm} = expected annual accident frequency for location type m at site j
 AMF_{mk} = accident modification factor applied to total accidents for countermeasure k at location type m
n = service life of countermeasure
m = 1 (for nonintersection locations) or 2 (for at-grade intersections)

For the example presented in Sections 4.3.1 and 4.3.2, the cost-effectiveness of widening lane width from 10 to 11 ft would be:

$$CE = \$569,712/[16.44 \times (1-0.92) \times 20] = \$21,659 \text{ per accident reduced}$$

The construction cost to reduce each accident would be \$21,659.

Consideration will also be given to providing a cost-effectiveness measure that is sensitive to the severity levels of the accidents reduced. For example, the equivalent property-damage-only (EPDO) accident concept could be implemented by replacing Equations (6) and (7) with:

$$CE_{jk} = CC_{jk}/EPDOAR_{jk} \quad (8)$$

$$EPDOAR_{jk} = \sum_{p=1}^{pmax} \sum_{m=1}^2 N_{jmp} (1 - AMF_{mkp}) n W_p \quad (9)$$

where:

- EPDOAR_{jk} = number of equivalent PDO accidents reduced for countermeasure k at site j
- N_{jmp} = expected annual accident frequency for severity level p and location type m at site j
- AMF_{mkp} = accident modification factor for accidents of severity level p and countermeasure k at location type m
- n = number of years included in analysis
- W_p = equivalent PDO accident weight assigned to accident severity level p
- p = accident severity level (e.g., five levels as shown in Section 4.3.1 for FHWA accident costs)

Some highway agencies use arbitrary EPDO weights such as a weight of 9 for a fatal accident, a weight of 4 for an injury accident, and a weight of 1 for a PDO accident. However, such arbitrary weights do not appear to be sufficiently well supported for use in *SafetyAnalyst*. FHWA accident cost data suggest that the EPDO weights (W_p) for specific severity levels should be more like:

- Fatal accident 1,300
- Incapacitating injury accident 90
- Serious injury accident 18
- Minor injury accident 10
- Property-damage-only accident 1

The argument can be made that this approach to setting EPDO weights gives too much weight to the random occurrence of a single fatal accident, but the use of the EB

approach should help assure that the occurrence of a single *observed* fatal accident does not bias the *expected* fatal accident frequency.

4.3.4 Benefit-Cost Ratio Formulation

Based on the benefit and cost estimates presented in Sections 4.3.1 and 4.3.2, the benefit-cost ratio equation can be written as follows:

$$B/C_{jk} = PSB_{jk} / CC_{jk} \quad (10)$$

For the example presented, the benefit cost ratio of widening the lane from 10 to 11 ft would be:

$$B/C = \$618,867 / \$569,712 = 1.098$$

Since the benefit-cost ratio is more than 1.0, it can be said that increasing the lane width from 10 to 11 ft in the example presented earlier is economically justified.

4.3.5 Net Benefit Formulation

The values of net benefit (NB_{jk}) for a specific countermeasure at a particular site can be determined with the following equation:

$$NB_{jk} = PSB_{jk} - CC_{jk} \quad (11)$$

where: NB_{jk} = net benefit for countermeasure k at site j
 PSB_{jk} = present value of safety benefits of countermeasure k at site j (see Equation 5)
 CC_{jk} = construction cost for countermeasure k at site j

For the example presented earlier, the net benefit of widening the lane from 10 to 11 ft would be:

$$NB = \$618,867 - \$569,712 = \$49,155$$

Since the net benefit is positive, it can be said that increasing the lane width from 10 to 11 ft in the example presented earlier is economically justified, which is the same result achieved with the benefit-cost ratio analysis. The next section shows how the results of the economic appraisal determined in this section may be presented to the user.

4.4 Display Economic Appraisal Results to the User

This capability allows the user to see the results of the economic appraisal based on the criterion (criteria) chosen for all sites and countermeasures selected. The user may choose to see the results of more than one economic criterion at the same time, and will

have the option to review these results on the screen, print them, or save them to a file. Table 2 presents a possible software output for the example problem presented in the previous section. The table was created assuming that the user had elected to appraise the improvement using all three economic criteria.

Table 2. Economic Appraisal Summary Output for Example Problem

Site	Location	Countermeasure	Cost-effectiveness (\$/accident reduced)	Benefit/cost ratio	Net benefit (\$)
01	Route 7 (MP 2-7)	Widening lane from 10 to 11 ft	\$21,659	1.098	\$49,155

4.5 Rank Alternatives Based on Economic Criteria Selected by the User

When the user wants to compare candidate improvements at one specific site, the user will utilize the economic appraisal tool for this purpose, but when the user wants a priority ranking of candidate improvements across multiple sites, the priority-ranking tool will be used. A key question to be addressed with the priority-ranking tool is which specific candidate improvements should be undertaken first. Several methods, covering a wide range of complexity, will be available for establishing priority rankings. At a minimum, the priority-ranking tool will be capable of ranking candidate improvements by project cost, expected project benefits, number of accidents reduced, number of fatal and injury accidents reduced, project cost-effectiveness, project benefit-cost ratio, and net project benefits. The user will have the ability to select the specific priority-ranking criterion to apply. The priority-ranking tool will also be capable of either ranking all countermeasures considered or present only the highest ranked alternative improvement for each site, and display the results in order of increasing project cost or in order of decreasing ranking criteria. Such rankings by themselves are not a decision making tool, but they do provide information that is useful to decision makers. Table 3 summarizes the priority-ranking tool’s capabilities that should be available to the user.

Table 3. Menu of Priority-Ranking Tool Capabilities Available to the User

Ranking criteria	Countermeasures to be ranked	Order of display
<input type="checkbox"/> Cost <input type="checkbox"/> Benefit <input type="checkbox"/> Cost-effectiveness <input type="checkbox"/> Benefit-cost ratio <input type="checkbox"/> Net benefit <input type="checkbox"/> Number of accidents reduced <input type="checkbox"/> Number of fatal and injury accidents reduced	<input type="checkbox"/> All countermeasures <input type="checkbox"/> Highest ranked countermeasure for each site	<input type="checkbox"/> Descending order <input type="checkbox"/> Ascending order

4.6 Determine the Alternatives That Should Be Implemented to Maximize Safety Benefits Given a Budgetary Constraint

The priority-ranking tool will enable the user to maximize the overall safety benefit of any expenditures, taking into consideration budgetary constraints which the user will have to input. Several mathematical optimization techniques exist for prioritizing resource allocations, including:

- incremental benefit-cost analysis
- integer programming
- linear programming
- dynamic programming
- goal programming
- network analysis techniques

Integer programming has been successfully implemented in the Resurfacing Safety Resource Allocation Program (RSRAP) developed in NCHRP Project 3-56 (Harwood, et al., 2002). RSRAP is a program that evaluates the need for safety improvements in conjunction with resurfacing projects. Based upon the *SafetyAnalyst* team's recent experience utilizing integer programming and based upon the review of optimization techniques conducted during Task A and documented in the Task A Working Paper (June 2001), integer programming is recommended as the optimization technique of choice for Module 3. A brief description of this optimization technique is provided in the following paragraphs.

Integer Programming (IP) is a linear programming technique in which some or all of the decision variables are restricted to integer values. A typical integer program can be illustrated as follows:

Maximize (or minimize) Y, where:

$$Y = \sum_{i=1}^n c_i x_i \quad (12)$$

subject to:

$$\sum_{i=1}^n a_{1i} x_i \leq b_1 \quad (13)$$

$$\sum_{i=1}^n a_{2i} x_i \leq b_2 \quad (14)$$

⋮

$$\sum_{i=1}^n a_{mi} x_i \leq b_m \quad (15)$$

Equation (12) is known as the objective function of the linear program because it represents the objective that is to be maximized or minimized. The variables c_1, \dots, c_n in the objective function are numerical values appropriate to the particular problem being evaluated; for example, c_1, \dots, c_n might represent the costs and benefits of particular improvement types or projects. The variables x_1, \dots, x_n in the objective function are called the decision variables, because assigning values to the variables is the decision that must be made. All of the decision variables in an integer program are limited to nonnegative integer values (i.e., greater than or equal to zero). The decision variable in an integer program might be constrained, for example, so that only 0 and 1 are acceptable values: 1 if a particular design alternative were selected for implementation as part of a particular project and 0 if that design alternative were *not* selected for implementation. Equations (13) through (15) represent the constraints on the values of the decision variables. Such constraints could be used to limit total expenditures to a fixed budget amount and to prevent incompatible or infeasible combination of alternatives from being implemented. The constraints can be either equations (equalities) or inequalities. For example, if several alternative designs (including the no-build alternative) were considered for a given site, a constraint would be provided for each project to limit the number of alternatives selected for that project to one and only one; this would be a simple constraint in which the sum of the decision variables for all design alternatives for that project must be exactly equal to one. Since an integer program can address only one objective function, all costs and benefits would need to be put on a common basis, typically by expressing them in monetary terms.

Integer programs can be solved with mathematical techniques such as the Simplex algorithm and various branch-and-bound algorithms. These algorithms determine the values of the decision variables, which produce the maximum (or minimum) value of the objective function, while not violating any of the constraints. Such algorithms can be applied manually but, for any realistic problem, the computations quickly become quite laborious and repetitive.

FHWA reports (FHWA, 1981; McFarland et al., 1979) state that limited progress had been made in the solution of large-scale highway safety problems using this method. However, RSRAP and other recent applications indicate that integer programming can be used effectively in highway safety applications.

Taking into account that the benefits and costs for each countermeasure (or combinations of countermeasures) have already been determined by the economic appraisal tool (see Section 4.3), the optimization process for the priority-ranking tool can be determined with the following equations:

$$\text{Maximize TB} = \sum_{j=1}^y \sum_{k=1}^z \text{NB}_{jk} X_{jk} \quad (16)$$

subject to the following constraints:

$$\sum_{k=1}^z X_{1k} = 1 \quad (17)$$

$$\sum_{k=1}^z X_{2k} = 1 \quad (18)$$

⋮

$$\sum_{k=1}^z X_{yk} = 1 \quad (19)$$

$$\sum_{j=1}^y \sum_{k=1}^z CC_{jk} X_{jk} \leq B \quad (20)$$

- where:
- TB = total benefits from all selected countermeasures
 - X_{jk} = an indicator value whose value is 1 if countermeasure k at site j is selected as part of the optimum allocation of funds and whose value is 0 if countermeasure k at site j is not selected as part of the optimum allocation of funds. For each site exactly one countermeasure (or combinations of countermeasures) should be selected.
 - CC_{jk} = construction cost for countermeasure k at site j
 - B = improvement budget or maximum funding available for improvement of the sites under consideration

Equation (16) is the objective function of the integer program, which represents the total benefits to be maximized. The constraints on the optimal solution are represented by the equalities and inequalities presented below the objective function. They require that one and only one countermeasure (or combinations of countermeasures) can be selected for each site. The last inequality constrains the total expenditure on improvements to be less than or equal to the available budget.

The optimal solution to the integer program is the group of improvement alternatives that provides the maximum total benefit subject to the constraints in Equations (17) through (20). This optimum solution consists of the improvement alternative for each site for which the value of X_{jk} in the integer program is equal to 1.

4.7 Summary of Inputs and Outputs

4.7.1 Inputs

The user will provide two types of inputs into the economic appraisal and priority-ranking tools: those that are input for each analysis and those that are input on an infrequent basis. Inputs made by the user for each analysis are referred to as required

inputs. Inputs made by the user occasionally, or infrequently, are referred to as optional inputs.

4.7.1.1 Required Inputs

Users will be required to provide three types of input for each analysis:

- the location(s) or sites(s) to be considered within the analysis
- the candidate improvements or combinations of improvements to be considered for each location or site
- budget constraints

For each analysis the user must select or identify the location(s)/site(s) and the candidate improvement(s) to be considered. As a starting point, the user may wish to include in the analysis the entire list of potential countermeasures for each site provided by the countermeasure selection tool, or the user may decide to select certain countermeasures within the list for each site for inclusion in the analysis. The user may also input certain location(s) and candidate improvement(s) or combinations of improvements selected through other means for inclusion in the economic analysis.

When allocating resources through mathematical optimization, the user must input any budget constraints that should be considered during the analysis. Obviously, the user will be required to input the amount of available funding for countermeasure improvements. The user will also be able to input other budgetary constraints such as allocating a percentage of funds for rural projects and a percentage of funds for urban projects.

4.7.1.2 Optional Inputs

Optional inputs will be provided by the user infrequently. These inputs include default variables provided within the tools that the user has the option to modify or adjust for local conditions. It is anticipated that if users decide to modify these default values, it will be when the users are becoming familiar with the tools, during the initial phases of implementing *SafetyAnalyst*, or as information becomes available at a later date. Once these values are accepted or modified by users, it could be quite some time before users exercise the option to adjust these values again. Thus, these optional inputs will serve as settings for all future analyses until otherwise adjusted by the user.

Optional inputs for the economic appraisal and priority-ranking tools will include:

- monetary value of respective accident severities and inputs for present worth
- AMFs/SPFs
- construction costs

During the initial use of these tools, the user must select the type of economic criterion by which to rank or evaluate the candidate improvements, either by project cost-effectiveness, project benefit-cost ratio, net project benefits, or resource allocation by mathematical optimization. The user will also have the ability to request that the candidate improvements be ranked by project benefits or project costs. For example, a user may wish to rank candidate improvements in terms of the number of accidents reduced (total and by severity level) or in terms of monetary savings from accidents reduced, disregarding for the moment implementation costs. Likewise, a user may wish to rank candidate improvements by implementation costs, either in increasing or decreasing order, possibly to identify projects which are short-term low cost solutions. It is likely that once highway agencies become accustomed to the capabilities and outputs of the economic appraisal and priority-ranking tools, highway agencies will adopt policies such that a certain type of economic criterion will be used for every analysis. Consideration will also be given for users to have the ability to select multiple types of economic criteria for ranking of candidate improvement for each analysis. Thus, a user will have the ability to select the type of output to be provided from each analysis.

When the user selects a ranking methodology that requires assigning monetary values to human lives or injuries, the user will have the capability to accept the default cost estimates or adjust them for local conditions. The default cost estimates for fatal accidents, incapacitating injury accidents, serious injury accidents, minor injury accidents, and property-damage-only accidents as currently recommended by FHWA are provided above. A user will also have the ability to modify variables for calculating present worth such as the minimum attractive rate of return (i) and service life of improvements (n).

AMFs are available for a limited number of improvement types, and a procedure has been developed to calibrate SPFs for given local conditions. Therefore, when the effectiveness of a given countermeasure improvement can be quantified, the quantitative estimates will serve as default values for calculating safety benefits. The user will have the ability to adjust the given AMFs or calibrate the SPFs for local conditions. When a potential countermeasure does not have a quantitative AMF/SPF associated with it, the tools will notify the user of this dilemma, and the user will have the capability to input a quantitative estimate of its safety effectiveness.

Construction cost estimates for candidate improvements will be provided within the economic appraisal and priority-ranking tools. These estimates will serve as the default values. The user will have the capability to modify the default estimates by inputting cost estimates based upon local experiences.

4.7.2 Outputs

The user will have the ability to customize the type of output provided by the economic appraisal and priority-ranking tools but not the format of the output. It is

expected that the user will be capable of obtaining the safety effectiveness of candidate improvements in ranked or prioritized order of:

- the number of accidents reduced (total and by severity level)
- the monetary savings from accidents reduced
- the implementation costs
- dollars spent per accident reduced (project cost-effectiveness)
- the ratio of the present benefit of a project to the construction costs (project benefit-cost ratio)
- the benefits minus the construction costs (net project benefits)

Output from the economic analysis tool for project development (specific to one site) will not have to identify the location or site for the respective countermeasure(s). Each candidate improvement will be associated with only the one location or site. However, when multiple sites are included in the analysis for program development, output from the priority-ranking tool will have to indicate the location or site of the candidate improvement, the type of candidate improvement, and the associated safety effectiveness. It might be that the output will be presented in a three-column array. When the safety benefits are maximized within a constrained budget through mathematical optimization, a similar type of three-column array will be output indicating the location or site of the candidate improvement, the type of candidate improvement, and the associated safety effectiveness. In addition, a table will summarize the safety effectiveness of implementing the respective program, given the economic criterion selected by the user.

Section 5

Planned Development Activities

This section itemizes planned development activities, with a view to planning the next steps and scheduling the work to be done over the course of the project.

5.1 Technical Development

The following activities are anticipated for development of the *SafetyAnalyst* economic appraisal and priority-ranking tools:

- interact/liaise with countermeasure selection tool development to provide guidance on desired output from countermeasure selection process and development of AMFs for some improvement types
- determine procedures for estimating the safety benefits of improvements which could possibly require developing AMFs for some improvement types and ensuring that a complete suite of SPFs is available for all potential *SafetyAnalyst* applications
- develop cost estimates for implementation of improvements
- evaluate how recent research advances can be incorporated into the techniques of benefit-cost analysis
- develop procedures for ranking candidate improvements by the number of accidents reduced (total and by severity level), the monetary savings from accidents reduced, the implementation costs, the dollar spent per number of accident reduced (project cost-effectiveness), the ratio of the present benefit of a project to the construction costs (project benefit-cost ratio), and the benefits minus the construction costs (net project benefits)

5.2 Issues to Be Resolved

The following issues concerning the *SafetyAnalyst* economic appraisal and priority-ranking tools remain to be resolved:

- AMFs are available for a limited number of improvement types (see Appendix A for a list of them). Should the research team determine and approve additional AMFs? An expert panel was formed to develop the AMFs for two-lane highways in the IHSDM Crash Prediction Module. Should there be a similar panel for *SafetyAnalyst*? Should this be handled internally by the research team?

- How to handle those improvement types in the analyses that do not have an associated AMF? Should such improvements be omitted from consideration by the economic appraisal and priority-ranking tools or should *SafetyAnalyst* users be able to provide their own benefit estimates?
- Should *SafetyAnalyst* consider nonsafety factors (either qualitative or quantitative)? For example, in some states the Endangered Species Act limits the ability to make safety improvements at some sites.

Section 6

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Appendix A

List of Existing and Desirable AMFs

This appendix presents a list of AMFs that have already been developed and a list of AMFs for which development would be desirable.

Existing AMFs

Listed below are the design element improvements for which AMFs have been already developed for rural two-lane highways and, in some cases, for rural multilane highways, as well:

- Lane width
- Shoulder width
- Shoulder type (paved, turf, gravel, composite)
- Horizontal curve (incorporates: length, radius, presence or absence of spiral transitions, and superelevation)
- Grades
- Driveway density
- Passing lane
- Two-way left-turn lanes
- Passing lanes/short four-lane sections
- Roadside conditions
- Turn-lanes at intersections (incorporates: skew angle, traffic control, exclusive left-turn lanes, exclusive right-turn lanes, and intersection sight distance)

Desired AMFs

Listed below are some design elements for which AMFs have not been yet developed. Development of such AMFs would be desirable.

- Vertical curves
- Rumble strips
- Ramp metering
- Visibility of signs
- Pavement markings
- Interchanges
- Access point density

Appendix B

Simplified Example of Safety Benefit Estimation From the IHSDM Crash Prediction Module

For illustrative purposes this appendix presents an example of the IHSDM safety benefit estimation procedure applied to an intersection. The example was developed by Harwood et al. (2000) and includes the use of the Empirical Bayes (EB) procedure.

Example: Consider a four-leg stop-controlled intersection, for which the full safety prediction model is:

$$\text{Accidents/year} = \exp(-9.34 + 0.60 \ln (\text{Major Road ADT}) + 0.61 \ln (\text{Minor Road ADT}) + 0.13(\text{ND}) - 0.0054 (\text{SKEW}))$$

where:

ND is the number of driveways within 76 m (250 ft) of the intersection on the major road

SKEW is the intersection skew angle (= 0 for right-angle intersections)

The base condition is no driveways, adequate sight distance, no turn lanes, and no skew. For this condition, the base model reduces to:

$$\text{Accidents/year} = \exp(-9.34 + 0.60 \ln (\text{Major Road ADT}) + 0.61 \ln (\text{Minor Road ADT}))$$

Accident modification factors (AMFs) assembled by a team of experts are then used to adjust the base model prediction to account for the effects of skew angle, traffic control, exclusive left- and right-turn lanes, and sight distance at a specific intersection.

For example, assuming the simplification of no agency-specific calibration adjustment for an intersection with a major road AADT of 8,000 veh/day and a minor road AADT of 1,000 veh/day gives a predicted safety performance for the base condition of:

$$\text{Accidents/year} = \exp(-9.34 + 0.60 \ln (8000) + 0.61 \ln (1000)) = 1.304$$

Suppose an intersection differs from the base condition as follows: Sight distance is limited in one quadrant of the intersection. For this the prescribed AMF is 1.05, that is, accidents are increased 5% by the presence of a sight restriction in one quadrant of the intersection. All other characteristics are in accordance with the base conditions—there are no exclusive right- or left-turn lanes and there is no skew. The predicted safety performance for the actual conditions is obtained by simply multiplying the base condition estimate by the AMFs.

$$\text{Accidents/year} = 1.304 \times 1.05 = 1.37$$

This would be our best estimate of the safety performance of this intersection in the absence of any crash history data. If we had such data, we could do better by using the EB procedure. Suppose the intersection actually recorded five crashes in the past 3 years. The expected crash frequency (E) considering both the model prediction and the observed frequency is given by

$$E = w (N_p) + (1-w) x$$

where:

N_p is the predicted frequency over a period of length equal to that of the observed accident count

x is the observed count

w is the weight $1/(1+k N_p)$

k is an over-dispersion parameter derived in the model calibration

For four-leg stop-controlled intersections, the value of k is 0.24. Thus:

$$N_p = 3 \times 1.37 = 4.11, w = 0.50$$

$$E = 0.50(4.11) + 0.50(5) = 4.56 \text{ accidents in 3 years}$$

Note this value is between the five accidents observed and the 4.11 accidents in 3 years (1.37/year) predicted without a consideration of the actual accidents experience. This is because the refined estimate of 4.56 crashes in 3 years is a weighted average of the 5 accidents observed and the 4.11 accidents predicted strictly on the basis of the traffic and design characteristics. Now suppose that the addition of a left-turn lane is being considered following the diagnosis phase. The AMF prescribed by the panel of experts for installing a left-turn lane is 0.76. The expected accident frequency considering the installation of left-turn lane can be calculated by multiplying the refined estimate by the AMF:

$$\text{Accidents in three years} = 4.56 \times 0.76 = 3.47$$

$$\text{or } 1.16 \text{ accidents per year}$$

Thus, the safety benefit (decrease in number of accidents) of installing the left-turn lane can then be estimated as:

$$E - (0.76 \times E) = 4.56 - (0.76 \times 4.56) = 1.09 \text{ accidents in 3 years or}$$

$$0.36 \text{ accidents per year}$$

It should be emphasized that this example is simplified. Consideration should be given to accident severity and to traffic volume changes; and estimates of uncertainty should be provided as well. Adjustment of the base model for application in a specific jurisdiction will usually be necessary as well, and Harwood et al. provides guidance on these aspects.