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# Development of a Design Flexibility Toolkit

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**JOINT TRANSPORTATION RESEARCH PROGRAM**
INDIANA DEPARTMENT OF TRANSPORTATION
AND PURDUE UNIVERSITY

# DEVELOPMENT OF A DESIGN FLEXIBILITY TOOLKIT

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**16. Abstract**

The American Association of State Highway and Transportation Officials (AASHTO) publication titled *A Policy on Geometric Design of Highways and Streets* (Green Book) provides guidance to the designer by referencing a recommended range of values for critical dimensions for the design of highway facilities. For various reasons, it may be necessary to design a section of highway with substandard values for some elements. Such design exceptions require appropriate assessment and justification of the potential impacts to highway safety and operations. This study was performed to develop a guideline for design exceptions. The guideline for development and evaluation of design exception projects was developed and presented. The guideline outlines the steps for developing and evaluating design exception projects. The potential impacts of design exception elements to highway safety and operations are listed for the 13 controlling criteria to provide designers with important and easy to use information. The possible counter measures for each of the controlling criteria are listed in a one-page table for easy reference. The proposed safety evaluation process was presented in terms of safety impacts of individual substandard elements as well as the combined impacts of the substandard elements. An Excel based computer program was developed for life-cycle benefit-cost analysis of design exception projects. A decision on design exceptions can thus be made rationally with the recommended guideline and methods.

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design exception, highway safety, highway operations, construction cost, user benefit

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## EXECUTIVE SUMMARY

# DEVELOPMENT OF A DESIGN FLEXIBILITY TOOLKIT

## Introduction

The American Association of State Highway and Transportation Officials (AASHTO) publication titled *A Policy on Geometric Design of Highways and Streets* (Green Book) provides guidance to the designer by referencing a recommended range of values for critical dimensions for the design of new alignments and those undergoing major reconstruction. These guidelines permit sufficient flexibility to encourage independent designs for specific situations. The approach allows the designer to use flexibility to introduce "lower than typical" design values for a specific element to address an impacted area. This process allows for adjusting almost every aspect of the geometric design and may require both state and federal approval. Use of design flexibility may include use of a design exception. The current version of the *Indiana Design Manual* (IDM) provides and promotes some level of flexibility, particularly on non-NHS routes. The selection of design criteria for a transportation project is typically screened by the highway system the project is located on, functional classification, area type, forecasted traffic data and classification of project type. The use of design exceptions is one way to obtain design flexibility. Design exceptions require appropriate level of justification.

A design flexibility toolkit would be an extremely useful tool for transportation designers to have. This toolkit would be a reference document and an on-line tool which could serve as a one stop location that illustrates the research behind the values for each design criteria element, potential safety and or operational effects of selecting certain values and potential compounding effects on operation if more than one design exception is utilized. The objective of this study was to develop a highway design flexibility toolkit that can be used by INDOT engineers as a design tool as well as a training tool.

The general research approach was to review the federal and state highway design standards; analyze the principles and reasoning behind these standards; identify the major factors affecting highway classifications and highway designs; and determine the areas of possible design flexibilities. The major tasks accomplished in this study include the following:

- Literature Review and Questionnaire Survey: A comprehensive literature review was conducted to identify available methods and practices of applying highway design exceptions. Through the literature review, the design exception practices of some states were identified. In addition, a questionnaire survey was conducted to obtain specific information from the neighboring states.
- Analysis of Impact of Major Design Controlling Criteria: The impacts of the major design controlling criteria were analyzed. The controlling criteria included design speed, lane width, shoulder width, bridge width, horizontal and vertical alignment, grade, stopping sight distance, cross slope, superelevation, and vertical and horizontal clearance.
- Safety Evaluation of Design Exception Projects: A number of actual INDOT design exception projects were analyzed. A field visit was made to some of the design exception projects to examine the operations and verify the geometric dimensions. The computer software *Interactive Highway Safety Design Model* (IHSDM) and the *Highway Safety Manual* (HSM) were utilized to evaluate the safety impacts of these design exception projects.
- Economic Analysis: An important factor for a design exception project is the cost of the project. Computer software was developed to conduct economic analysis of design exception projects to compare the life cycle costs of different design options. The software can be used to estimate the benefits and costs in terms agency cost, operation cost, and safety impact.
- Development of the Design Flexibility Toolkit: The toolkit was developed with the analysis results to provide step-by-step instructions for engineers.

## Findings

A thorough evaluation of IHSDM and HSM was conducted to explore the feasibility of using the tools for safety assessment of design exception projects. A case study was performed to illustrate the process of safety evaluation. It was demonstrated that IHSDM can be used to generate quantitative measures of safety impacts of design exception projects. IHSDM is capable of analyzing safety impacts of an individual substandard element as well as combined effects of a number of substandard elements. With IHSDM, the sensitivity of substandard elements can be analyzed by changing the values of design criteria. Using different combinations of substandard elements, such as lane width and shoulder width combinations, designers can choose the best alternative that would minimize the negative safety impacts. It is therefore recommended that INDOT use IHSDM in design exception projects for safety impact assessment. IHSDM has incorporated most of the methods and calculations in HSM, but there are still some of the items in HSM that are not included in IHSDM. It is possible that designers may need to use HSM in addition to IHSDM for design exceptions, such as in evaluating safety impacts of roundabout intersections.

One of the commonly used methods for justifying design exception projects is to use the savings in construction cost. However, this method is not a reasonable one because it does not include the impacts of a substandard highway section to the highway safety and operations. In this study, benefit-cost analysis method was used to evaluate the effectiveness of design exceptions. An Excel based computer program was developed to conduct benefit-cost analysis for design exceptions. This method includes not only the savings in construction cost and other initial costs, but also the user benefits in terms of travel time, vehicle operation, and safety. The computer program will be a useful and convenient tool for INDOT to evaluate design exception projects.

The guidelines for development and evaluation of design exception projects were developed and presented. The guidelines recommend the steps for developing and evaluating design exception projects. The potential impacts of design exception elements to highway safety and operations are listed for the 13 controlling criteria to provide designers with important and easy to use information. The possible counter measures for each of the controlling criteria are listed in a one-page table for easy reference. It is recommended that IHSDM be used to analyze safety effects and the Excel based computer program be used to conduct benefit-cost analysis for design exception projects.

## Implementation

This study provided INDOT with guidelines for design exception projects. The guidelines include the steps for developing and evaluating design exception projects. Following the recommended steps, a designer will be able to choose appropriate design exception elements in considerations of their individual potential impacts to highway safety and operations. Once the design exception alternatives are developed, the combined effects of the substandard elements on highway safety and operations can be analyzed with the IHSDM software package. Effective safety measures will be selected from the recommended list. The life-cycle benefit-cost will then be conducted with the Excel based computer program developed in this study. The final choice of the design exception alternative based on the thorough analyses outlined in this study will reflect the best available information and engineering rationale and judgment. In addition, the guidelines can also be used by INDOT as a training tool.

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# 1. INTRODUCTION

The American Association of State Highway and Transportation Officials (AASHTO) publication titled *A Policy on Geometric Design of Highways and Streets* (Green Book) (*1*) provides guidance to the designer by referencing a recommended range of values for critical dimensions for the design of new alignments and those undergoing major reconstruction. These guidelines permit sufficient flexibility to encourage independent designs for specific situations. The approach allows the designer to use flexibility to introduce "lower than typical" design values for a specific element to address an impacted area. This process allows for adjusting almost every aspect of the geometric design and may require both state and federal approval. Use of design flexibility may include use of a design exception.

The current version of the *Indiana Design Manual* (IDM) (*2*) provides and promotes some level of flexibility, particularly on non-NHS routes, which can be found in Chapter 40, Sections 40.8.02 (01), 40.8.02 (02), and 40.8.02 (03). The selection of design criteria for a transportation project is typically screened by the highway system the project is located on, functional classification, area type, forecasted traffic data and classification of project type. The use of design exceptions is one way to obtain design flexibility. Design exceptions require appropriate level of justification.

A design flexibility toolkit would be an extremely useful tool for transportation designers to have. This toolkit would be a reference document and an on-line tool which could serve as a one stop location that illustrates the research behind the values for each design criteria element, potential safety and or operational effects of selecting certain values and potential compounding effects on operation if more than one design exception is utilized. The objective of this study was to develop a highway design flexibility toolkit that can be used by INDOT engineers as a design tool as well as a training tool.

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- **Analysis of Impact of Major Design Controlling Criteria**: The impacts of the major design controlling criteria were analyzed. The controlling criteria included design speed, lane width, shoulder width, bridge width, horizontal and vertical alignment, grade, stopping sight distance, cross slope, superelevation, and vertical and horizontal clearance.
- **Safety Evaluation of Design Exception Projects**: A number of actual INDOT design exception projects were analyzed. A field visit was made to some of the design exception projects to examine the operations and verify the geometric dimensions. The computer software *Interactive Highway Safety Design Model* (IHSDM) (*3*) and the *Highway Safety Manual* (HSM) (*4*) were utilized to evaluate the safety impacts of these design exception projects.
- **Economic Analysis**: An important factor for a design exception project is the cost of the project. Computer software was developed to conduct economic analysis of design exception projects to compare the life cycle costs of different design options. The software can be used to estimate the benefits and costs in terms agency cost, operation cost, and safety impact.
- **Development of the Design Flexibility Toolkit**: The toolkit was developed with the analysis results to provide step-by-step instructions for engineers.

# 2. LITERATURE REVIEW AND QUESTIONNAIRE SURVEY

## 2.1 Literature Review

Design Exceptions have been studied by many researchers. NCHRP Report 330 (*5*) concluded that even though the use of narrower lanes may increase the potential of vehicle crash, the inclusion of other safety features may offset these increases and produce an overall improved safety. This study also indicated the potential of interactive effects between various design elements and the need for careful evaluation of the use of narrower roadway lanes. The Federal Highway Administration (FHWA) published a guide for designing highways that incorporate community values and are safe and efficient for the movement of people and goods (*6*). This publication provides case studies from several states.

A National Cooperative Highway Research Program (NCHRP) report of the Transportation Research Board describes the range of design exception practices among state Departments of Transportation (DOT) and discusses the problems and suggested improvements based on the experience of state agency personnel (*7*). This synthesis characterizes (1) conditions that require a design exception, (2) data collection and analysis techniques, and (3) internal state DOT and external rules. The report also describes benefits and problems experienced by State DOTs and identify suggestions for improving and streamlining the design exception process. A survey questionnaire was distributed to all 50 states and the District of Columbia, and 46 completed surveys were returned. The written design exception procedures of 30 state DOTs were obtained and reviewed. The report shows that the most frequent design elements utilizing design exceptions are horizontal alignment of roadways, shoulder widths, stopping sight distance, lane width, and design speed.

NCHRP Synthesis 422 (*8*) identified eleven typical categories of trade-offs in highway geometric designs, including (1) access management, (2) cost, (3) environmental issue, (4) historic impact, (5) human factors/driver expectancy, (6) operational efficiency, (7) right-of-way (ROW) availability, (8) safety, (9) schedule, (10) social concerns, and 11) tort liability exposure. This NCHRP report provided ranking scores of controlling design criteria in terms of their likelihood for the highway engineers to consider in design exceptions. The ranking scores were determined according to the scores given by state DOTs in the survey. Table 2.1 (*8*) shows the ranking results from state DOTs based on a scale of 1 to 10 with 10 being most likely. This table indicates that shoulder width had the highest likelihood (7.7) for design exception consideration and structural capacity has the lowest likelihood (2.0) for design exception consideration. Other highly ranked criteria include vertical alignment (6.4), lane width (6.2), grade (6.1), and horizontal alignment (5.7).

Another NCHRP study analyzed relationships among design, operating, and posted speeds in highway design (*9*). The study results indicate that design speed had minimal impact on operating speeds unless on a tight horizontal radius. Large variance in operating speed was found on rural two-lane highways. Hauer (*10*) examined the relationship between design standards and roadway safety. The study indicated the need and importance of further investigation of the impacts of design flexibility on roadway safety. Agent, Pigman and Stamatiadis (*11*) examined past design exception projects in Kentucky and documented the frequencies of various types of those design exceptions. They found that the most commonly applied design exceptions included design speed, sight distance, curve radius, and shoulder width. An INDOT sponsored study (*12*) was conducted to analyze the effects of design exception projects on highway safety in Indiana. The results showed that the design exception projects did not have statistically significant effect on the frequencies or severities of highway crashes. Stein and Neuman (*13*) developed a guide on design exception mitigation strategies that provides a review of the areas where such variance can be applied and identifies means that could be used as solutions to address design exceptions and variances.

TABLE 2.1
**Average Willingness Scores of Controlling Criteria for Design Exceptions**

| Design Exception | Score |
|---|---|
| Shoulder width | 7.7 |
| Vertical alignment | 6.4 |
| Lane width | 6.2 |
| Grade | 6.1 |
| Horizontal alignment | 5.7 |
| Bridge width | 5.5 |
| Superelevation | 5.5 |
| Cross slope | 5.4 |
| Horizontal clearance | 5.2 |
| Stopping sight distance | 4.5 |
| Vertical clearance | 4.5 |
| Design speed | 3.9 |
| Structural capacity | 2.0 |

NCHRP Synthesis 299 (*14*) conducted an extensive literature review on geometric design elements for improving safety and operations. They identified the key areas in design that could have impacts on highway

TABLE 2.2
**Safety Measures for Design Exceptions (*16*)**

| Design Exception | Safety Measures |
|---|---|
| Stopping sight distance | Fixed object removal<br>Shoulder widening<br>Highway lighting (sag curves)<br>Advisory speed signs<br>Reducing speed limits<br>Warning signs<br>No turn on red signs<br>Left turn slots<br>Stop and yield signs<br>Turning prohibitions |
| Superelevation (mainline and interchange ramps) | Delineators<br>Shoulder widening<br>Flatten side slopes |
| Minimum radius of curve (mainline and interchange ramps) | Pavement antiskid treatment<br>Warning signs<br>Fixed object removal<br>Improved drainage system<br>Raised pavement markers<br>Rumble strips |
| Cross slope | Slippery when wet signs<br>Transverse pavement grooving<br>Improved drainage system |
| Minimum grades | Re-grading of the border<br>Provide additional drainage |
| Maximum grades | Warning signs<br>Advisory speed limits<br>Climbing lanes |
| Lane width (through and auxiliary) | Pavement edge lines<br>Raised pavement markers<br>Delineators |
| Shoulder width | Removing fixed objects<br>Eliminating steep slopes<br>Signage (narrow lane, narrowed shoulder)<br>Rumble strip<br>Beaded / reflective pavement edge, lines |
| Through-lane drop transition length | Warning signs<br>Advisory speed limits |
| Acceleration and deceleration lane length (for ramps) | Additional pavement markings and signing<br>Delineators |
| Bridge width | Traffic control devices<br>Approach guide rail<br>Object and pavement markings<br>Flashers<br>Warning signs |
| **Vertical clearance over roadway** | Warning signs |
| **Structural capacity** | Warning signs |

safety. AASHTO (*15*) developed a guide for achieving design flexibility in highway design. The guide emphasizes that flexible design does not entail a fundamentally new design process, nor does it suggest new or revised design criteria. It indicates that achieving a reasonable flexible design solution requires designers to understand the reasons behind processes, design values, and design procedures.

To assure highway safety with design exception projects, appropriate measures must be applied to offset the negative effects of the highway features that do not meet the standard. The New Jersey Department of Transportation (NJDOT) recommended the safety measures for the common design criteria in its manual for design exceptions (*16*). Table 2.2 presents the NJDOT recommended safety measures for design exceptions. These safety measures provide highway engineers with useful information for design exceptions.

The most significant advancement in highway safety evaluation is the publication of the *Highway Safety Manual* (HSM) (*4*). The HSM is a combined result of many research efforts in tens of years. It provides safety knowledge and tools in a useful form to facilitate improved decision making based on safety performance. It also provides quantitative information for decision making. HSM assembles currently available information and methodologies on measuring, estimating and evaluating roadways in terms of crash frequency (number of crashes per year) and crash severity (level of injuries due to crashes). The HSM tools and methodologies can be used for safety evaluations in highway planning, programming, project development, construction, operations, and maintenance. HSM provides analytical tools and techniques for highway planner and engineers to evaluate the potential effects on crashes of proposed highway designs. In terms of design flexibility, HSM provides us a timely tool for this study to quantify the safety impacts of design exception projects.

### 2.2 Questionnaire Survey

To obtain the information on design exception practices in other states, a questionnaire survey was conducted. As the study advisory committee (SAC) of this study recommended, the questionnaire was distributed to the state DOTs of the neighboring states of Indiana. The Missouri Department of Transportation listed five design exception projects in 2010. All of the five projects are related to stopping sight distances. The Ohio Department of Transportation indicated that on average Ohio would have 90 design exception projects per year. The top three types of these projects are related to stopping sight distance, horizontal alignment, and superelevation and the top three reasons for design exceptions are environmental issues, historic impacts, and right-of-way availability.

The Illinois Department of Transportation provided a list of its design exception projects in 2010 with specific types of design exceptions in these projects. Table 2.3 presents the types of design exceptions and the number of projects in each type of these design exceptions. As can be seen in the table, taper length and storage length were the two most utilized types of design exceptions in Illinois in 2010. The table shows that the projects with these two types of design exceptions are all located in urban areas. In addition, the table also indicates that all but one of the design exception projects were on state roads.

The Kentucky Department of Transportation provided a list of design exception projects between 1993 and 2000. The design exception projects after 2000 was not provided by Kentucky as the records of these projects were not compiled. Table 2.4 lists the types and numbers of design exception projects in each year. The table clearly indicates that design speed, sight distance, horizontal curve radius, and shoulder width are the most commonly utilized design exceptions in Kentucky. The main reasons for these design exception projects and their corresponding numbers of projects are shown in Table 2.5. In terms of the numbers of the projects, the top three reasons for design exceptions in Kentucky are environment, right-of-way, and cost.

## 3. REVIEW OF DESIGN EXCEPTION PROJECTS IN INDIANA

In order to find out the status of design exception projects in Indiana, the documents and records of 56 selected INDOT design exception projects were exam-

TABLE 2.3
**Types and Frequencies of Design Exceptions in Illinois (2010)**

| Type of Design Exception | Number of Projects Involved | Highway Type | Location |
|---|---|---|---|
| Superelevation | 1 | Interstate | Rural |
| Superelevation | 8 | State Road | Rural |
| Shoulder width | 2 | State Road | Rural |
| Cross slope | 2 | State Road | Rural |
| Clear zone | 3 | State Road | Rural |
| Vertical alignment | 4 | State Road | Rural |
| Guardrail | 10 | State Road | Rural |
| Storage length | 43 | State Road | Urban |
| Taper length | 46 | State Road | Urban |

TABLE 2.4
**Numbers of Different Types of Design Exceptions in Kentucky**

| | Year | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Type of Exception** | **1993** | **1994** | **1995** | **1996** | **1997** | **1998** | **1999** | **2000** | **TOTAL** |
| Design speed | 9 | 30 | 31 | 33 | 30 | 29 | 14 | 15 | 191 |
| Minimum sight distance | 3 | 6 | 9 | 12 | 13 | 10 | 5 | 10 | 68 |
| Minimum radius (curvature) | 11 | 2 | 7 | 16 | 6 | 13 | 6 | 6 | 67 |
| Shoulder width | 7 | 12 | 3 | 5 | 5 | 16 | 9 | 6 | 63 |
| Ditch width | 4 | 4 | 5 | 6 | 5 | 8 | 5 | 6 | 43 |
| Pavement/lane width | 4 | 2 | 1 | 15 | 7 | 8 | 1 | 4 | 42 |
| Bridge width | 1 | 3 | 0 | 14 | 7 | 6 | 1 | 3 | 35 |
| Number of lanes | 0 | 0 | 0 | 5 | 3 | 3 | 0 | 5 | 16 |
| Maximum grade | 1 | 2 | 2 | 2 | 0 | 4 | 3 | 1 | 15 |
| Superelevation | 0 | 1 | 0 | 1 | 0 | 9 | 1 | 0 | 12 |
| Acceleration lane | 0 | 1 | 2 | 1 | 0 | 0 | 0 | 0 | 4 |
| Clear zone/border | 0 | 0 | 0 | 0 | 0 | 2 | 1 | 0 | 3 |
| Earth cut/fill slope | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 2 |
| Bridge railing | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| Tie down | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 |
| Access spacing | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| Guardrail end treatment | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| TOTAL | 41 | 64 | 60 | 110 | 77 | 109 | 46 | 58 | 565 |

ined. These design exception projects were proposed and approved between 2007 and 2010. On average, INDOT had about 50 design exception projects each year. The design exception projects were proposed based on the values of basic control criteria specified in the *Indiana Design Manual* (IDM) (*2*). The INDOT specific values for the design criteria (*2*) along with the corresponding values from the Green Book (*1*) are listed in Table 3.1. Although the INDOT values of the design criteria are in general agreement with the AASHTO recommended ones, they differ in specific values for many of the design criteria.

Among the 56 selected INDOT design exception projects, the numbers of design exception projects in each of the categories are summarized and presented in Table 3.2. The total number of design exceptions in Table 3.2 is 66, which is larger than the total number of projects of 56. This is because that some of the 56 design exception projects contained more than one design exceptions. The percents of each of the design exceptions in Table 3.2 are plotted in Figure 3.1. As the table and figure show, the highest numbers of design exception projects are related to superelevation and shoulder width. It should be emphasized that the values in Table 3.2 and Figure 3.1 were obtained from only the 56 selected projects. They are used only as a sample of the INDOT design exception projects. Therefore, the values in the Table 3.2 and Figure 3.1 do not necessarily reflect the actual proportions of all design exception projects in Indiana.

TABLE 2.5
**Reasons for Design Exceptions in Kentucky (1993–2000)**

| **Reason** | **Number** | **Frequency (%)** |
|---|---|---|
| Existing conditions | 207 | 40.0 |
| Right-of-way | 103 | 19.9 |
| Cost | 78 | 15.1 |
| Length (scope) | 35 | 6.8 |
| Environmental | 27 | 5.2 |
| Adjacent property issue | 25 | 4.8 |
| Stop condition | 18 | 3.5 |
| Utility | 17 | 3.3 |
| Defer construction | 4 | 0.8 |
| Railroad issue | 2 | 0.4 |
| Lighting | 1 | 0.2 |
| Congestion | 1 | 0.2 |
| TOTAL | 518 | 100 |

The distributions of the design exceptions during the four years are illustrated in Figure 3.2 in terms of numbers of specific design exceptions. This figure clearly indicates that the numbers of design exceptions related to superelevation and shoulder width were always relatively higher than other types of design exceptions in each of the four years.

The selected design exception projects were on different types of highways, as shown in Figure 3.3 and Table 3.3. The majority of the design exception projects were on state roads (32.56%), county roads (30.23%), and local roads (20.93). As a comparison, the percents of design exception projects on different roads in Illinois are plotted in Figure 3.4. As indicated in Figure 3.4, Illinois DOT reported that in Illinois 99% of the design exception projects were on state roads and only 1% of them were on interstate. Since other state DOTs that responded to the survey did not provide the types of roads in their design exception projects, these percents cannot be compared with those in other states

TABLE 3.1
**INDOT and AASHTO Design Criteria**

| Design Exception | Design Speed (mph) | Green Book | | IDM | |
|---|---|---|---|---|---|
| | | Max | Min | Max | Min |
| Superelevation | 45 | 10–12% | — | 6% | — |
| Shoulder width | 35 | 12 ft | 1 ft | — | 1 ft |
| Horizontal curve radius | 30 | — | 187 ft | — | 133 ft |
| Stopping sight distance | 45 | — | 360 ft | — | 423 ft |
| Lane width | 25 | 12 ft | 9 ft | — | 10 ft |
| Bridge width | 30 | — | — | 15 ft for a one-lane bridge | |
| Maximum grade | 30 | 10% | — | 12% | — |
| Vertical clearance | 30 | — | 14 ft | — | 14 ft |

TABLE 3.2
**Numbers of Design Exception Projects in Various Categories**

| Design Exception | 2007 | 2008 | 2009 | 2010 | Total |
|---|---|---|---|---|---|
| Superelevation | 2 | 4 | 8 | 4 | 18 |
| Shoulder width | 1 | 1 | 9 | 4 | 15 |
| Horizontal curve radius | 1 | 0 | 3 | 3 | 7 |
| Stopping sight distance | 2 | 1 | 2 | 2 | 7 |
| Lane width | 0 | 1 | 4 | 1 | 6 |
| Bridge width | 1 | 1 | 2 | 1 | 5 |
| Bridge railing | 1 | 1 | 0 | 2 | 4 |
| Cross slope | 0 | 1 | 0 | 1 | 2 |
| Maximum grade | 0 | 0 | 1 | 0 | 1 |
| Horizontal clearances | 1 | 0 | 0 | 0 | 1 |
| TOTAL | 9 | 10 | 29 | 18 | 66 |

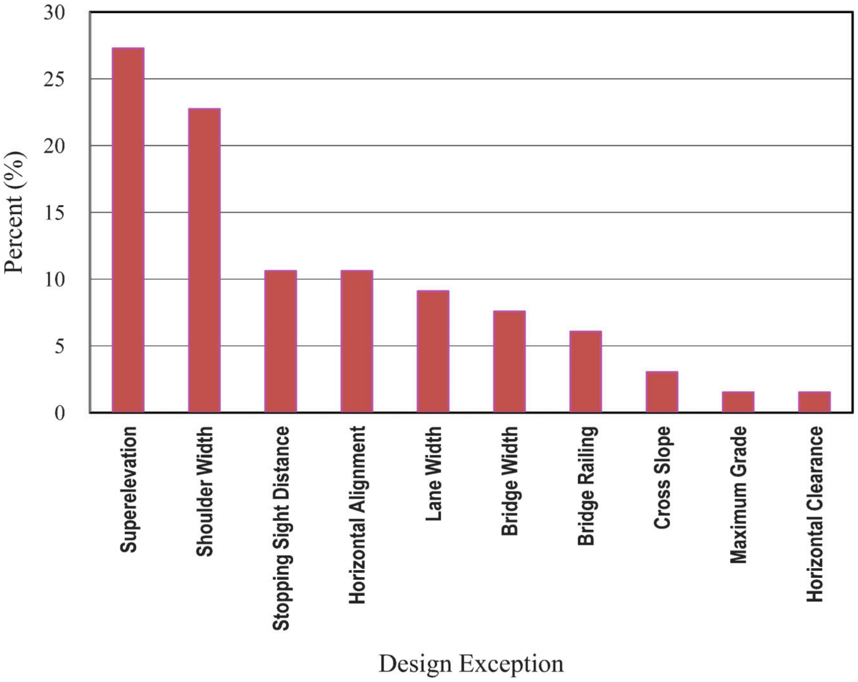


**Figure 3.1** Frequencies of design exceptions in Indiana.

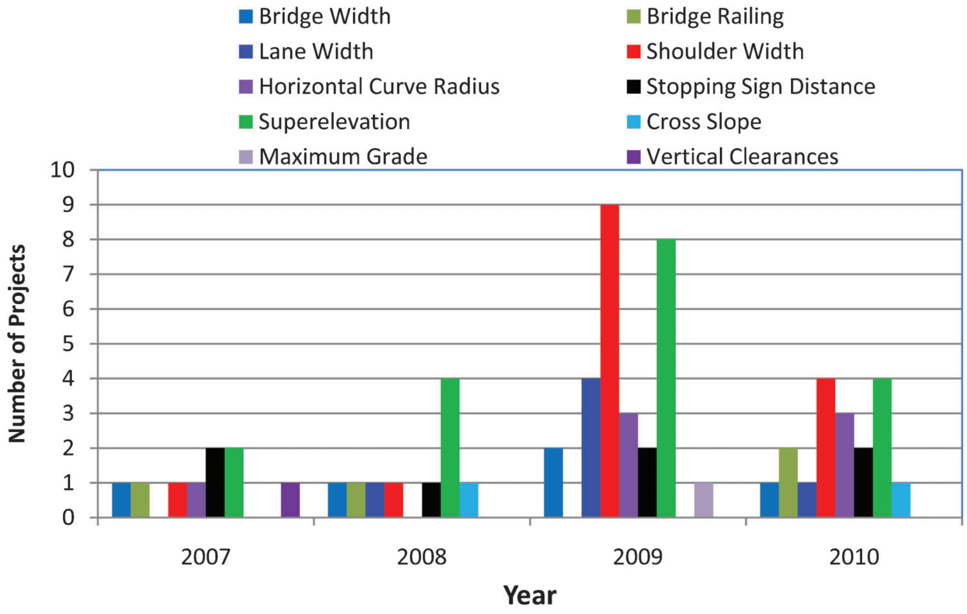


**Figure 3.2** Distributions of the selected INDOT design exception projects.

other than Illinois. However, it is understandable that most of the design exception projects were on state, county and local roads rather than on interstates because in general design exceptions are more suitable for low volume or low speed roads. The effects of the types of design exceptions on safety in Table 3.3 were not specified in the original designs of these projects. It should be pointed out that the safety impact depends on many factors and the specifics of individual projects and it may not be possible to generalize the types of design exceptions in the order of safety effectiveness.

Eleven of the 56 design exception projects were on the National Highway System (NHS). Figure 3.5 shows the percents of the design exception projects on NHS and non-NHS roadways. The geographical locations of the 56 design exception projects are shown in Figure 3.6. The number adjacent to each county's name in the map represents the number of design exception projects located in the county. The counties with more than one design exception projects are highlighted in Figure 3.5.

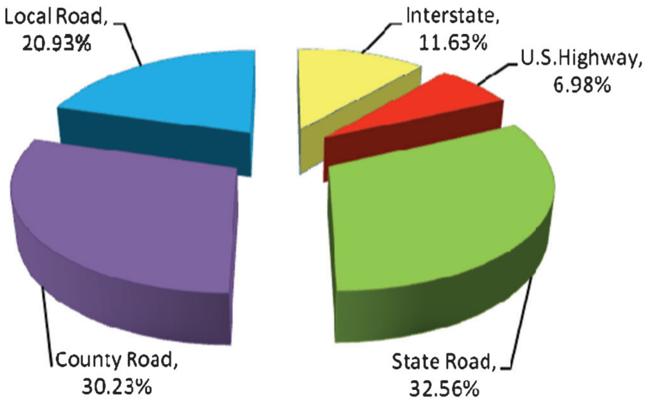


**Figure 3.3** Indiana Design Exception Projects on Different Types of Highways.

It can be found in each of the design exception documents what the reason or justification was for the proposed design exception project. The reasons and their corresponding numbers and percentages are summarized and listed in Table 3.4. As can be seen in the table, seven main reasons were used to justify design exceptions. Among the seven reasons, the top three reasons are "cost savings," existing conditions" and "right of way," in which "cost savings" had considerably higher percent than any of other cited reasons. The percentages of types of design exceptions in Indiana (Table 3.4) are compared with those in Kentucky as shown in Figure 3.7. In Kentucky, the top three reasons for design exceptions are the same as in Indiana, but in a different order, i.e., "existing conditions," "right of way" and "cost savings."

It is understandable that design exceptions may pose potential risk to highway safety because these projects contain features that do not meet the established design standards. To offset the negative effects of design exceptions, some safety measures or counter measures can be applied to improve highway safety. Most of the safety measures proved to be quite effective, even though they might not be expensive. In the reviewed 56 Indiana design exception projects, about 80% of them used safety measures to minimize the potential negative effects of the design exceptions on highway safety. The safety measures utilized in these design exception

TABLE 3.3
**Types and Reasons of Design Exception Projects**

| Type of Highway | Number of Projects | Type of Design Exception | Reasons | Safety Measure |
|---|---|---|---|---|
| Interstate | 4 | Shoulder width | Match existing bridge width; cost saving | — |
| | 1 | Horizontal stopping sight distance | Cost saving | Speed limit signs |
| U.S. highway | 1 | Horizontal curve radius | — | "Stop ahead" signs |
| | 1 | Lane width | Match existing structure | — |
| | 1 | Shoulder width | Cost saving | — |
| State road | 4 | Shoulder width | Environmental and scenic; cost saving | Warning signs |
| | 4 | Superelevation | Limit of right-of-way; cost saving | Warning signs |
| | 2 | Lane width | Cost saving | Shift marking; warning signs |
| | 1 | Stopping sight distance | — | — |
| | 1 | Cross slope | Cost saving | — |
| | 1 | Structural capacity | Cost saving | — |
| | 1 | Bridge railing | — | — |
| County road | 5 | Superelevation | Low traffic volume | Warning signs |
| | 3 | Horizontal curve radius | Cost saving | Advisory speed limit signs |
| | 2 | Shoulder width | Cost saving | Warning signs |
| | 1 | Lane width | Limit of right-of-way | Warning signs |
| | 1 | Bridge width | Retain historic character | — |
| | 1 | Stopping sight distance | Match existing structure | Warning signs |
| Local road | 3 | Stopping sight distance | Cost saving; keep historic property | Advanced warning signs |
| | 2 | Lane width | Match existing structure | — |
| | 2 | Bridge width | Match existing structure | Speed limit or warning signs |
| | 2 | Superelevation | Cost saving | Advisory speed limit signs |

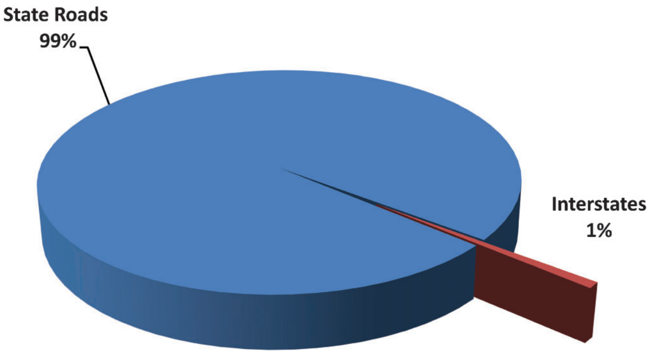


**Figure 3.4** Illinois design exception projects on different types of highways.

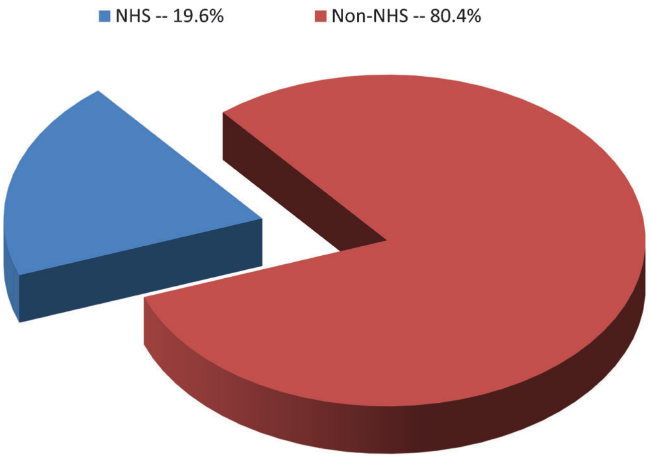


**Figure 3.5** Indiana design exception projects on NHS and non-NHS roadways.

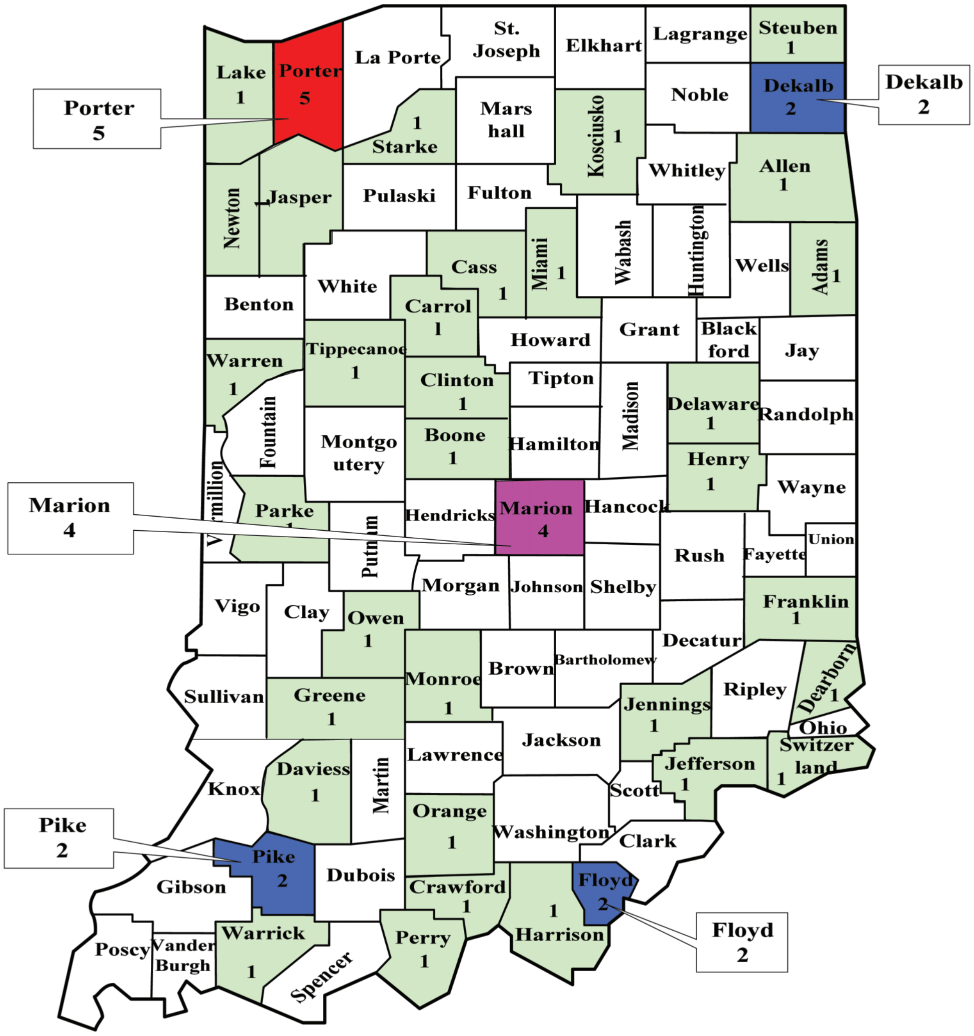


**Figure 3.6** Geographical locations of design exception projects.

projects are presented in Table 3.5. For each type of design exceptions, the safety measures applied in Indiana are listed in the table. The information in the table indicates that the safety measures were mainly uses of warning signs or advisory speed reduction signs. The effectiveness for some of the safety measures in Table 3.5 is expressed as adjustment factors in the *Highway Safety Manual* (HSM) (*4*), which will be discussed in the late part of this report. However, the safety adjustment factors for most of these safety measures are not currently available in the HSM or in any other literatures. It is therefore not feasible at present to identify which of the safety measures are more effective.

TABLE 3.4
**Main Reasons for INDOT Design Exception Projects**

| Reason | Number | Percent (%) |
|---|---|---|
| Cost saving | 33 | 58.9 |
| Existing conditions | 6 | 10.7 |
| Right-of-way issues | 3 | 5.4 |
| Protect historic character | 3 | 5.4 |
| Environmental | 3 | 5.4 |
| Adjacent property issues | 2 | 3.6 |
| Temporary construction | 2 | 3.6 |
| Others | 4 | 7.1 |
| TOTAL | 56 | 100 |

As presented in Table 3.4, the top reason for the Indiana design exception projects was cost savings. It is apparent that applying design exceptions would result in considerable savings in initial costs in comparison with the options that would build the projects to meet the standard requirements. The estimated initial cost savings of the reviewed Indiana design exception projects are summarized in Table 3.6. In order to illustrate the cost savings of each type of design exception projects, the construction cost savings are grouped according to the types of the design exception projects. Table 3.6 provides the cost savings of individual projects as well as the average construction savings

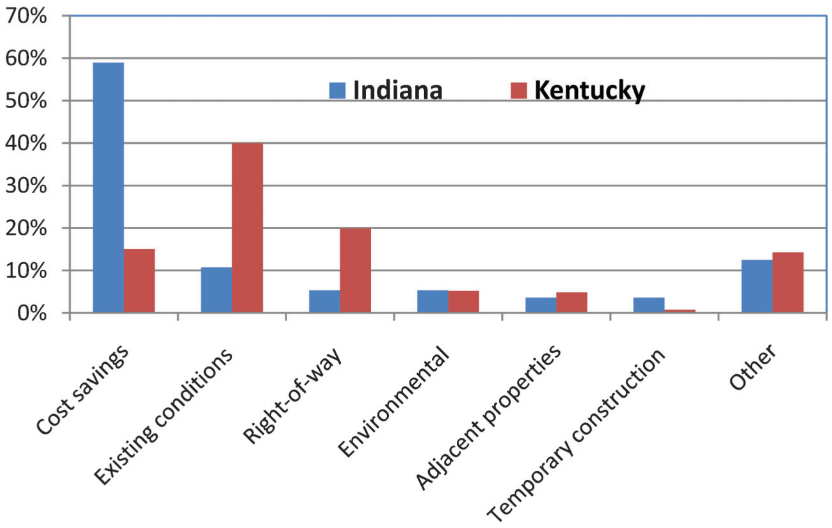


**Figure 3.7** Frequencies of Indiana and Kentucky design exceptions.

TABLE 3.5
**Safety Measures in Design Exception Projects**

| Design Exception | Number of Projects | Number of Projects with Safety Measures | Safety Measures |
|---|---|---|---|
| Superelevation | 18 | 9 | Curve ahead warning signs; milled shoulder corrugations; advisory speed limit signs; chevrons; large panel arrows; delineators around curves; snowplowable raised pavement markers in curves |
| Shoulder width | 15 | 7 | Warning signs; advisory speed limit signs; shift lane markings |
| Horizontal curve radius | 7 | 5 | Curve ahead signs; advisory speed limit signs; stop ahead signs before intersection |
| Stopping sight distance | 7 | 7 | Warning signs and advisory speed signs |
| Lane width | 6 | 4 | Limited sight distance signs; temporary construction signs |
| Bridge width | 5 | 2 | Speed limit signs; reduce speed ahead signs; one-lane arrow bridge signs |
| Bridge railing | 4 | 1 | Reduce speed ahead signs; low structure ahead signs |
| Cross slope | 2 | 1 | Curve ahead sign; milled shoulder corrugations |
| Maximum grade | 1 | 1 | Warning sign |
| Horizontal clearances | 1 | 1 | Advanced warning symbolic curve sign |

of each type of design exceptions. For easy comparison and illustration, some of the cost savings are plotted in Figure 3.8. This figure shows that the cost savings in construction costs were noticeably greater than other types of cost savings.

## 4. SAFETY EVALUATIONS OF DESIGN EXCEPTION PROJECTS

A major concern for design exception projects is their potential effects on roadway safety due to the features that are designed below the standard requirements. Therefore, it is essential to be able to evaluate the safety impact of design exception projects. The newly published *Highway Safety Manual* (HSM) (*4*) provides comprehensive and powerful tools for evaluating safety effects of various types of highway projects. Also available is the *Interactive Highway Safety Design Model* (IHSDM) (*3*), which a suite of software analysis tools for evaluating safety and operational effects of highway projects with respect to geometric design characteristics. IHSDM was developed in coordination with HSM. Most of the HSM procedures and mathematic equations are incorporated into the IHSDM

TABLE 3.6
**Cost Savings of INDOT Design Exception Projects**

| Type of Design Exception | Reason | Number of Projects | Cost Savings | Average Cost Savings |
|---|---|---|---|---|
| Superelevation and superelevation transition | Right-of-way | 2 | $870,000 | $445,236 |
| | Stop conditions | 1 | $686,000 | |
| | Match existing structure | 1 | $36,800 | |
| | Construction cost | 14 | $6,421,463 | |
| Shoulder width | Protect Environment | 1 | $120,000 | $378,108 |
| | Match existing structure | 2 | $90,600 | |
| | Right-of-way | 2 | $0.00 | |
| | Construction cost | 10 | $5,461,020 | |
| Horizontal alignment | Match existing structure | 1 | $788,000 | $861,214 |
| | Construction cost | 6 | $5,240,500 | |
| Stopping sight distance | Stop condition | 1 | $686,000 | $1,247,200 |
| | Match existing structure | 2 | $999,900 | |
| | Construction cost | 4 | $7,044,500 | |
| Lane width | Right-of-way | 1 | $245,000 | $770,503 |
| | Temporary construction | 1 | $23,200 | |
| | Protect historic character | 1 | $1,104,921 | |
| | Match existing structure | 2 | $126,400 | |
| | Construction cost | 1 | $3,123,500 | |
| Bridge width | Match existing structure | 1 | $245,000 | $245,200 |
| | Protect historic character | 2 | $981,000 | |
| | Construction cost | 2 | — | |
| Bridge railing | Protect historic character | 2 | $262,400 | $414,600 |
| | Construction cost | 2 | $1,396,000 | |
| Cross slope | Match existing structure | 1 | — | $2,170,500 |
| | Construction cost | 1 | $4,341,000 | |
| Maximum grade | Construction cost | 1 | $1,134,500 | $1,134,500 |
| Vertical clearances | Protect historic character | 1 | — | — |

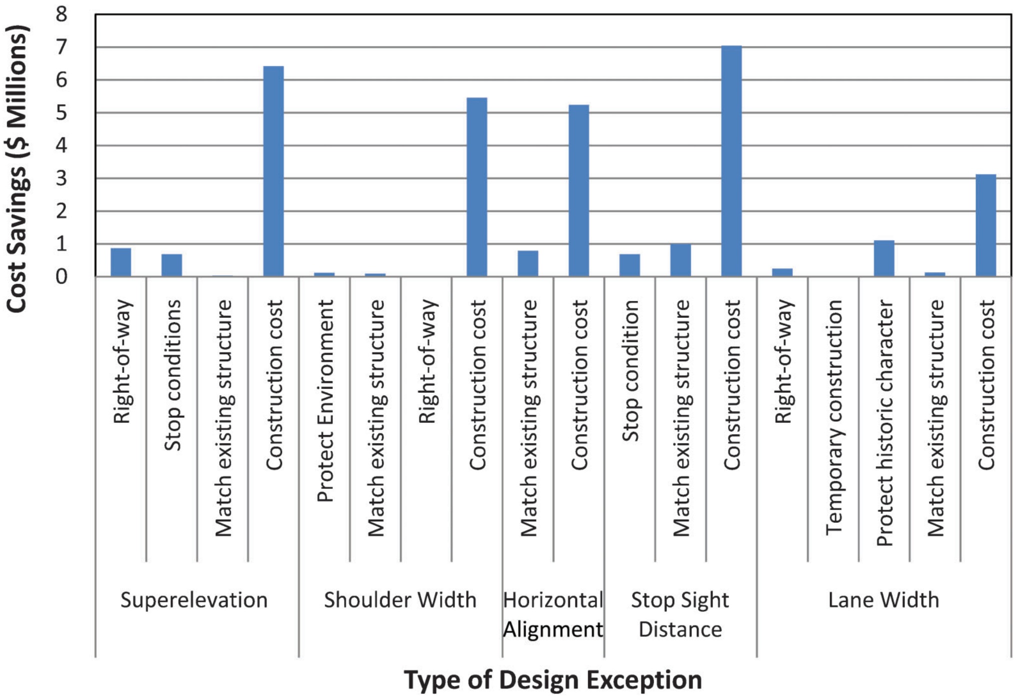


**Figure 3.8** Cost savings of INDOT design exceptions.

software package, so that the necessary and tedious computations are computerized.

## 4.1 Main Functions of IHSDM

The current version of IHSDM contains six evaluation modules, i.e., Crash Prediction, Design Consistency, Intersection Review, Policy Review, Traffic Analysis, and Driver/Vehicle. The functions of these six modules are described in the following (*3*):

- **Crash Prediction Module (CPM)**—The Crash Prediction Module provides estimates of expected crash frequency and severity.
- **Design Consistency Module (DCM)**—The Design Consistency Module estimates expected operating speeds and measures of operating-speed consistency.
- **Intersection Review Module (IRM)**—The Intersection Review Module leads users through a systematic review of intersection design elements relative to their likely safety and operational performance.
- **Policy Review Module (PRM)**—The Policy Review Module checks a design relative to the range of values for critical dimensions recommended in AASHTO design policy.
- **Traffic Analysis Module (TAM)**—The Traffic Analysis Module estimates measures of traffic operations used in highway capacity and quality of service evaluations.
- **Driver/Vehicle Module (DVM)**—The Driver/Vehicle Module simulates driving behavior and vehicle dynamics on a two lane highway. The DVM provides predicted time histories of speed and other response variables, along with statistical measures of safety-related performance metrics, via a simulation of a single driver/vehicle combination.

IHSDM provides a step-by-step instruction, called Wizard, for users to follow. The Wizard leads a user from data input to evaluation output. The general steps of IHSDM Wizard are described in Figure 4.1 (*3*). Figure 4.2 (*3*) illustrates the detailed information on setting up a project for IHSDM evaluation. Figures 4.3 and 4.4 are two examples of input screens for creation of a new highway project in IHSDM. After completion of the steps shown in Figure 4.2, the evaluation process can be started to generate evaluation results flowing the steps as described in Figure 4.5.

The evaluation results from IHSDM will provide detailed reports on the highway data, traffic data, and predicted crash rates. The individual reports that IHSDM will generate are listed below (*3*):

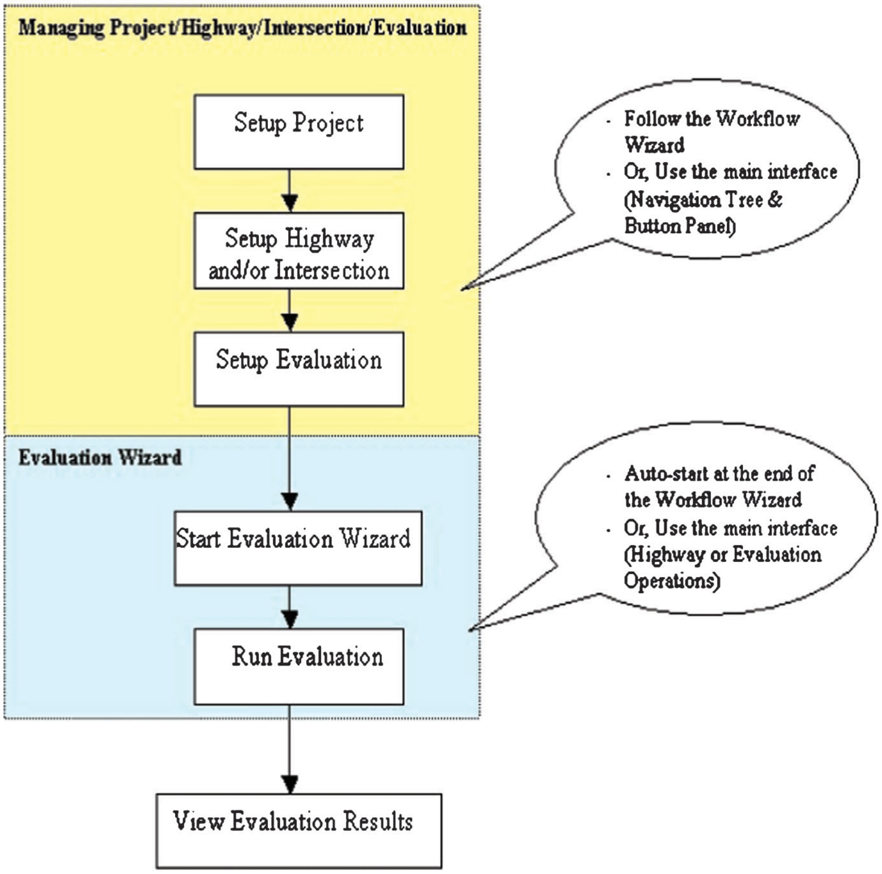


**Figure 4.1** General steps of IHSDM wizard.

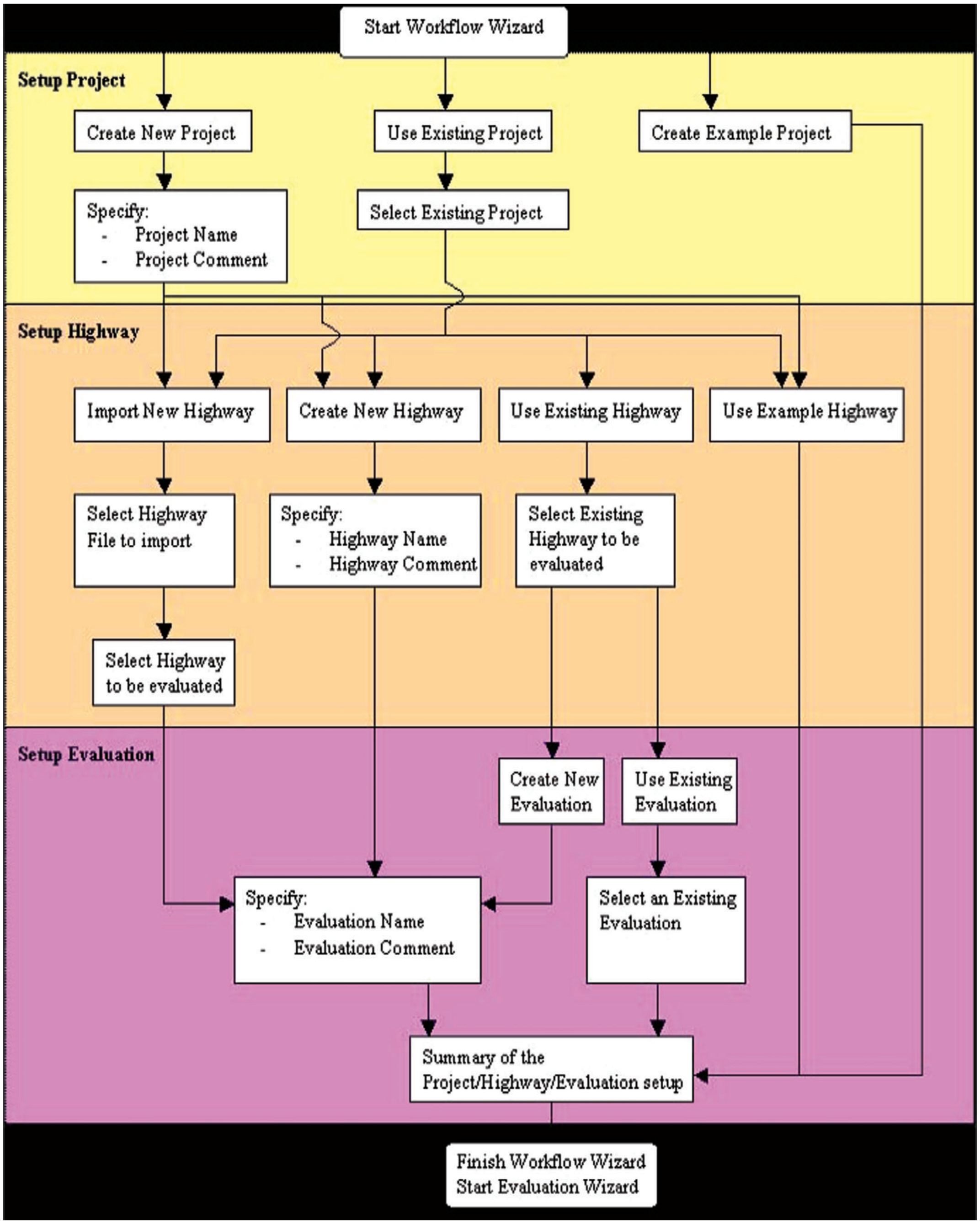
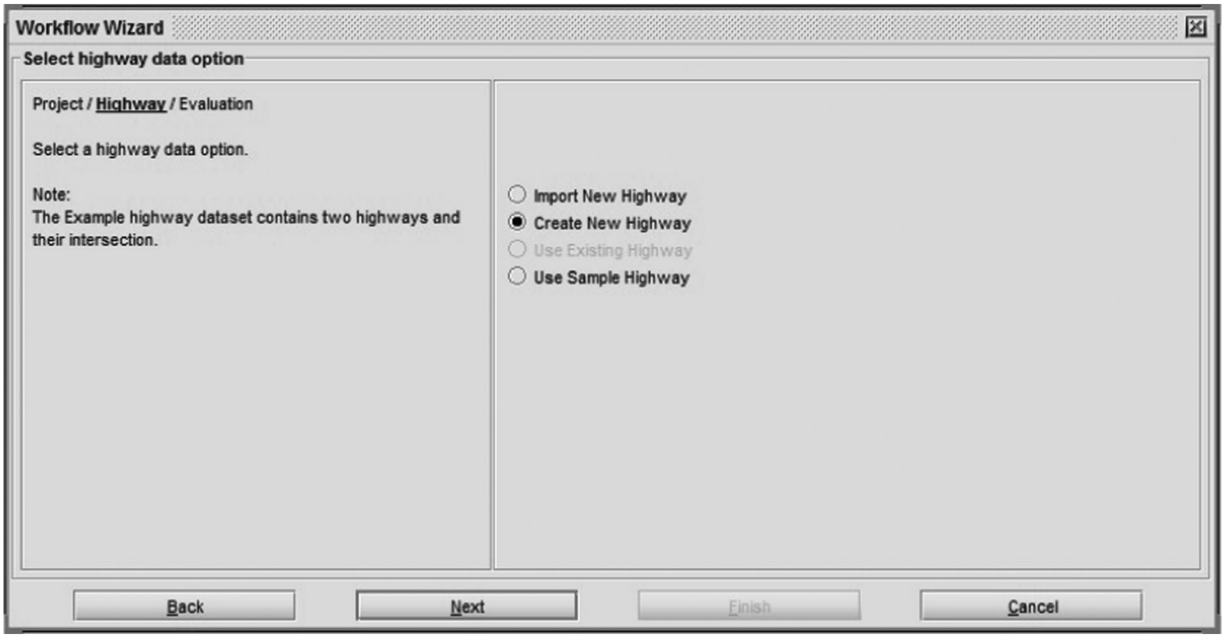


**Figure 4.2** Flow chart of project setup in IHSDM.

1. Highway Data Summary:
   a. Proposed Highway Segments
   b. Proposed Horizontal Curves
   c. Proposed Intersections
   d. Current Highway Segments
   e. Current Horizontal Curves
   f. Current Intersections
2. Traffic Volume Data Summary:
   a. Proposed Segment Traffic Volumes
   b. Proposed Intersecting Highway Traffic Volumes
   c. Current Segment Traffic Volumes
   d. Current Intersecting Highway Traffic Volumes
3. Expected Crash Summary:
   a. Expected Crash Rates and Crash Frequencies
   b. Expected Crash Rates and Crash Frequencies of Roadway Segments and Intersections
   c. Expected Crash Rates and Crash Frequencies of Horizontal Design Elements
4. Crash Prediction Result Plots:
   a. Plots of Horizontal and Vertical Alignments
   b. Plot of Expected Crash Rates by Roadway Segments



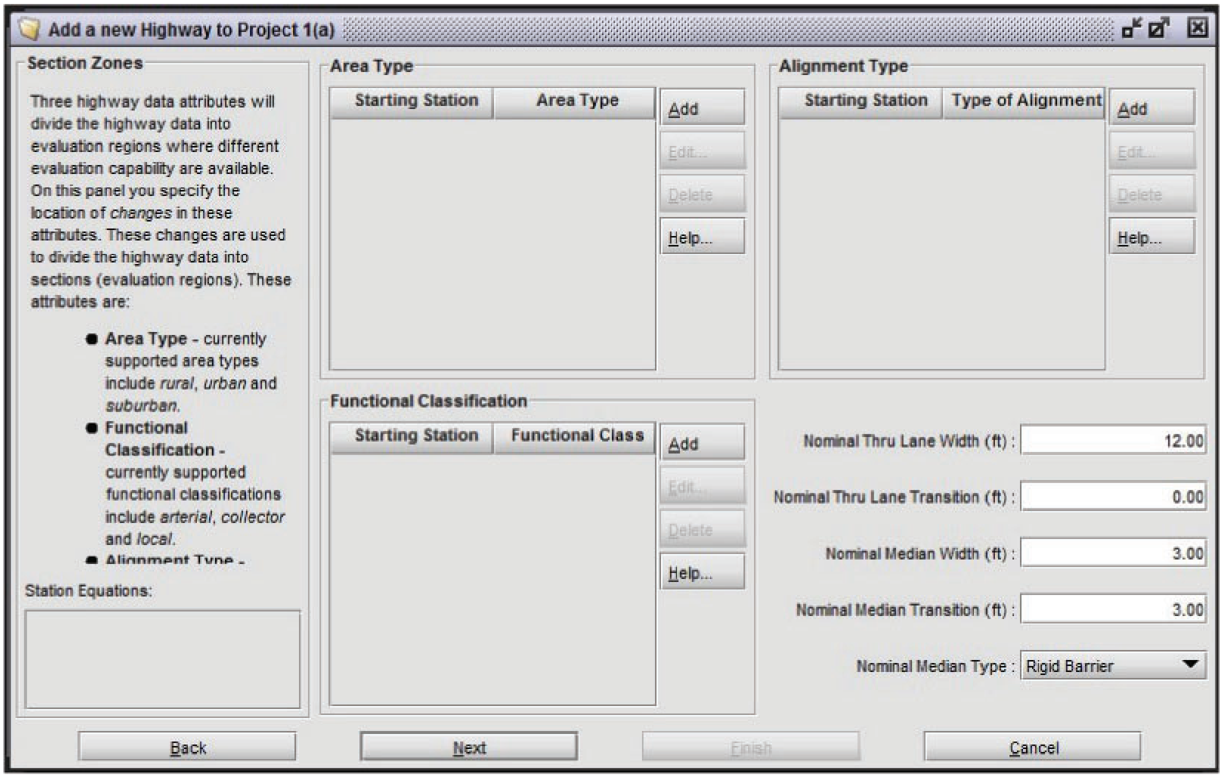
Project / **Highway** / Evaluation

Select a highway data option.

Note:
The Example highway dataset contains two highways and their intersection.

○ Import New Highway
● Create New Highway
○ Use Existing Highway
○ Use Sample Highway

**Figure 4.3** Creation of new highway project in IHSDM.



Three highway data attributes will divide the highway data into evaluation regions where different evaluation capability are available. On this panel you specify the location of *changes* in these attributes. These changes are used to divide the highway data into sections (evaluation regions). These attributes are:

- **Area Type** - currently supported area types include *rural*, *urban* and *suburban*.
- **Functional Classification** - currently supported functional classifications include *arterial*, *collector* and *local*.
- **Alignment Type** -

Nominal Thru Lane Width (ft) : 12.00

Nominal Thru Lane Transition (ft) : 0.00

Nominal Median Width (ft) : 3.00

Nominal Median Transition (ft) : 3.00

Nominal Median Type : Rigid Barrier

**Figure 4.4** Data input screen for new highway project in IHSDM.

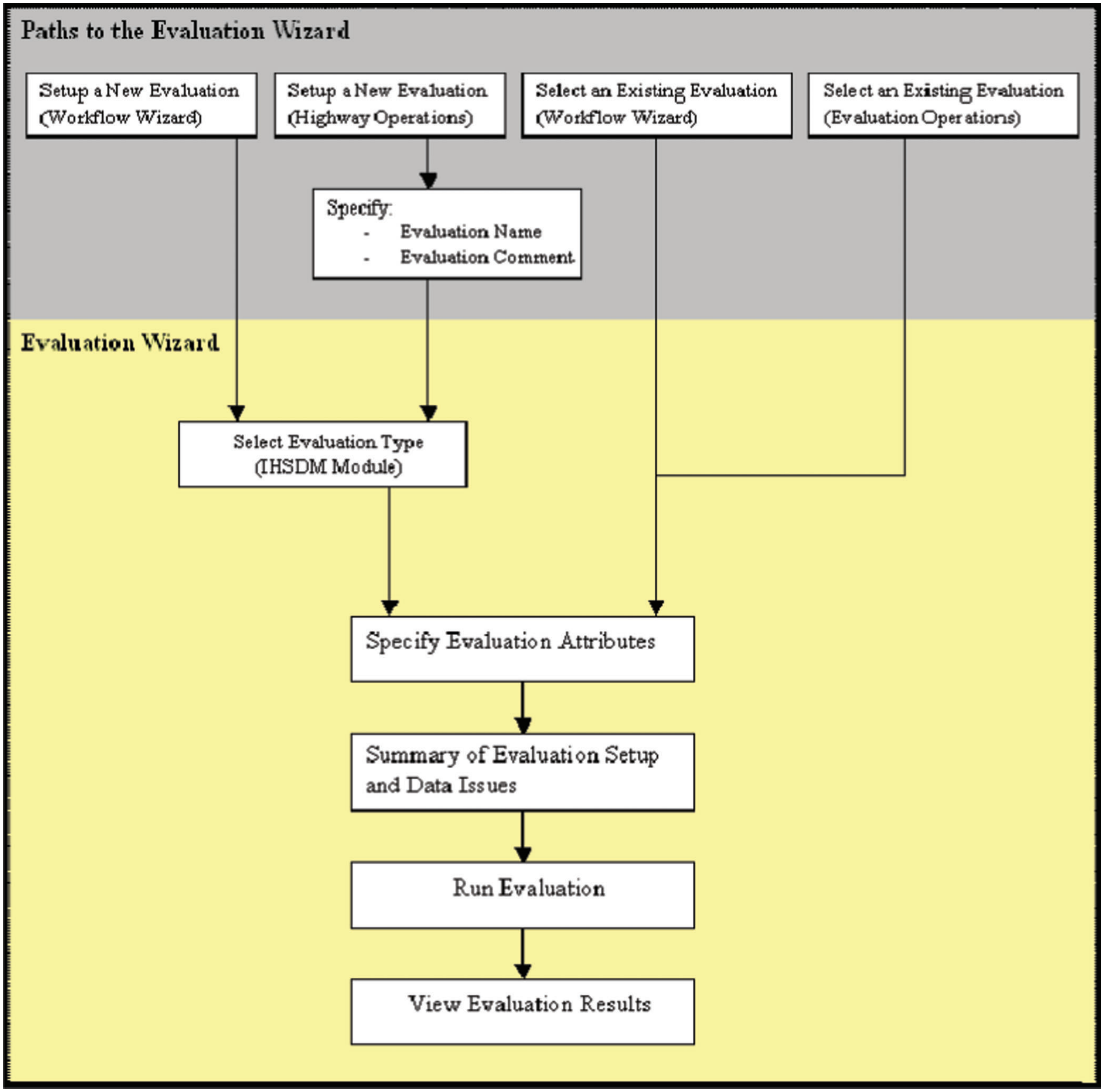


**Figure 4.5** Evaluation process of IHSDM.

c. Plot of Expected Crash Rates at Intersections
d. Plot of Expected Crash Rates of Horizontal Design Elements

## 4.2 An Example Problem of Safety Evaluation with IHSDM

To demonstrate the process of safety evaluation with IHSDM, an example problem is presented in the following. A section of SR-46 was used to conduct the safety evaluation using IHSDM. The project was located on SR-46 about 4 miles of east of US 231 as shown in Figure 4.6. The design exception was proposed to use 11-foot lanes and 2-foot shoulders, rather than the standard 12-foot travel lanes and 6 feet shoulders. A photo of a section of the design exception project is shown in Figure 4.7.

The values of the required design elements are given in Table 4.1. One of the required input values is the roadside hazard rating. A roadside hazard rating is determined in IHSDM according to the roadside safety conditions, ranging from 1 to 7 with 1 being the most favorable roadside safety condition. The roadside hazard rating for this project is rated as 6 based on the following facts: (1) the roadside clear zone is less

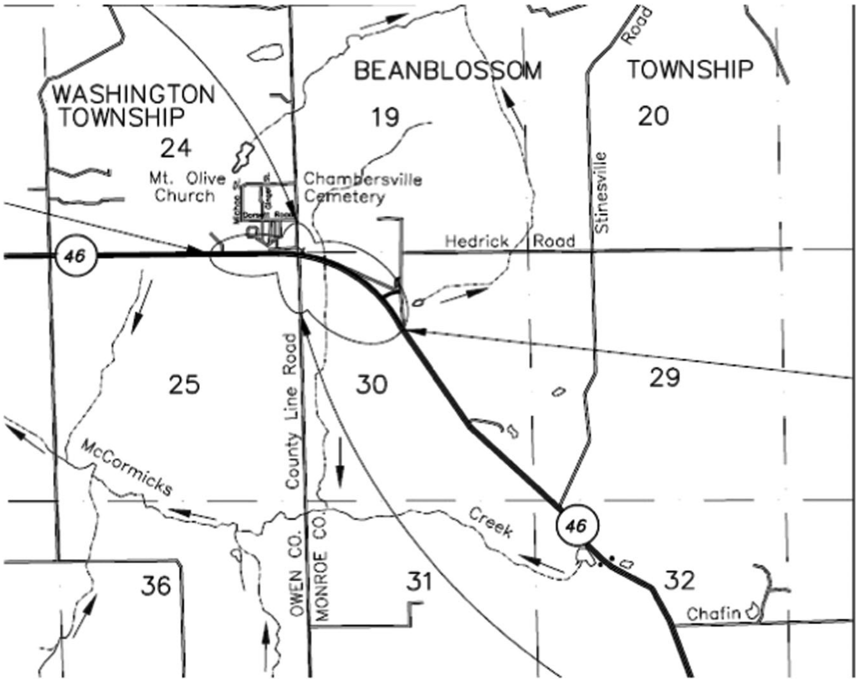


**Figure 4.6** Project location.

than five feet; (2) the side slope is approximately 3:1; (3) there are no guardrails, and (4) some rigid obstacles are present within 0 to 6.5 feet from the pavement edge line.

The project was divided into a number of segments in terms of geometric characteristics. The tangent and curve segments and their relevant geometric values are listed in Table 4.2. The horizontal curve segments are listed in Table 4.3 along with their radii and lengths. The information in Tables 4.1, 4.2, and 4.3 provides the main input values for IHSDM to perform safety evaluation.

Using the input information described above, the IHSDM Crash Prediction/Accident Analysis Module generated a set of safety evaluation reports. The analysis was specified as a six-year period, 2011 through 2016. The evaluation reports include summaries of the input data as well as the estimated crash frequencies and crash rates. A set of graphs are produced by the software to visually analyze the roadway safety. The graphs illustrate crash rates by segments. The moving average of the crash rates per mile is provided. In addition, roadway elevation and radius are also

**Figure 4.7** A section of the design exception project on SR46.

TABLE 4.1
**Design Elements of the Design Exception Project**

| | |
|---|---|
| **Start/end stations** | 13+76.970–31+41.560 |
| **Length (mile)** | 0.3342 |
| **AADT (measured in 2011)** | 2400 |
| **Project design criteria** | 3R (Non freeway) |
| **Functional classification** | Rural principal arterial |
| **Terrain** | Rolling |
| **Design speed** | 45 mph |
| **Access control** | None |
| **Number of lanes and width** | 2@ 11 feet |
| **Shoulders** | 2 feet (paved) |
| **Maximum shoulder width** | 2.05 feet |
| **Minimum shoulder width** | 0.95 feet |
| **Side slopes** | 3:1 (6:1 at rock slopes) |
| **Superelevation (%)** | 2 |
| **Roadside hazard rating** | 6.0 |
| **Driveway density (dwys/mi)** | 26.9 |

provided. As shown in the graphs, several segments (from Station 13+76.970 to Station 15+07.430, from 15+35.830 to 16+66.300, and from 30+03.420 to 31+41.560) have relatively high estimated crash rates. It is interesting to note that these segments contain sharper curves. The expected crash summaries in the six-year period are compiled in Tables 4.4 and 4.5. Figure 4.8 plots the expected six-year crashes of the eight segments. It should be noted that the values in these tables are only for this particular project, they should not be generalized to represent the crash levels of the state highway system.

## 4.3 Introduction to the *Highway Safety Manual*

The *Highway Safety Manual* (HSM) (*4*) provides an array of tools for roadway safety analysis. The current edition of the HSM provides comprehensive methodologies on measuring, estimating and evaluating roadways in terms of number of crashes and crash severities. HSM can be used to identify highway sections with potential safety problems, the factors contributing to these safety issues, and the potential countermeasures to address these issues. It can also be used to conduct economic appraisals of proposed improvements and to evaluate safety benefits of proposed or implemented treatments. HSM provides effective tools for highway engineers and planners to make appropriate and rational decisions on various types of highway projects. The HSM tools are useful in all the stages of highway projects as shown in Figure 4.9 (*4*), including system planning, project planning and preliminary engineering, design and construction, and operations and maintenance.

An important and useful part of HSM is the crash prediction capability. The crash prediction methodology can be used with or without site-specific crash history data. When crash data is available for a specific highway site, the HSM method incorporates the site specific crash history and produces crash predictions suitable for the given site. If the crash data is not available for a highway site, HSM will use the representative crash data for the type of highways based on the national database of crashes for the analysis. This application is usually for planned roadways that have not yet been constructed as well as for an existing roadway without site-specific crash history data. The analysis steps of HSM crash predictions with and without site-specific crash data are illustrated in Figures 4.10 and 4.11 (*4*), respectively.

To analyze the safety effects of a given highway section, the HSM crash prediction model first applies general safety performance functions (SPFs) for a baseline condition and then adjusts the safety performance using a set of crash modification factors (CMFs). The crash modification factors are used to adjust the safety measures to a particular jurisdiction or geographical area.

HSM offers specific equations for different types of highways, for the purpose of introduction and demonstration, only presented in the following are the set of equations for undivided two-way highways. All the equations and the data presented in this section are from HSM (*4*). The general form of the HSM crash prediction is based on the following equation:

$$N_{rs} = C_r \times N_{spf\text{-}rs} \times (CMF_{1r} \times \ldots \times CMF_{nr}) \tag{4.1}$$

Where:

$N_{rs}$ = Predicted number of crashes per year;

$N_{spf\text{-}rs}$ = Predicted number of crashes per year for nominal or baseline conditions;

TABLE 4.2
**Highway Segment Data**

| **Segment** | **Station** | | **Length (ft)** | **Lane Width (ft)** | | **Shoulder Width(ft)** | | **Shoulder Type** | | **Driveway Density (dwys/mi)** | **Roadside Hazard Rating** | **Grade (%)** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Start** | **End** | | **Right** | **Left** | **Right** | **Left** | **Right** | **Left** | | | |
| Curve 1 | 13+76.970 | 15+07.430 | 130.46 | 11.00 | 11.00 | 2.0 | 2.0 | paved | paved | 26.9 | 6.0 | -6.16 |
| Tangent 1 | 15+07.430 | 15+35.830 | 28.40 | 11.00 | 11.00 | 2.0 | 2.0 | paved | paved | 26.9 | 6.0 | -6.16 |
| Curve 2 | 15+35.830 | 16+66.300 | 130.47 | 11.00 | 11.00 | 2.0 | 2.0 | paved | paved | 26.9 | 6.0 | -6.16 |
| Tangent 2 | 16+66.300 | 18+56.000 | 189.70 | 11.00 | 11.00 | 2.0 | 2.0 | paved | paved | 26.9 | 6.0 | -6.16 |
| Tangent 3 | 18+56.000 | 23+94.560 | 538.56 | 11.00 | 11.00 | 2.0 | 2.0 | paved | paved | 26.9 | 6.0 | 4.00 |
| Curve 3 | 23+94.560 | 28+15.000 | 420.44 | 11.00 | 11.00 | 2.0 | 2.0 | paved | paved | 26.9 | 6.0 | 4.00 |
| Curve 4 | 28+15.000 | 30+03.420 | 188.42 | 11.00 | 11.00 | 2.0 | 2.0 | paved | paved | 26.9 | 6.0 | -2.29 |
| Curve 5 | 30+03.420 | 31+41.560 | 138.23 | 11.00 | 11.00 | 2.0 | 2.0 | paved | paved | 26.9 | 6.0 | -2.29 |

TABLE 4.3
**Horizontal Curve Data**

| Segment | Station Start | Station End | Length of Curve (ft) | Radius (ft) | Superelevation (%) | Design Speed (mph) |
|---|---|---|---|---|---|---|
| Curve 1 | 13+76.970 | 15+07.430 | 130.46 | 1150.00 | 2.0 | 45 |
| Curve 2 | 15+35.830 | 16+66.300 | 130.47 | 1150.00 | 2.0 | 45 |
| Curve 3 | 23+94.560 | 30+03.420 | 608.86 | 7669.44 | 2.0 | 45 |
| Curve 4 | 23+94.560 | 30+03.420 | 608.86 | 7669.44 | 2.0 | 45 |
| Curve 5 | 30+03.420 | 31+41.560 | 138.23 | 1650.00 | 2.0 | 45 |

$C_r$ = Calibration factor for a particular jurisdiction or geographical area;

$CMF_{nr}$ = Crash modification factors for roadway segments.

The equation for the predicted number of crashes for baseline condition is:

$$N_{spf\text{-}rs} = AADT \times L \times 365 \times 10^{-6} \times e^{-0.312} \quad (4.2)$$

Where:

ADT = Average daily traffic (veh/day) on roadway segment;

L = Length of roadway segment (mi).

The baseline conditions for the crash predictions are specified as 12 ft of lane width, 6 ft of shoulder width, roadside hazard rating of 3, driveway density of 5, no horizontal curvature, no grade, no centerline rumble strip, no auxiliary lane, no lighting and no automated speed enforcement. The coefficients in the above equation are replaceable by users coefficients if they have those values calculated for their jurisdictions.

If the actual lane width is different from the 12 feet, a crash modification factor for lane width should be used to modify the crash prediction:

$$CMF_{1r} = (CMF_{ra} - 1.0) \times p_{ra} + 1.0 \quad (4.3)$$

Where:

$CMF_{1r}$ = Crash modification factor for lane width;

$CMF_{ra}$ = Crash modification factor for related crashes (run-off-the-road, head-on, and sideswipe) as shown in Table 4.6 (*4*);

$p_{ra}$ = Proportion of total crashes constituted by related crashes.

For an undivided highway with a shoulder width other than 6 feet, a crash modification factor for shoulder width can be calculated.

$$CMF_{2r} = (CMF_{wra} \times CMF_{tra} - 1.0) \times p_{ra} + 1.0 \quad (4.4)$$

Where:

$CMF_{2r}$ = Crash modification factor for shoulder width;

$CMF_{wra}$ = Crash modification factor for related crashes (single-vehicle run-off-the-road, multiple-vehicle head-on, opposite-direction sideswipe, and same-direction sideswipe crashes) as shown in Table 4.7 (*4*);

TABLE 4.4
**Expected Crashes (2011–2016)**

| Expected Crashes (six years) | |
|---|---|
| Total Crashes | 5.32 |
| Fatal and Injury Crashes | 1.71 |
| Fatal and Serious Injury Crashes | 0.94 |
| Property-Damage-Only Crashes | 3.62 |
| **Percent of Total Expected Crashes** | |
| Percent Fatal and Injury Crashes (%) | 32 |
| Percent Fatal and Serious Injury Crashes (%) | 18 |
| Percent Property-Damage-Only Crashes (%) | 68 |
| **Expected Crash Rate** | |
| Crash Rate (crashes/mi/yr) | 2.6550 |
| Fatal and Injury Crash Rate (crashes/mi/yr) | 0.8523 |
| Fatal and Serious Injury Crash Rate (crashes/mi/yr) | 0.4673 |
| Property-Damage-Only Crash Rate (crashes/mi/yr) | 1.8027 |

TABLE 4.5
**Expected Crashes of Roadway Segments**

| Start Station | End Station | Length (mi) | Expected Crashes | Crash Rate (crashes/mi/yr) |
|---|---|---|---|---|
| 13+76.970 | 15+07.430 | 0.0247 | 0.92 | 6.1772 |
| 15+07.430 | 15+35.830 | 0.0054 | 0.06 | 1.8008 |
| 15+35.830 | 16+66.300 | 0.0247 | 0.92 | 6.1769 |
| 16+66.300 | 18+56.000 | 0.0376 | 0.41 | 1.8008 |
| 18+56.000 | 23+94.560 | 0.1003 | 1.03 | 1.7076 |
| 23+94.560 | 28+15.000 | 0.0796 | 0.97 | 2.0245 |
| 28+15.000 | 30+03.420 | 0.0357 | 0.39 | 1.8404 |
| 30+03.420 | 31+41.560 | 0.0262 | 0.64 | 4.0684 |

$\mathrm{CMF}_{tra}$ = Crash Modification Factor for related crashes as shown in Table 4.8 (*4*);

$p_{ra}$ = proportion of total crashes constituted by related crashes.

The crash modification factors for horizontal curvatures are determined in terms of the curve length, radius, and presence or absence of spiral transitions.

$$\mathrm{CMF}_{3r} = (1.55L_c + 80.2/R - 0.12S)/1.55L_c \tag{4.5}$$

Where:

$\mathrm{CMF}_{3r}$ = Crash modification factor for horizontal alignments;

$L_c$ = Length of horizontal curve (miles);

R = Radius of curvature (feet);

S = 1, if spiral transition curve is present; 0, if spiral transition curve is not present; or 0.5 if a spiral transition curve is present at one but not both ends of the horizontal curve.

The equations for determining crash modification factors for superelevation of horizontal curves are listed below:

$$\mathrm{CMF}_{4r} = 1.0, \text{ if } SV < 0.01 \tag{4.6}$$

$$\mathrm{CMF}_{4r} = 1.0 + 6(SV - 0.01), \text{ if } 0.01 \leq SV < 0.02 \tag{4.7}$$

$$\mathrm{CMF}_{4r} = 1.06 + 3(SV - 0.02), \text{ if } SV \geq 0.02 \tag{4.8}$$

Where:

$\mathrm{CMF}_{4r}$ = Crash modification factor for superelevation variance;

SV = Superelevation variance (ft/ft), which represents the superelevation recommended by the AASHTO Green Book (*1*) minus the actual superelevation of the curve.

The crash modification factors, $\mathrm{CMF}_{5r}$, for roadway grades are given in Table 4.9 (*4*).

The crash modification factors for driveway density are calculated using the following equation.

$$\mathrm{CMF}_{6r} = \{0.322 + DD \times [0.05 - 0.005\mathrm{Ln}(AADT)]\} / \{0.322 + 5[0.05 - 0.005\mathrm{Ln}(AADT)]\} \tag{4.9}$$

Where:

$\mathrm{CMF}_{6r}$ = Crash modification factor for driveway density;

AADT = Average annual daily traffic of the roadway being evaluated (vehicles per day);

DD = Driveway density, considering driveways on both sides of roadway (driveways/mile).

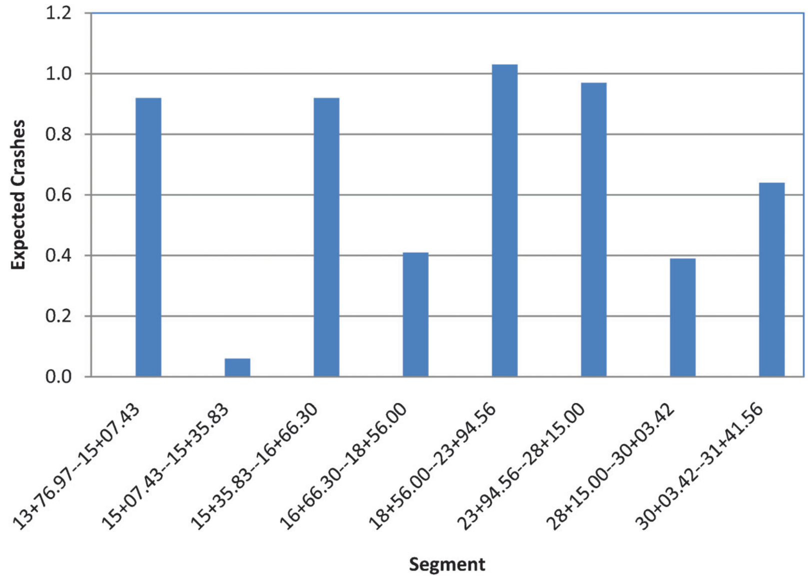


**Figure 4.8** Expected crashes of the roadway segments.

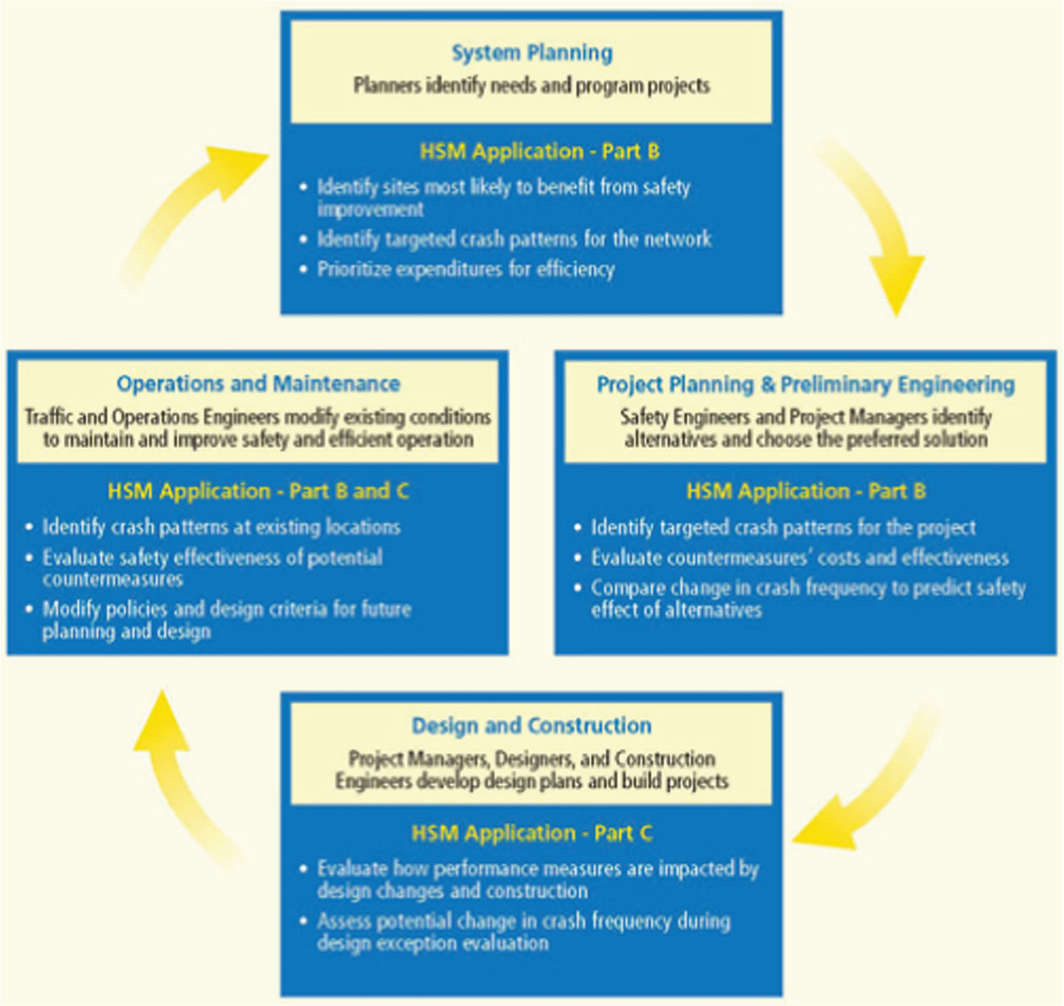


**Figure 4.9** HSM components.

The crash modification factor for centerline rumble strips ($CMF_{7r}$) is given as 0.94 for rural two-lane two-way highways. $CMF_{7r}$ can only be applied for two-lane undivided highways with no separation other than a centerline marking between the lanes in opposite directions of travel.

The crash modification factor for added passing lane or climbing lane ($CMF_{8r}$) can be determined based on the characteristics of the added lane and on the roadway conditions.

The crash modification factor for two-way left-turn lane (TWLTL) ($CMF_{9r}$) can be calculated with the following equation.

$$CMF_{9r} = 1.0 - 0.7 \times p_{dwy \times} p_{LT/D} \qquad (4.10)$$

Where:

$CMF_{9r}$ = Crash modification factor for two-way left turn lanes;

$p_{dwy}$ = Driveway-related crashes as a proportion of total crashes;

$p_{LT/D}$ = Left-turn crashes susceptible to correction by a TWLTL as a proportion of driveway-related crashes. The default value is 0.5.

The value of $p_{dwy}$ is given by:

$$p_{dwy} = \left(0.0047DD + 0.0024DD^2\right) / \left(1.199 + 0.0047DD + 0.0024DD^2\right) \qquad (4.11)$$

Where:

DD = driveway density (driveways/mile).

$CMF_{9r}$ should be applied only if the driveway density is greater than 5. Otherwise, $CMF_{9r}$ should be set to 1.0.

The equation for crash modification factor for roadside hazard rating ($CMF_{10r}$) is below. The roadside hazard rating for a roadway section ranges from 1 to 7 with 1 being the most favorable roadside safety condition.

$$CMF_{10r} = e^{(-0.6869 + 0.0668RHR)} / e^{(-0.4865)} \qquad (4.12)$$

Where:

$CMF_{10r}$ = Crash modification factor for roadside design;

RHR = Roadside hazard rating for the roadway segment.

If there exists roadway lighting, the crash modification factor for roadway lighting ($CMF_{11r}$) should be determined with the following equation.

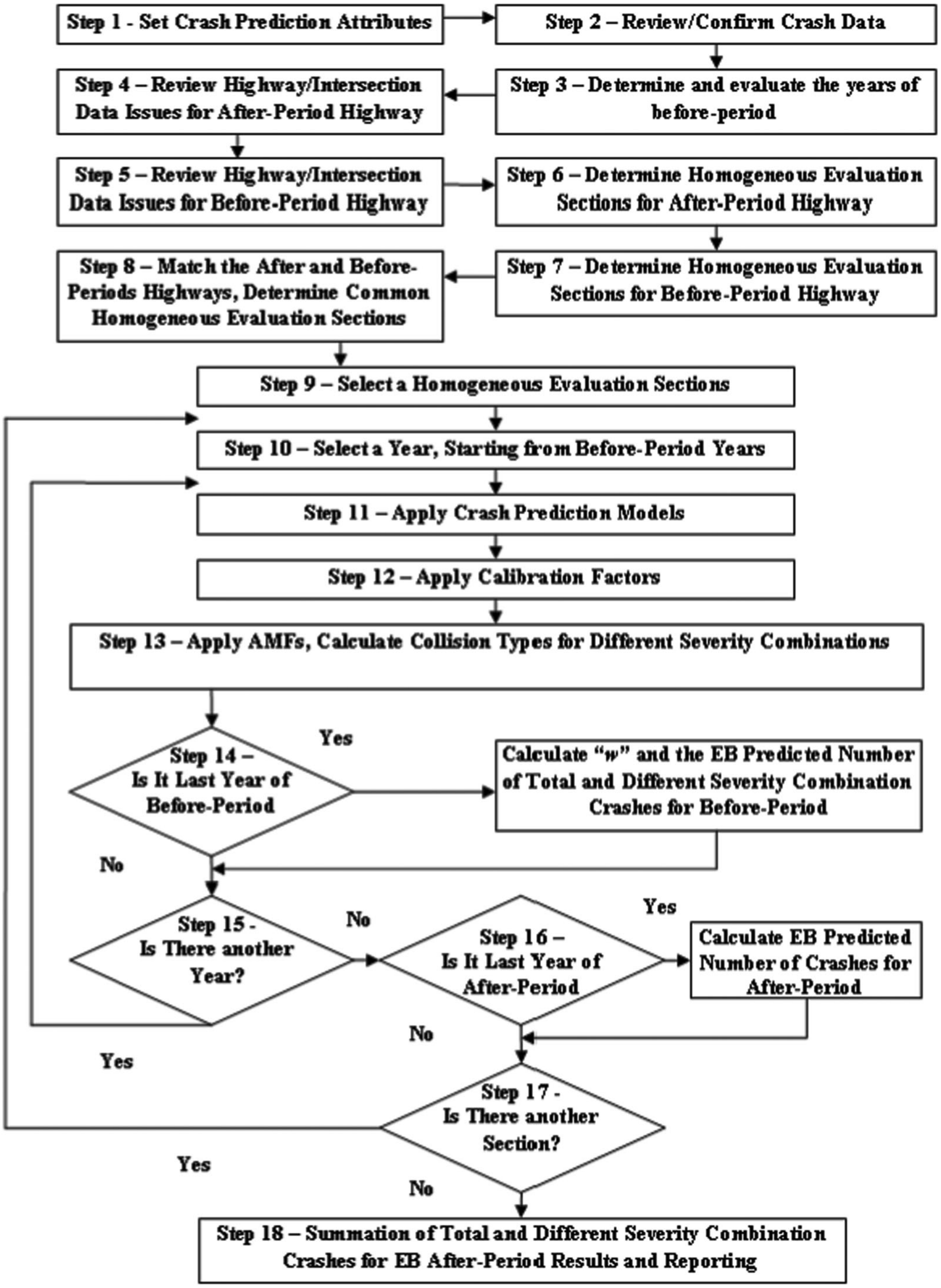


**Figure 4.10** Flow diagram of HSM safety prediction with site-specific crash data.

$$CMF_{11r} = 1.0 - \left[ \left( 1.0 - 0.72 p_{inr} - 0.83 p_{pnr} \right) p_{nr} \right] \quad (4.13)$$

Where:

$CMF_{11r}$ = Crash modification factor for roadway lighting;

$p_{inr}$ = Proportion of total nighttime crashes for unlighted roadway segments that involve a fatality or injury (FI);

$p_{pnr}$ = Proportion of total nighttime crashes for unlighted roadway segments that involve property damage only (PDO);

$p_{nr}$ = Proportion of total crashes for unlighted roadway segments that occur at night.

When the automated speed enforcement is present at the roadway section, the crash modification factor ($CMF_{12r}$) should be determined and used to reflect the positive effects of the speed enforcement. Under normal

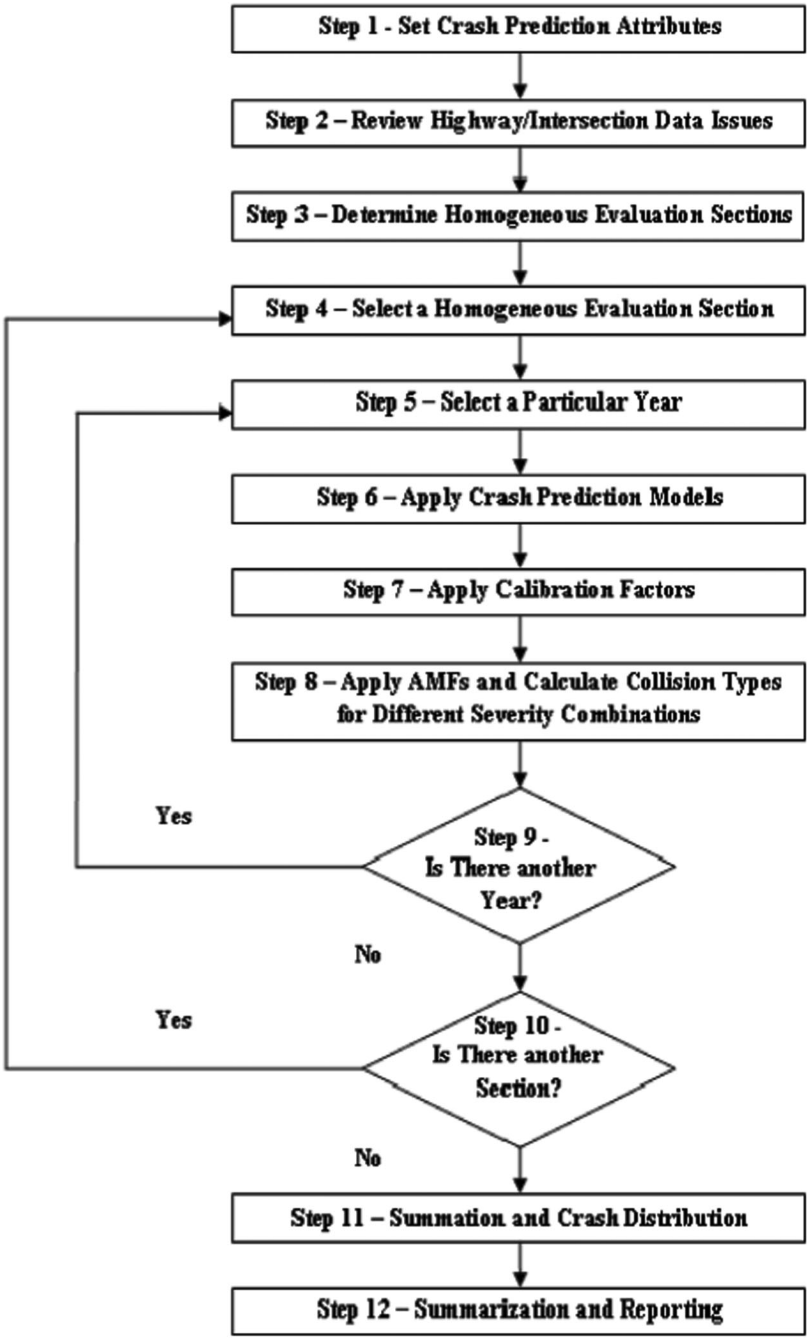


**Figure 4.11** Flow diagram of HSM safety prediction without site-specific crash data.

TABLE 4.6
**$CMF_{ra}$ Values for Lane Width**

| Lane Width (ft) | ADT<400 (veh/day) | ADT =400 to 2000 (veh/day) | ADT>2000 (veh/day) |
|---|---|---|---|
| 9 | 1.05 | 1.05+0.000281 × (ADT-400) | 1.50 |
| 10 | 1.02 | 1.02+0.000175 × (ADT-400) | 1.30 |
| 11 | 1.01 | 1.01+0.000025 × (ADT-400) | 1.05 |
| 12 | 1.00 | 1.00 | 1.00 |

TABLE 4.7
**$CMF_{wra}$ Values for Shoulder Width**

| Shoulder Width (ft) | ADT<400 (veh/day) | ADT =400 to 2000 (veh/day) | ADT>2000 (veh/day) |
|---|---|---|---|
| 0 | 1.10 | 1.10+0.00025 × (ADT-400) | 1.50 |
| 2 | 1.07 | 1.07+0.000143 × (ADT-400) | 1.30 |
| 4 | 1.02 | 1.02+0.00008125 × (ADT-400) | 1.15 |
| 6 | 1.00 | 1.00 | 1.00 |
| 8 | 0.98 | 0.98-0.00006875 × (ADT-400) | 0.87 |

TABLE 4.8
**$CMF_{tra}$ Values for Shoulder Type and Shoulder Width**

| | ShoulderWidth (ft) | | | | | | |
|---|---|---|---|---|---|---|---|
| Shoulder type | 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 (50% width paved and 50% width turf) | 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 base condition for shoulder type is paved. For a given shoulder width, the values should be compared vertically in each column in the table.

conditions, the value of $CMF_{12r}$ for automated speed enforcement is 0.93.

## 4.4 An Example Problem of Safety Evaluation with HSM

To demonstrate the process of safety evaluation with HSM, an example problem is presented in the following. As in the example problem in Section 4.2 of this report, the same section of SR-46 was also used to conduct the safety evaluation using HSM. The design exception was proposed to use 11-foot lanes and 2-foot shoulders, rather than the standard 12-foot travel lanes and 6 feet shoulders. The project location and geometric design data are shown in Section 4.2 of this report in Figure 4.6 and in Tables 4.1, 4.2, and 4.3. To illustrate the process of estimating potential highway crashes with HSM, the detailed computations of the first tangent segment (Station 15+07.430 to Station 15+35.830) are presented in the following.

As shown in Equation 4.1, the predicted number of crashes can be calculated as:

$$N_{rs} = C_r \times N_{spf-rs} \times (CMF_{1r} \times \ldots \times CMF_{nr}) \qquad (4.1)$$

Where:

$N_{rs}$ = Predicted number of crashes per year;
$N_{spf\text{-}rs}$ = Predicted number of crashes per year for nominal or baseline conditions;
$C_r$ = Calibration factor for a particular jurisdiction or geographical area;
$CMF_{nr}$ = Crash modification factors for roadway segments.

In HSM, the calibration factor for this type of condition can be set as 1.10, that is:

$$\mathbf{C_r = 1.10}$$

As shown in Equation 4.2, the predicted number of crashes per year for baseline conditions is:

$$N_{spf\text{-}rs} = AADT \times L \times 365 \times 10^{-6} \times e^{-0.312} \qquad (4.2)$$

Where:
ADT = Average daily traffic (veh/day) on roadway segment;
L = Length of roadway segment (mi).

For this segment, the AADT is 2,400 and the length L is 1.5 miles, thus:

$$\begin{aligned} \mathbf{N_{spf\text{-}rs}} &= \mathbf{AADT \times L \times 365 \times 10^{-6} \times e^{-0.312}} \\ &= \mathbf{2400 \times 1.5 \times 365 \times 10^{-6} \times e^{-0.312} = 0.003449} \end{aligned}$$

If the actual lane width is different from the 12 feet, a crash modification factor for lane width should be used to modify the crash prediction. This factor should be calculated using Equation 4.3:

$$CMF_{1r} = (CMF_{ra} - 1.0) \times p_{ra} + 1.0 \qquad (4.3)$$

TABLE 4.9
**$CMF_{5r}$ Values for Roadway Grade**

| Grade (%) | $CMF_{5r}$ |
|---|---|
| Level Grade (grade ≤ 3%) | 1.00 |
| Moderate Terrain (3%< grade ≤6%) | 1.10 |
| Steep Terrain (grade > 6%) | 1.16 |

Where:
$CMF_{1r}$ = Crash modification factor for lane width;
$CMF_{ra}$ = Crash modification factor for related crashes (run-off-the-road, head-on, and sideswipe) as shown in Table 4.6;
$p_{ra}$ = Proportion of total crashes constituted by related crashes.

From Table 4.6, for 11-foot lane width and AADT of 2400:

$$CMF_{ra} = 1.05$$

The default value for proportion of total crashes constituted by related crashes is 0.574, or

$$p_{ra} = 0.574$$

Thus, the crash modification factor is calculated as:

$$\begin{aligned} \mathbf{CMF_{1r}} &= (\mathbf{CMF_{ra}} - \mathbf{1.0}) \times \mathbf{p_{ra}} + \mathbf{1.0} \\ &= (\mathbf{1.05} - \mathbf{1.0}) \times \mathbf{0.574} + \mathbf{1.0} = \mathbf{1.0287} \end{aligned}$$

For an undivided highway with a shoulder width other than 6 feet, a crash modification factor for shoulder width can be calculated using Equation 4.4.

$$CMF_{2r} = (CMF_{wra} \times CMF_{tra} - 1.0) \times p_{ra} + 1.0 \qquad (4.4)$$

Where:
$CMF_{2r}$ = Crash modification factor for shoulder width;
$CMF_{wra}$ = Crash modification factor for related crashes (single-vehicle run-off-the-road, multiple-vehicle head-on, opposite-direction sideswipe, and same-direction sideswipe crashes) as shown in Table 4.7;
$CMF_{tra}$ = Crash Modification Factor for related crashes as shown in Table 4.8;
$p_{ra}$ = proportion of total crashes constituted by related crashes.

From Table 4.7, for 2-foot should width and AADT of 2,400, $CMF_{wra}$ can be determined as:

$$CMF_{wra} = 1.3$$

Similarly, $CMF_{tra}$ can be found in Table 4.8:

$$CMF_{tra} = 1.0$$

The default value for proportion of total crashes constituted by related crashes is 0.574, or

$$p_{ra} = 0.574$$

Then the crash modification factor for shoulder width is:

$$\begin{aligned} \mathbf{CMF_{2r}} &= (\mathbf{CMF_{wra}} \times \mathbf{CMF_{tra}} - \mathbf{1.0}) \times \mathbf{p_{ra}} + \mathbf{1.0} \\ &= (\mathbf{1.3} * \mathbf{1.0} - \mathbf{1.0}) * \mathbf{0.574} + \mathbf{1.0} = \mathbf{1.1722} \end{aligned}$$

Since this segment of the roadway is a tangent section, the crash modification factors related to horizontal curvatures should be 1.0.

The crash modification factor for horizontal alignments, $CMF_{3r}$:

$$\mathbf{CMF_{3r}} = \mathbf{1.0}$$

The crash modification factors for superelevation of horizontal curves, $CMF_{4r}$:

$$\mathbf{CMF_{4r}} = \mathbf{1.0}$$

Since the roadway grade of this segment is 6.16%, from Table 4.9, the crash modification factor for roadway grades is 1.16, or

$$\mathbf{CMF_{5r}} = \mathbf{1.16}$$

The crash modification factors for driveway density are calculated using the following equation.

$$CMF_{6r} = \{0.322 + DD \times [0.05 - 0.005 Ln(AADT)]\} / \{0.322 + 5[0.05 - 0.005 Ln(AADT)]\} \qquad (4.9)$$

Where:
$CMF_{6r}$ = Crash modification factor for driveway density;
AADT = Average annual daily traffic of the roadway being evaluated (vehicles per day);
DD = Driveway density, considering driveways on both sides of roadway (driveways/mile).

In this segment, the driveway density (DD) is 26.9 driveways per mile and AADT is 2,400, thus:

$$\begin{aligned} CMF_{6r} &= \frac{\mathbf{0.322} + \mathbf{DD} \times [\mathbf{0.05} - \mathbf{0.005} \times \mathbf{ln}(\mathbf{AADT})]}{\mathbf{0.322} + \mathbf{5} \times [\mathbf{0.05} - \mathbf{0.005} \times \mathbf{ln}(\mathbf{AADT})]} \\ &= \frac{\mathbf{0.322} + \mathbf{26.9} \times [\mathbf{0.05} - \mathbf{0.005} \times \mathbf{ln}(\mathbf{2400})]}{\mathbf{0.322} + \mathbf{5} \times [\mathbf{0.05} - \mathbf{0.005} \times \mathbf{ln}(\mathbf{2400})]} = \mathbf{1.643149} \end{aligned}$$

Since there are no centerline rumble strips on the roadway, the crash modification factor for centerline rumble strips is 1.0, or

$$\mathbf{CMF_{7r}} = \mathbf{1.0}$$

Since there are no passing lanes on the roadway, the crash modification factor for passing lanes is 1.0, or

$$\mathbf{CMF_{8r}} = \mathbf{1.00}$$

Since there are no two-way left-turn lanes on the roadway, the crash modification factor for two-way left-turn lanes is 1.0, or

$$\mathbf{CMF_{9r}} = \mathbf{1.00}$$

The equation for crash modification factor for roadside hazard rating ($CMF_{10r}$) is below. The roadside hazard rating (RHR) for this segment is 6 based on HSM because there are no guardrails and there exist rigid obstacles within 6.5 feet of the roadside.

$$CMF_{10r} = e^{(-0.6869 + 0.0668RHR)} / e^{(-0.4865)} \qquad (4.12)$$

Where:
$CMF_{10r}$ = Crash modification factor for roadside design;

TABLE 4.10
**Predicted Crashes from IHSDM and HSM**

| Segment | Start Station | End Station | Length (mi) | IHSDM Predicted Crashes | HSM Predicted Crashes |
|---|---|---|---|---|---|
| Curve 1 | 13+76.970 | 15+07.430 | 0.0247 | 0.15 | 0.15 |
| Tangent 1 | 15+07.430 | 15+35.830 | 0.0054 | 0.01 | 0.01 |
| Curve 2 | 15+35.830 | 16+66.300 | 0.0247 | 0.15 | 0.15 |
| Tangent 2 | 16+66.300 | 18+56.000 | 0.0376 | 0.07 | 0.07 |
| Tangent 3 | 18+56.000 | 23+94.560 | 0.1003 | 0.17 | 0.17 |
| Curve 3 | 23+94.560 | 28+15.000 | 0.0796 | 0.16 | 0.17 |
| Curve 4 | 28+15.000 | 30+03.420 | 0.0357 | 0.07 | 0.08 |
| Curve 5 | 30+03.420 | 31+41.560 | 0.0262 | 0.11 | 0.11 |
| **TOTAL** | | | | **0.89** | **0.91** |

RHR = Roadside hazard rating for the roadway segment.

$$\mathbf{CMF_{10r}} = \frac{e^{-0.6869 + 0.0068 \times RHR}}{e^{-0.4865}} = \frac{e^{-0.6869 + 0.0668 \times 6}}{e^{-0.4865}} = 1.2219$$

Since there is no lighting on the roadway, the crash modification factor for lighting is:

$$\mathbf{CMF_{11r} = 1.00}$$

Since there is no automated speed enforcement on the roadway, the crash modification factor for automated speed enforcement is:

$$\mathbf{CMF_{12r} = 1.00}$$

With all the crash modification factors, the predicted crashes can be computed:

$$\begin{aligned} N_{rs} &= C_r \times N_{spf-rs} \times (CMF_{1r} \times \ldots \times CMF_{nr}) \\ &= 1.10 \times 0.003449 \times (1.0287 \times 1.1722 \times 1.0 \\ &\quad \times 1.0 \times 1.16 \times 1.64319 \times 1.0 \times 1.0 \times 1.0 \\ &\quad \times 1.2219 \times 1.0 \times 1.0) = 0.012 \end{aligned}$$

Therefore, the predicted number of crashes for this segment is 0.012 per year. Using the same procedure, the predicted crashes can be obtained for other segments of this project. The predicted crashes for all the segments from HSM along with those from the IHSDM are listed in Table 4.10. As can be seen from the table, the predicted crashes from the two methods are very close.

Therefore, it is desirable that IHSDM is used to analyze highway safety whenever it is possible because this software package has computerized all the tedious calculations and contains all the related default coefficients. However, it should be noted that not all the methodologies in HSM are included in the IHSDM software package. Therefore, HSM is still needed to handle some of the highway safety issues as discussed in the following section.

### 4.5 Comparison of HSM and IHSDM Capabilities

Both HSM and IHSDM can be used to predict crashes for a given section of highway. It is believed that IHSDM incorporated many of the functions and methods. Through this study, however, it is realized that there still exist some differences between these two in terms of functions and applications. The comparisons of the major functions of the two are demonstrated in Table 4.11. The table indicates if IHSDM or HSM is able to perform the listed functions.

With respect to different treatments of roadways, both IHSDM and HSM are capable to analyze many

TABLE 4.11
**Function Comparison between HSM and IHSDM**

| Function | HSM | IHSDM |
|---|---|---|
| Identify sites with the most potential for crash frequency or severity reduction. | YES | YES |
| Identify factors contributing to crashes and associated potential countermeasures to address these issues. | YES | YES |
| Evaluate the crash reduction benefits of implemented treatments. | YES | NO |
| Conduct economic appraisals of improvements to prioritize projects. | YES | NO |
| Calculate the effect of various design alternatives on crash frequency and severity. | YES | YES |
| Estimate potential crash frequency and severity on highway networks, and the potential effects of transportation decisions on crashes. | YES | NO |
| Check geometric design elements against relevant design policy documents. | NO | YES |
| Evaluate the operational effects of existing and projected future traffic on a highway section and the effects of alternative road improvements. | NO | YES |

TABLE 4.12
**Comparison of Predictive Capabilities of IHSDM and HSM**

| | | Rural Two-Lane Road | | Rural Multilane Road | | Freeway | | Expressway | | Urban Arterial | | Suburban Arterial | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Treatment** | **HSM** | **IHSDM** | **HSM** | **IHSDM** | **HSM** | **IHSDM** | **HSM** | **IHSDM** | **HSM** | **IHSDM** | **HSM** | **IHSDM** |
| Roadway | Modify lane width | √ | √ | √ | √ | — | — | — | — | — | — | — | — |
| | Add lanes by narrowing existing lanes and shoulders | N/A | √ | — | — | N/A | √ | — | — | — | — | — | — |
| | Remove through lanes | N/A | √ | N/A | √ | N/A | N/A | N/A | N/A | √ | √ | N/A | N/A |
| | Add or widen paved shoulder | √ | √ | √ | √ | — | — | — | — | — | — | — | — |
| | Modify shoulder type | √ | √ | — | — | — | — | — | — | — | — | — | — |
| | Provide a raised median | — | — | √ | √ | — | — | — | — | √ | √ | — | — |
| | Change width of existing median | N/A | √ | √ | √ | — | — | — | — | √ | √ | — | — |
| | Increase median width | — | — | T | √ | T | √ | T | √ | — | — | — | — |
| Roadside | Flatten sideslopes | √ | √ | √ | √ | — | — | — | — | — | — | — | — |
| | Increase distance to roadside features | √ | √ | — | — | √ | √ | — | — | — | — | — | — |
| | Change roadside barrier along embankment to less rigid type | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ |
| | Install median barrier | N/A | √ | √ | √ | T | √ | — | — | — | — | — | — |
| | Install crash cushions at fixed roadside features | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ |
| | Reduce roadside hazard rating | √ | √ | — | — | — | — | — | — | — | — | — | — |
| | Increase clear roadside recovery distance | T | √ | — | — | — | — | — | — | — | — | — | — |
| | Install curbs | — | — | — | — | — | — | — | — | T | — | T | — |
| | Increase the distance to utility poles and decrease utility pole density | T | — | T | — | T | — | T | — | T | — | T | — |
| | Install roadside barrier along embankments | T | — | T | — | T | — | T | — | T | — | T | — |
| Alignment | Modify horizontal curve radius and length, and provide spiral transitions | √ | √ | — | — | — | — | — | — | — | — | — | — |
| | Improve superelevation of horizontal curve | √ | √ | — | — | — | — | — | — | — | — | — | — |
| | Change vertical grade | √ | √ | — | — | — | — | — | — | — | — | — | — |
| | Modify tangent length prior to curve | T | √ | T | — | T | — | T | — | T | — | T | — |
| | Modify horizontal curve radius | — | — | — | — | — | — | — | — | T | — | T | — |
| Roadway Signs | Install combination horizontal alignment/advisory speed signs | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ |
| | Install changeable crash ahead warning signs | — | — | — | — | √ | — | — | — | — | — | — | — |
| | Install changeable speed warning signs | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ |
| Delineation | Install Post-Mounted Delineators (PMDs) | √ | — | — | — | — | — | — | — | — | — | — | — |
| | Place standard edgeline markings | √ | — | — | — | — | — | — | — | — | — | — | — |
| | Place wide edgeline markings | √ | — | — | — | — | — | — | — | — | — | — | — |
| | Place centerline markings | √ | — | — | — | N/A | — | N/A | — | — | — | — | — |
| | Place edgeline and centerline markings | √ | — | √ | — | N/A | — | N/A | — | — | — | — | — |
| | Install edgelines, centerlines and PMDs | √ | — | √ | — | N/A | — | N/A | — | — | — | — | — |
| | Install snowplowable, permanent RPMs | √ | — | — | — | √ | — | — | — | — | — | — | — |
| | Install chevron signs on horizontal curves | — | — | — | — | — | — | — | — | T | — | T | — |
| | Place edgeline and directional pavement marking on horizontal curves | T | — | — | — | — | — | — | — | — | — | — | — |

TABLE 4.12
*(Continued)*

| | | Rural Two-Lane Road | | Rural Multilane Road | | Freeway | | Expressway | | Urban Arterial | | Suburban Arterial | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Treatment** | **HSM** | **IHSDM** | **HSM** | **IHSDM** | **HSM** | **IHSDM** | **HSM** | **IHSDM** | **HSM** | **IHSDM** | **HSM** | **IHSDM** |
| Rumble Strips | Install continuous shoulder rumble strips | — | — | √ | — | √ | — | — | — | — | — | — | — |
| | Install centerline rumble strips | √ | √ | — | — | N/A | — | N/A | — | — | — | — | — |
| | Install continuous shoulder rumble strips and wider shoulders | — | — | — | — | T | — | — | — | — | — | — | — |
| | Install transverse rumble strips | T | — | — | — | — | — | — | — | — | — | — | — |
| Traffic Calming | Install speed humps | N/A | — | N/A | — | N/A | — | N/A | — | √ | — | √ | — |
| | Install transverse rumble strips | — | — | — | — | N/A | — | N/A | — | T | — | T | — |
| | Apply several traffic calming measures to a road segment | N/A | — | N/A | — | N/A | — | N/A | — | √ | — | — | — |
| On-Street Parking | Prohibit on-street parking | N/A | — | N/A | — | N/A | — | N/A | — | √ | √ | N/A | — |
| | Convert free to regulated on-street parking | N/A | — | N/A | — | N/A | — | N/A | — | √ | √ | N/A | — |
| | Implement time-limited on-street parking | N/A | — | N/A | — | N/A | — | N/A | — | √ | √ | N/A | — |
| | Convert angle parking to parallel parking | N/A | — | N/A | — | N/A | — | N/A | — | √ | √ | N/A | — |
| Access Management | Modify access point density | √ | √ | — | — | N/A | — | — | — | √ | √ | √ | √ |
| | Reduce number of median crossings and intersections | — | — | — | — | N/A | — | — | — | T | — | T | — |
| Weather Issues | Implement faster response times for winter maintenance | √ | — | √ | — | √ | — | √ | — | √ | — | √ | — |
| | Apply preventive chemical anti-icing during the whole winter season | T | — | T | — | T | — | T | — | T | — | T | — |
| | Install changeable fog warnings signs | — | — | — | — | T | — | — | — | — | — | — | — |
| | Install snow fence for the whole winter season | T | — | T | — | — | — | — | — | N/A | — | N/A | — |

NOTE: √ = CMF IS AVAILABLE FOR THIS TREATMENT.
T = CMF is not available but a trend regarding the potential change in crashes or user behavior is known.
— = CMF is not available and a trend is not known.
N/A = the treatment is not applicable to the corresponding setting.

TABLE 4.13
**Comparison of Predictive Capabilities of IHSDM and HSM in Roadway Intersections**

| | Urban | | | | Suburban | | | | Rural | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Stop | | Signal | | Stop | | Signal | | Stop | | Signal | |
| **Treatment** | **Minor Road** | **All-Way** | **3-Leg** | **4-Leg** | **Minor Road** | **All-Way** | **3-Leg** | **4-Leg** | **Minor Road** | **All-Way** | **3-Leg** | **4-Leg** |
| Convert four-leg intersection to two three-leg intersection | √ | — | — | — | — | — | — | — | — | — | — | — |
| Convert signalized intersection to a modern roundabout | N/A | N/A | √ | √ | N/A | N/A | √ | √ | N/A | N/A | √ | √ |
| Convert stop-controlled intersection to a modern roundabout | √ | √ | N/A | N/A | √ | √ | N/A | N/A | √ | √ | N/A | N/A |
| Convert minor-road stop-control to all-way stop-control | √ | — | — | — | — | — | — | — | √ | — | — | — |
| Remove unwarranted signal on one-way streets (i.e., convert from signal to stop control) | — | — | √ | √ | — | — | — | — | — | — | — | — |
| Convert stop control to signal control | √ | T | N/A | N/A | — | — | N/A | N/A | √ | — | N/A | N/A |

NOTE: √ = CMF is available for this treatment.
T = CMF is not available but a trend regarding the potential change in crashes or user behavior is known.
— = CMF is not available and a trend is not known.
N/A = the treatment is not applicable to the corresponding setting.

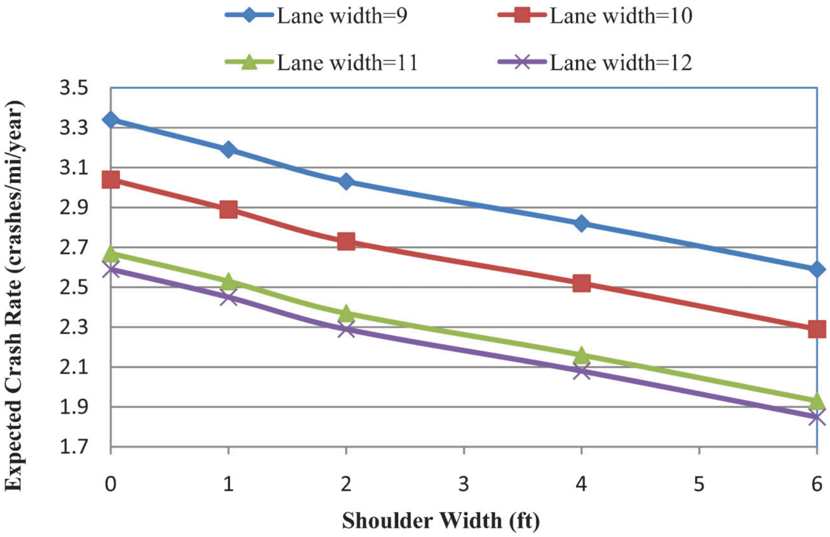


**Figure 5.1** Expected Crash Rates for Various Lane Widths and Shoulder Widths.

types of treatments. Table 4.12 presents a comprehensive list of roadway treatments and indicates if any of the two methods can be used to analyze the specific roadway treatments. In addition, Table 4.12 also indicates if there are potential possibilities that the any of the two methods can have the capabilities to analyze the specific treatments in the future. In a similar fashion, Table 4.13 shows the comparison of the two methods in terms of capabilities of analyzing safety effects of various types of intersection projects.

# 5. SAFETY EFFECTS OF GEOMETRIC ELEMENTS

As most design exceptions involve highway geometric dimensions that do not meet the requirements of the design standards, it is essential to understand the safety implications of these geometric dimension shortfalls. To quantitatively assess the safety effects of highway geometric dimensions, IHSDM was used to determine the predicted number of crashes on a highway section with respect of various types of roadway dimensions. The section of SR-46 in the example problems in the previous chapter was again used in this analysis. As described in the previous chapter, the highway section was a two-way two-lane rural highway from Station 13+76.970 to Station 31+41.650. The lane width throughout this section was 11 feet and the shoulder width was 2 feet. To examine the effects of roadway geometrics on safety, different roadway dimensions were utilized in the safety analysis to reveal their safety effects.

## 5.1 Safety Effects of Lane Width and Shoulder Width

To study the safety effects of roadway lane width and shoulder width, the expected crash rates in terms of number of crashes per mile of roadway per year were computed with different lane width and shoulder width combinations. The expected crash rates from IHSDM outputs are plotted in Figure 5.1. Each curve in the figure represents the expected crash rates over a six year period (2001 to 2016) with different shoulder widths for a given lane width. All of the curves indicate that for a give lane width, the crash rate decreases as the shoulder width increases. The curves also show the differences in the expected crash rates for lane widths ranging from 9 feet to 12 feet.

TABLE 5.1
**Expected Crash Rates for Different Lane Widths**

| Shoulder Width (feet) | Lane Width (feet) | Expected Crash Rate (crashes/mi/yr) | Expected Fatal and Injury Crash Rate (crashes/mi/yr) |
|---|---|---|---|
| 2 | 9 | 3.25 | 1.04 |
| 2 | 10 | 2.96 | 0.95 |
| 2 | 11 | 2.59 | 0.83 |
| 2 | 12 | 2.52 | 0.81 |
| 2 | 13 | 2.52 | 0.81 |
| 2 | 14 | 2.52 | 0.81 |

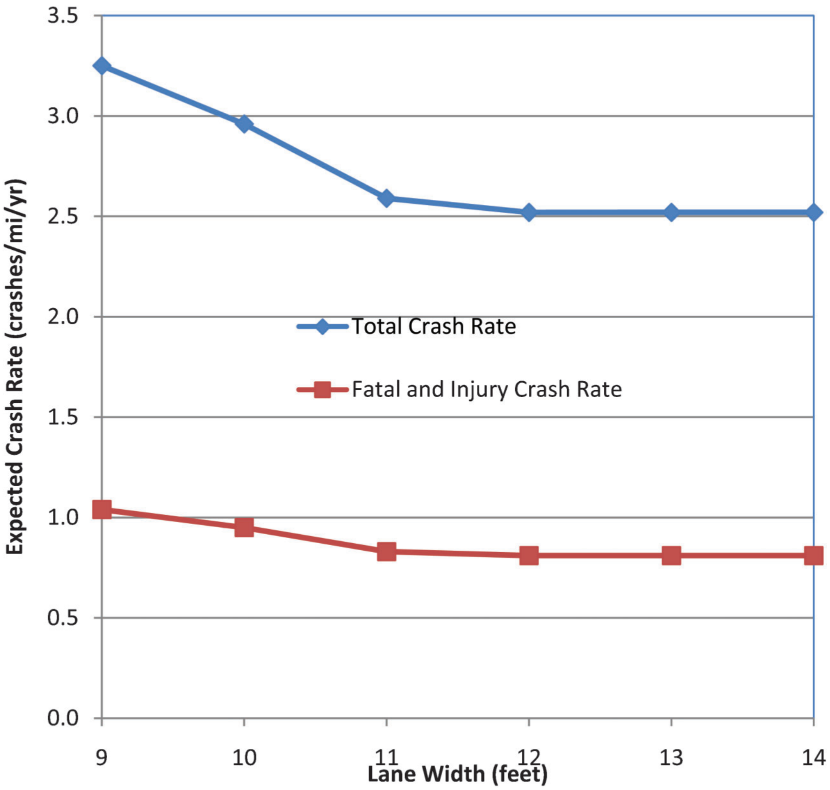


**Figure 5.2** Expected crash rates for different lane widths.

To examine the safety effects of lane widths, the expected crash rates were calculated for different lane widths with a fixed shoulder width of 2 feet as shown in Table 5.1 and Figure 5.2. In addition to the expected crash rates, IHSDM also provides the total fatal and injury crash rates that are included in the Table 5.1 and Figure 5.2. The crash rates for lane widths of 13 and 14 feet are included to show that a lane width more than 12 feet would not add any benefit to the roadway safety. As shown in Figure 5.2 the crash rate increases more quickly when the lane width is reduced to 11 feet or less.

The expected crashes and crash rates are listed in Table 5.2 for various combinations of lane widths and shoulder widths over the six year analysis period. The values in Table 5.2 are listed in the order of predicted crash rates from low to high. Thus, the combinations of lane widths and shoulder widths on the top part of the table are the safer arrangements than those in the bottom part. As can be seen from Table 5.2, with the same total widths (lane width plus shoulder width), the safety impacts are different with different lane width and shoulder width combinations. It is interesting to note that the 11+3 arrangement has lower expected crashes than the 12+2 arrangement. The expected crashes for the lane and shoulder combinations are plotted in Figure 5.3 for illustration purpose. For a design exception project, the engineer or designer should evaluate a number of alternatives and compare their safety impacts with such a graph as Figure 5.3. This will enable the engineer or designer to choose a safest alternative.

## 5.2 Safety Effects of Curve Radius

There was a horizontal curve between Station 13+76.970 and Station 15+07.430 with a radius of 1,150 feet. Under the given condition, it can be calculated with IHSDM that over a six year period the segment would have expected crashes of 0.89 and expected crash rate of 6.0 crashes per mile per year. To analyze the safety effects of horizontal curves, the expected crashes and crash rates were calculated for curves with different radii. The expected crashes and crash rates are listed in Table 5.3. The expected crash rates and their corresponding curve radii are exhibited in Figure 5.4. The slope or the tangent of the curve in Figure 5.4 indicates that, when the radius is reduced below 400 feet, the expected crash rate will increase at a quicker pace.

## 5.3 Safety Effects of Vertical Grade

IHSDM has the capability of analyzing the safety effects of roadway vertical alignments in terms of vertical grades. The vertical grades used in the IHSDM safety analysis include three ranges: grade$\leq$3%, 3%$<$grade$\leq$6%, and grade$>$6%. To examine the safety

TABLE 5.2
**Expected Crashes and Crash Rates for Different Lane and Shoulder Widths**

| Lane Width + Shoulder Width (feet) | Total Width (feet) | Predicted Crashes (for 6 year period) | Crash Rate (crashes/mi/yr) |
|---|---|---|---|
| 12+6 | 18 | 4.42 | 2.20 |
| 11+3 | 14 | 5.13 | 2.56 |
| 12+2 | 14 | 5.18 | 2.58 |
| 12+1 | 13 | 5.43 | 2.71 |
| 11+1 | 12 | 5.58 | 2.78 |
| 10+4 | 14 | 5.62 | 2.8 |
| 12+0 | 12 | 5.68 | 2.83 |
| 11+0 | 11 | 5.84 | 2.92 |
| 10+3 | 13 | 5.84 | 2.91 |
| 10+2 | 12 | 6.07 | 3.02 |
| 9+4 | 13 | 6.17 | 3.08 |
| 10+1 | 11 | 6.36 | 3.17 |
| 9+3 | 12 | 6.42 | 3.20 |

effects of vertical grades in combination with shoulder widths, the expected crashes were computed for the segment of SR-46 project from Station 13+76.970 to Station 31+41.560. The segment had a lane width of 10 feet. The expected crashes over a six year period were calculated for three assumed shoulder widths, i.e., 2 feet, 4 feet, and 6 feet. The expected crashes are drawn in Figure 5.5. As expected, Figure 5.5 shows that a narrower shoulder width would result in a higher number of crashes. The three curves in the figure also exhibit that the expected crashes follow similar patters with the increases of vertical grades.

Similarly, the expected crashes for different lane widths with a shoulder width of 2 feet over a six year period were also calculated in Figure 5.6. The figure shows the expected crashes on this roadway segment for four lane widths at different vertical grades. Figure 5.6 reveals that the increases of the expected crashes follow similar patterns for all four lane widths. The distances between adjacent curves indicate that when a lane width

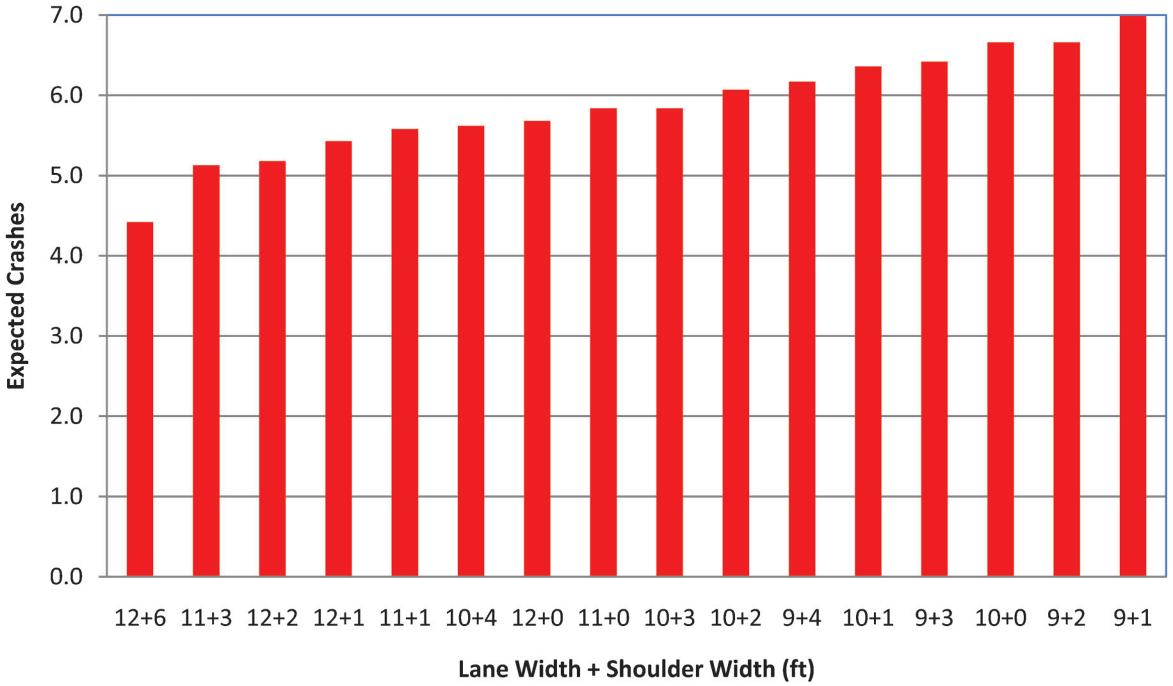


**Figure 5.3** Expected crashes for different lane and shoulder widths.

TABLE 5.3

**Expected Crashes and Crash Rates for Different Curve Radii**

| Horizontal Curve Radius (feet) | Expected Crashes (for 6 year period) | Expected Crash Rate (crashes/mi/yr) |
|---|---|---|
| 1,200 | 0.86 | 5.81 |
| 1,150 | 0.89 | 6.00 |
| 1,100 | 0.92 | 6.18 |
| 1,000 | 0.98 | 6.62 |
| 900 | 1.06 | 7.18 |
| 800 | 1.16 | 7.85 |
| 700 | 1.28 | 8.66 |
| 600 | 1.44 | 9.75 |
| 500 | 1.67 | 11.26 |
| 400 | 2.01 | 13.53 |
| 300 | 2.57 | 17.32 |
| 200 | 3.69 | 24.90 |
| 100 | 7.06 | 47.63 |

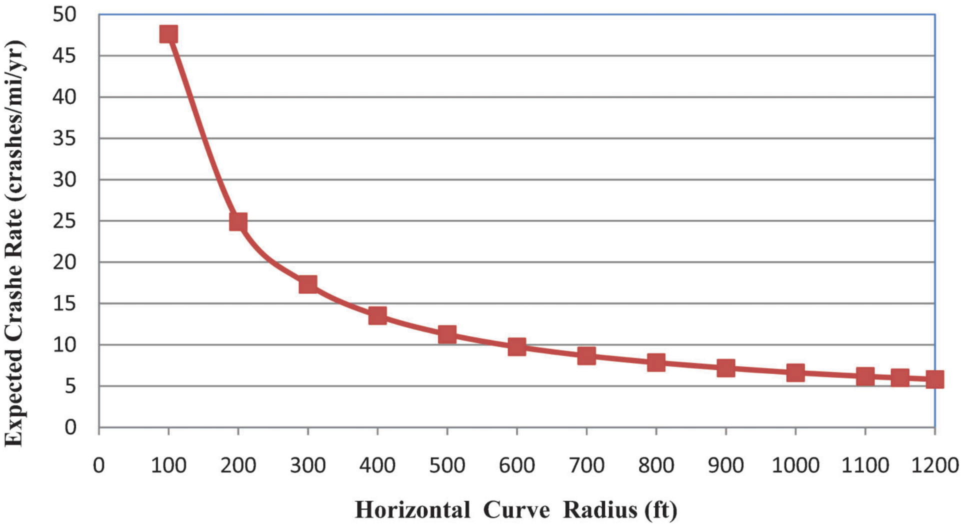


**Figure 5.4** Expected crash rates for different horizontal curve radii.

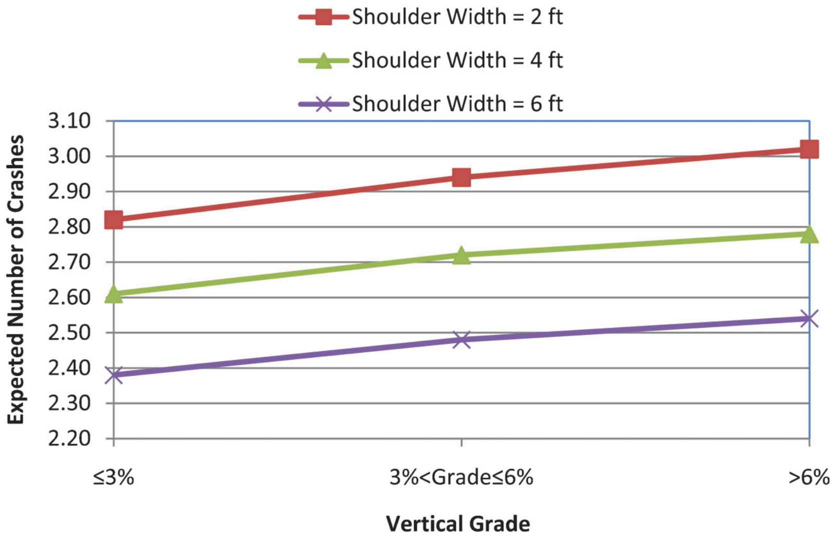


**Figure 5.5** Safety effects of vertical grades for different shoulder widths.

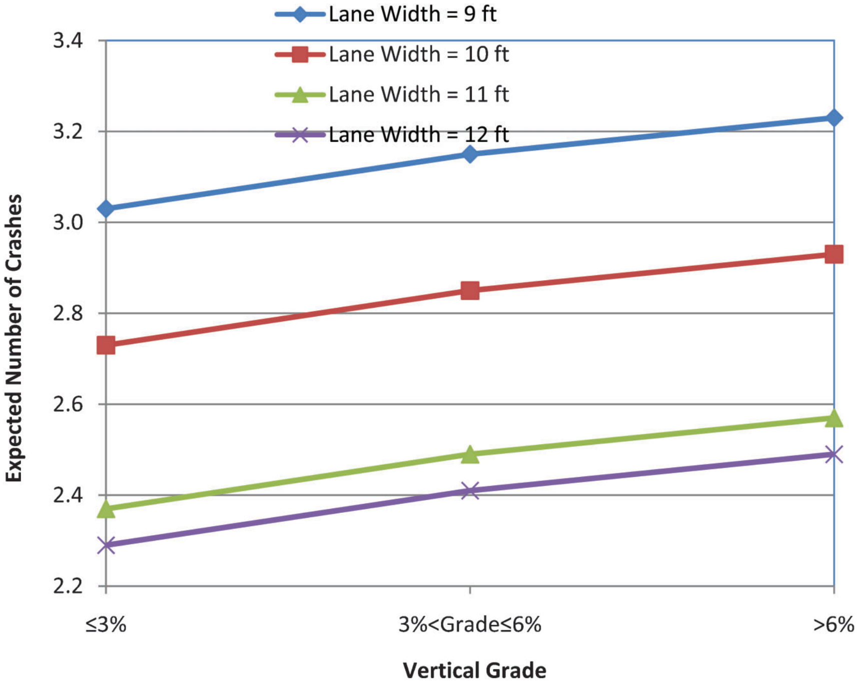
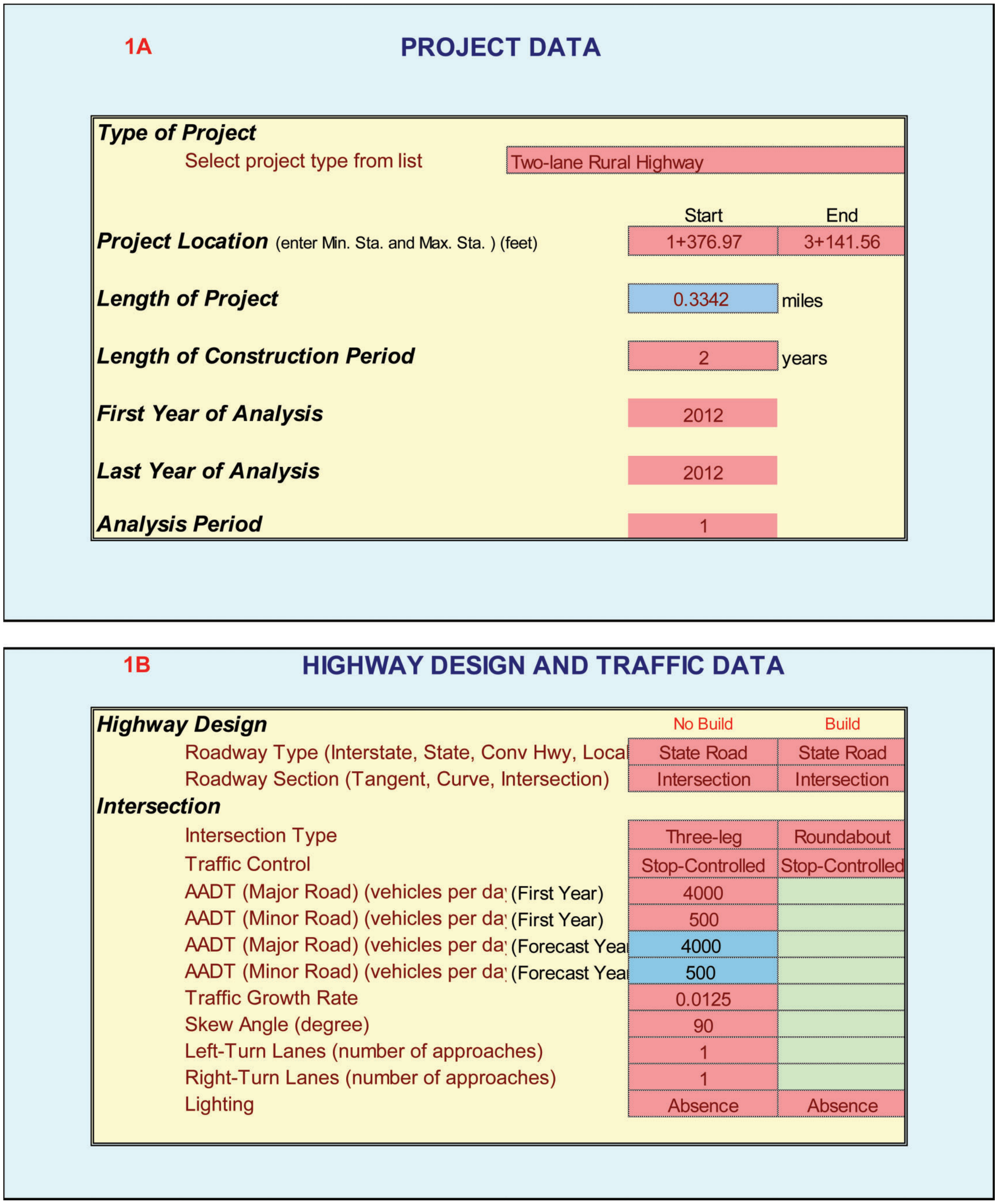


**Figure 5.6** Safety effects of vertical grades for different lane widths.

is less than 11 feet, the expected crashes increase more significantly.

## 5.4 Safety Evaluation of Converting Normal Intersection to Roundabout

The *Highway Safety Manual* (HSM) provides the methods for safety evaluation of intersections. One of the applications is to evaluate the safety effects of converting a normal intersection into a roundabout. The methods for such evaluations, however, have not been included in IHSDM. In order to facilitate the evaluation process, an Excel based program was developed. With this program, as soon as a user input the necessary information on the intersection and the proposed roundabout, the program will instantly produce the estimated crashes at the intersection and at the proposed roundabout. The estimated crash reduction of the conversion can then be used to judge if the proposed roundabout is justified. Figures 5.7 and 5.8 show the captured screens of an application example.



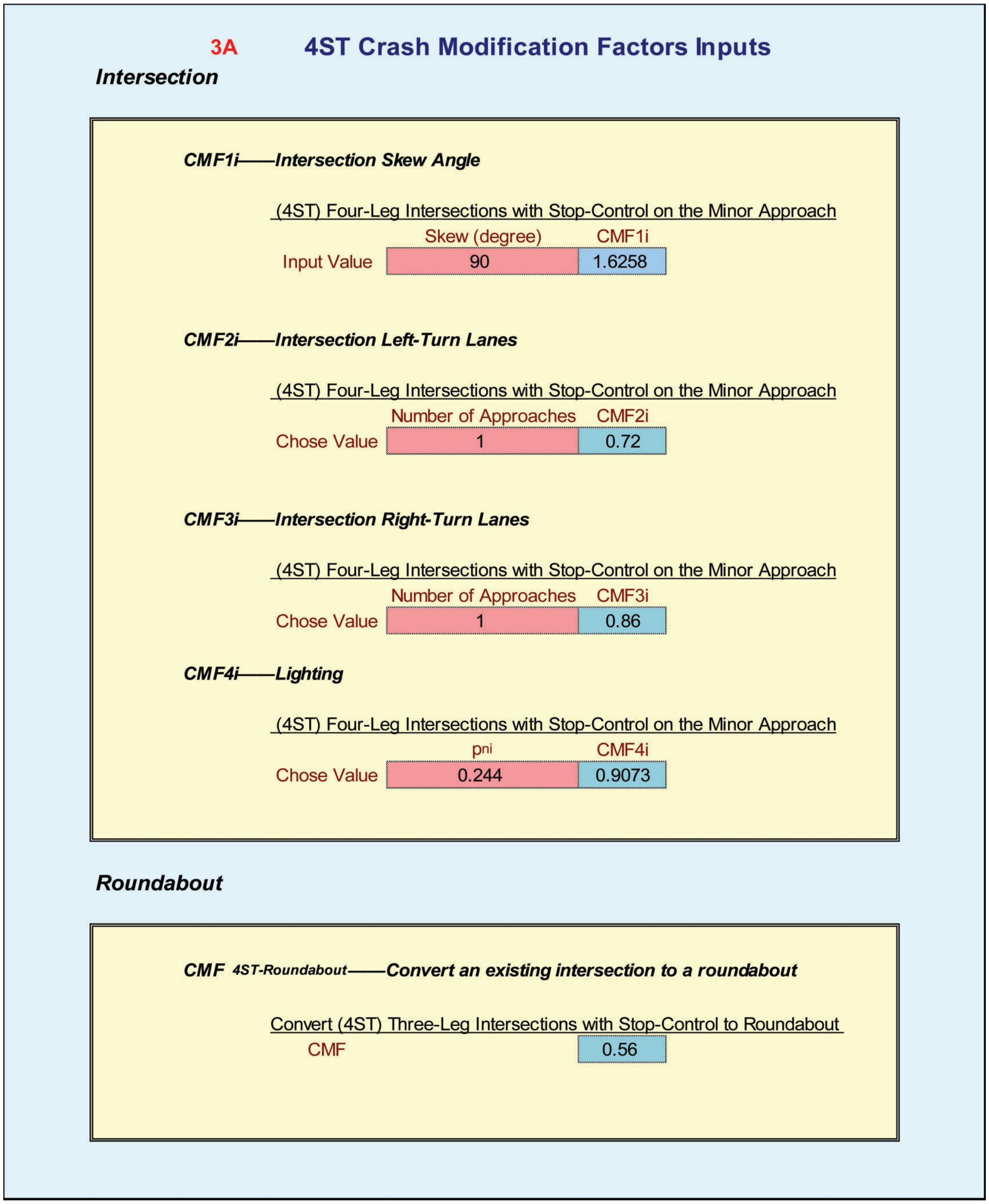
1A PROJECT DATA

| | | |
|---|---|---|
| **Type of Project** | | |
| Select project type from list | Two-lane Rural Highway | |
| | Start | End |
| **Project Location** (enter Min. Sta. and Max. Sta. ) (feet) | 1+376.97 | 3+141.56 |
| **Length of Project** | 0.3342 | miles |
| **Length of Construction Period** | 2 | years |
| **First Year of Analysis** | 2012 | |
| **Last Year of Analysis** | 2012 | |
| **Analysis Period** | 1 | |

1B HIGHWAY DESIGN AND TRAFFIC DATA

| | No Build | Build |
|---|---|---|
| **Highway Design** | | |
| Roadway Type (Interstate, State, Conv Hwy, Local | State Road | State Road |
| Roadway Section (Tangent, Curve, Intersection) | Intersection | Intersection |
| **Intersection** | | |
| Intersection Type | Three-leg | Roundabout |
| Traffic Control | Stop-Controlled | Stop-Controlled |
| AADT (Major Road) (vehicles per da (First Year) | 4000 | |
| AADT (Minor Road) (vehicles per da (First Year) | 500 | |
| AADT (Major Road) (vehicles per da (Forecast Yea | 4000 | |
| AADT (Minor Road) (vehicles per da (Forecast Yea | 500 | |
| Traffic Growth Rate | 0.0125 | |
| Skew Angle (degree) | 90 | |
| Left-Turn Lanes (number of approaches) | 1 | |
| Right-Turn Lanes (number of approaches) | 1 | |
| Lighting | Absence | Absence |

**Figure 5.7** Input screen of roundabout safety analysis.



3A 4ST Crash Modification Factors Inputs

**Intersection**

**CMF1i——Intersection Skew Angle**

(4ST) Four-Leg Intersections with Stop-Control on the Minor Approach

| | Skew (degree) | CMF1i |
|---|---|---|
| Input Value | 90 | 1.6258 |

**CMF2i——Intersection Left-Turn Lanes**

(4ST) Four-Leg Intersections with Stop-Control on the Minor Approach

| | Number of Approaches | CMF2i |
|---|---|---|
| Chose Value | 1 | 0.72 |

**CMF3i——Intersection Right-Turn Lanes**

(4ST) Four-Leg Intersections with Stop-Control on the Minor Approach

| | Number of Approaches | CMF3i |
|---|---|---|
| Chose Value | 1 | 0.86 |

**CMF4i——Lighting**

(4ST) Four-Leg Intersections with Stop-Control on the Minor Approach

| | pni | CMF4i |
|---|---|---|
| Chose Value | 0.244 | 0.9073 |

**Roundabout**

**CMF 4ST-Roundabout——Convert an existing intersection to a roundabout**

Convert (4ST) Three-Leg Intersections with Stop-Control to Roundabout

CMF 0.56

**Figure 5.8** Output screen of roundabout safety analysis.

## 6. ECONOMIC ANALYSIS OF DESIGN EXCEPTION PROJECTS

Economic analysis is a critical component of a comprehensive project or program evaluation methodology that considers all key quantitative and qualitative impacts of highway investments. It allows highway agencies to identify, quantify, and value the economic benefits and costs of highway projects and programs over a multiyear timeframe. With this information, highway agencies are better able to target scarce resources to their best uses in terms of maximizing benefits to the public and to account for their decisions. It is important in the transportation development process that each transportation alternative is properly evaluated for its costs and benefits during its entire life-cycle. Highway agencies make use of measures such as the net present value of costs and benefits, benefit-cost ratio, or the internal rate of return to compare different competing alternatives. The alternative that gives the highest net present value, benefit-cost ratio or return on investment is selected and is placed to be funded, programmed, and eventually implemented. Cost items in the economic analysis include capital, operating, maintenance and preservation costs while the considered benefits are travel time savings, reduction in vehicle operating costs, and safety benefits.

One of the important reasons for design exceptions is to reduce cost. It is necessary to conduct economic analyses for proposed design exception projects to compare with the standard designed projects. However, when conducting economic analysis, not only the agency costs (design and engineering cost and construction cost) should be considered, but also the user costs and benefits should be considered. An economic analysis should consider all costs as well as benefits resulted from a proposed built project in terms of monetary values. One of the economic analysis methods is life cycle cost analysis (LCCA). It is a useful economic tool for selecting among alternatives where benefits of the possible project alternatives are essentially identical. For design exception projects, the benefits of alternative projects are usually not the same. Therefore, LCCA method is not suitable for evaluating design exception projects. The appropriate economic tool for design exception projects is benefit-cost analysis (BCA), which considers life-cycle benefits as well as life-cycle costs (*17*).

## 6.1 Benefit-Cost Analysis

The FHWA publication, "Economic Analysis Primer" (*18*), is a great source of economic analysis methods for highway projects. The FHWA publication explains the differences between LCCA and BCA methods and the appropriate applications of them as follows. LCCA is applied when an agency must undertake a project and is seeking to determine the lowest life-cycle-cost (i.e., most cost-effective) means to accomplish the project's objectives. LCCA enables the analyst to make sure that the selection of a design alternative is not based solely on the lowest initial costs, but also considers all the future costs (appropriately discounted) over the project's usable life. LCCA is used appropriately only to select from among design alternatives that would yield the same level of performance or benefits to the project's users during normal operations. If benefits vary among the design alternatives (e.g., they would accommodate different levels of traffic), then the alternatives cannot be compared solely on the basis of cost. Rather, the analyst would need to employ benefit-cost analysis (BCA), which measures the monetary value of life-cycle benefits as well as costs. Accordingly, LCCA should be viewed as a distinct, cost-only subset of BCA. The BCA process begins with the establishment of objectives for a highway project and development a set of alternatives for evaluation. For applications of BCA in design exceptions, the alternatives can be a design that would meet the standard and the proposed design exception options. BCA can evaluate and compare several alternatives, so it can include more than one proposed design exception options in the evaluation. To ensure that the alternatives can be compared fairly, the analyst specifies a multiyear analysis period over which the life-cycle costs and benefits of all alternatives will be measured. The investment costs, hours of delay, crash rates, and other effects of each alternative are measured. The analyst assigns dollar values to the different effects and discounts them to a present value amount. Risk associated with uncertain costs, traffic levels, and economic values also is assessed.

The Economic Analysis Primer (*18*) describes the two most common measures to compare benefits to costs in BCA below.

Net present value (NPV). NPV is perhaps the most straightforward BCA measure. All benefits and costs over an alternative's life cycle are discounted to the present, and the costs are subtracted from the benefits to yield a NPV. If benefits exceed costs, the NPV is positive and the project is worth pursuing. Where two or more alternatives for a project exist, the one with the highest NPV over an equivalent analysis period should usually be pursued. Policy issues, perceived risk, and funding availability, however, may lead to the selection of an alternative with a lower, positive NPV.

Benefit-cost ratio (BCR): The BCR is frequently used to select among projects when funding restrictions apply. In this measure, the present value of benefits (including negative benefits) is placed in the numerator of the ratio and the present value of the initial agency investment cost is placed in the denominator. The ratio is usually expressed as a quotient. For any given budget, the projects with the highest BCRs can be selected to form a package of projects that yields the greatest multiple of benefits to costs. FHWA recommends that only the initial agency investment cost be included in the denominator of the ratio. All other BCA values, including periodic rehabilitation costs or user costs, such as delay associated with construction, should be included in the ratio's numerator as positive or negative benefits. Adherence to this guidance facilitates consistent project comparisons.

Based on the review of the INDOT design exception projects, it is determined that the cost and benefit items shown in Table 6.1 should be included in the BCA. Agency costs are estimated by engineers or designers based on past experience, bid prices, design specifications, materials costs, and other information. Although land acquisition is not usually involved in INDOT's design exception projects, it is included in the agency

TABLE 6.1
**Benefits and Costs for Design Exception Projects**

| Agency Costs |
|---|
| Design and engineering<br>Land acquisition<br>Construction |
| **User Costs/Benefits Associated with Highway Operations** |
| Travel time<br>Vehicle operating costs<br>Crashes |

TABLE 6.2
**Recommended Values of Travel Time Savings**

| Category | Purpose of Travel | Hourly Earnings Rates for Values of Travel Time Savings (2009 U.S. $ per person-hour) | % of Earning for Economic Evaluation |
|---|---|---|---|
| Local Travel | Personal | $23.9 | 50% |
| | Business | $22.9 | 100% |
| Intercity Travel | Personal | $23.9 | 70% |
| | Business | $22.9 | 100% |

costs in case additional land is needed to meet the standard design requirements.

Travel time and delay costs are usually valued as a percentage of average personal wages. The U.S. Department of Transportation (USDOT) provides the average wages of different categories of travelers and recommends the percents of average wages for economic analysis shown in Table 6.2 (*19*). The value of reduced travel time often accounts for the greatest share of a transportation project's benefits (*19*).

Crash costs are the monetary values for fatalities and injuries associated with crashes. The crash cost values used by different agencies vary significantly. Table 6.3 shows the crash cost values from INDOT (*20*) and FHWA (*21*). The cost values in Table 6.3 indicate that the use of crash costs from different agencies may make considerable differences in the benefit-cost analysis.

The vehicle operating costs can be affected by a highway project due to the changes that it causes in highway speeds, traffic congestion, pavement surface, and other conditions that affect vehicle fuel consumption and wear and tear. The AASHTO publication, User and Non-User Benefit Analysis for Highways (*22*), provides good information on the valuation of vehicle operating costs (VOC).

Traffic volumes affect greatly the results of benefit and cost of a highway project in terms of user benefits and vehicle operating cost savings. Therefore, accurate measurements and forecasts of traffic volumes are critical to obtaining valid results from BCA. The most commonly used method for predicting the future traffic volumes is the use of an annual growth rate of traffic. It should be pointed out that use of a fixed growth rate of traffic after a highway project is constructed may not be realistic in many cases.

In order to provide an efficient tool for conducting benefit-cost analysis for design exception projects, an Excel based computer program was developed. With this computer program, INDOT engineers will be able to conduct benefit-cost analysis efficiently and accurately for design exception projects. In the benefit analysis, the design exception alternatives will be compared to the design that meets all the design standards. In addition to the initial costs, the user benefits or costs of the roadway section during the service period will also be considered in the benefit-cost analysis. It is believed that this program will significantly facilitate the economic analysis process for exception projects.

## 6.2 Application Example of Benefit-Cost Analysis

To demonstrate how to conduct a benefit-cost analysis for design exception projects, an example is presented below. The section of SR-46 discussed in Chapter 4 is again used in this example with the key information shown in Table 6.4. The standard design requires a lane width of

TABLE 6.3
**INDOT and FHWA Recommended Crash Costs**

| Crash Severity | Indiana | FHWA |
|---|---|---|
| Fatal/Injury | $81,866 | $158,200 |
| Property Damage Only | $6,822 | $7,400 |

TABLE 6.4
**Information on the Design Exception Project**

| | |
|---|---|
| **Start/End Stations** | 13+76.970–31+41.560 |
| **Length (mile)** | 0.3342 |
| **Current (2011) AADT** | 2400 |
| **Peak Hour Factor (PHF)** | 0.95 |
| **Base free-flow speed** | 45 mph |
| **Standard design widths** | Lane width = 12 feet shoulder width = 6 feet (paved) |
| **Design exception widths** | Lane width = 11 feet shoulder width = 2 feet (paved) |
| **(Initial cost of standard design construction) – (Initial cost of design exception construction)** | $243,250 |

12 feet and a shoulder width of 6 feet. It is proposed to build this section of the roadway with a lane width of 11 feet and a shoulder width of 2 feet and to use additional speed limit and warning signs.

To analyze and compare the benefits and costs of the standard design and the design exception, the standard design is used as the base and the design exception is used as an alternative. The initial costs and the user benefits/costs of the base and the alternative should be estimated in the benefit-cost analysis. The initial costs of a project include engineering cost, right-of-way cost, and construction cost. As shown in Table 6.4, the difference between the initial costs of the standard design project and the initial costs of the design exception project is estimated as $243,250. That is, if the project is built based on the proposed design exception, it will save the agency an initial cost of $243,250 in comparison with the standard design. Therefore, the design exception would save $243,250 for INDOT in terms of initial costs. This saving is called agency benefit.

In addition to the agency benefit, the user benefits associated with highway operations after completion of the construction should also be considered in the benefit-cost analysis. These user benefits include the monetary values of travel time costs, vehicle operating costs, and crash costs. They are estimated by calculating the differences in the costs between the standard design and the design exception. When the difference in costs is positive, it means the design exception alternative reduces cost and thus a benefit is realized. If the difference in costs is negative, it means the design exception increases cost in comparison with the standard design. A negative user benefit can be considered a user cost. Since user benefits and costs are incurred annually, they are often converted to the present value with a discount rate to compare all the cost and benefit items in the same base year. The net present value (NPV) of the total benefit of a proposed design exception project can be expressed as:

$$\begin{aligned} NPV = {} & Agency\ Benefit + Travel\ Time\ Savings + \\ & Venicle\ Operating\ Savings + Crash\ Savings \end{aligned} \tag{6.1}$$

It should be noted that values of the user savings in Equation 6.1 are often negative because they are related to the operations of the highway that were designed with lower criteria than the standard specifications. It is therefore expected that NPV will decrease as time increases.

### 6.2.1 Agency Benefit

The agency benefit for a design exception project can be calculated as:

$$\begin{aligned} \text{AgencyBenefit} = {} & \text{(Initial cost of standard design)} - \\ & \text{(Initial cost of design exception)} \end{aligned} \tag{6.2}$$

### 6.2.2 Travel Time Cost Savings

Travel time costs are directly related to the vehicle speeds as well as traffic flow rates on the roadway section. The difference of the costs between the standard design alternative and the design exception alternative is the user benefit for using the roadway with the design exception. The average travel speeds on the standard design roadway and on the design exception roadway can be calculated using the method from the *Highway Capacity Manual 2010* (*23*). Since lane widths and shoulder widths affect the average travel speeds, the standard design and design exception will result in different average travel speeds. The steps for calculating travel time savings are presented below:

*Step 1: Predicting traffic volume based on the current traffic volume:*

$$\text{AADT}_t = AADT_0(1+r)^t \tag{6.3}$$

Where:
$\text{AADT}_\text{t}$ = Average Annual Daily Traffic in Year t;
$\text{AADT}_0$ = Average Annual Daily Traffic in Year 0;
r = annual traffic volume growth rate.

*Step 2: Determining hourly traffic flow rate for each vehicle class:*

$$\begin{aligned} &\text{Hourly Traffic Flow Rate} = \text{AADT} \times \\ &\text{(Hourly Traffic Distribution Factor)} \end{aligned} \tag{6.3}$$

*Step 3: Determining average speed for each vehicle class* (*23*):

$$\text{Average Speed} = \frac{\text{Free Flow Speed}}{\left(1 + 0.15 \times \left(\frac{\text{V}}{\text{C}}\right)^4\right)} \tag{6.4}$$

Where:
V = Hourly traffic volume or flow rate;
C = Highway capacity, the maximum number of vehicles that can pass a given section during a given period of time under prevailing roadway, traffic and control condition.

*Step 4: Calculating travel time for vehicles to traverse the given section of roadway.*

$$\text{Travel Time} = \frac{\text{Roadway Length}}{\text{Average Speed}} \tag{6.5}$$

*Step 5: Calculating hourly travel time savings of the design exception in comparison with the standard design:*

$$\text{HPT} = \text{Houry Traffic Volume} \times \text{AVO} \tag{6.6}$$

$$\begin{aligned} \text{HTTS} = {} & \frac{1}{2} \times (\text{TT}_\text{SD} - \text{TT}_\text{DE}) \times \\ & (\text{HPT}_\text{SD} + \text{HPT}_\text{DE}) \times \text{VT} \end{aligned} \tag{6.7}$$

Where:
HPT = Hourly Person Trips;
AVO = Average Vehicle Occupancy;
HTTS = Hourly Travel Time Savings;
TT = Travel Time;
DE = Design Exception;
SD = Standard Design;
VT = Value of time ($/person).

*Step 6: Calculating yearly travel time savings (year 1 and the last year of the analysis period):*

$$\text{Yearly VOC Savings} = \sum_{i=1}^{24} \mathit{Hourly\ VOC\ Savings}_i \times 365 \tag{6.8}$$

*Step 7: Calculating intermediate yearly travel time savings by interpolation:*

$$\text{Year m TT Savings} = \frac{\text{YTTS}_\text{N} - \text{YTTS}_1}{AP - 1} \times (m-1) + \text{YTTS}_1 \tag{6.9}$$

Where:
YTTS = Yearly Travel Time Savings;
AP = Analysis Period;
N = the last year of the analysis period;
m= the m$^{\text{th}}$ year within the analysis period.

*Step 8: Converting each year's travel time savings into present money value:*

$$\text{P} = \text{F}_n \times \frac{1}{(1+i)^n} \tag{6.10}$$

Where:
P = Present Value;
$\text{F}_\text{n}$ = Value in the n$^{\text{th}}$ year;
i = Interest Rate/Discount Rate.

### 6.2.3 Vehicle Operating Cost Savings

Similar to travel time costs, vehicle operating costs are also directly related to the vehicle speeds as well as traffic flow rates on the roadway section. The difference of the vehicle operating costs between the standard design alternative and the design exception alternative is the user benefit for using the roadway with the design exception. The procedures for estimating vehicle operating costs are as follows:

*Step 1: Determining hourly fuel cost for each vehicle class:*

$$\text{VMT} = \text{AADT} \times \text{Hourly Traffic Distribution} \times \text{L} \tag{6.11}$$

Where:
VMT = Hourly vehicle-miles traveled;
L = Length of the roadway section.

$$\text{Hourly Fuel Cost} = \text{VMT} \times \text{Fuel Consumption Rate} \times \text{Unit Fuel Cost} \tag{6.12}$$

*Step 2: Determining truck inventory cost:*

$$\text{Hourly Truck Inventory Cost} = \text{VMT} \times \text{Cargo Value} \times \frac{\text{Interest Rate}}{365 \times 24} \times \left(\frac{1}{\text{Average } \mathit{Speed}}\right) \tag{6.13}$$

*Step 3: Determining hourly total VOC and VOC savings:*

$$\text{Hourly Total VOC} = \text{Hourly Fuel Cost} \times \text{VOC factor} + \text{Hourly Truck Inventory Cost} \tag{6.14}$$

Where:
VOC factor = 1/0.7 =1.43, assuming fuel costs account for 70% of total VOC.

$$\text{Hourly VOC Savings} = \text{Hourly Total VOC}_\text{SD} - \text{Hourly Total VOC}_\text{DE} \tag{6.15}$$

Where:
DE = Design Exception;
SD = Standard Design;

*Step 4: Calculating yearly VOC savings (year 1 and the last year of the analysis period):*

$$\text{Yearly VOC Savings} = \sum_{i=1}^{24} \mathit{Hourly\ VOC\ Savings}_i \times 365 \tag{6.16}$$

*Step 5: Calculating intermediate yearly travel time savings by interpolation:*

$$\text{Year m VOC Savings} = \frac{\text{YVOCS}_N - \text{YVOCS}_1}{AP - 1} \times (m-1) + \text{YVOCS}_1 \tag{6.17}$$

Where:
YVOCS = Yearly VOC Savings;
AP = Analysis Period;
N = the last year of the analysis period;
m = the m$^{\text{th}}$ year within the analysis period.

*Step 6: Converting each year's VOC savings into present money value using Equation 6.10:*

$$\text{P} = \text{F}_\text{n} \times \frac{1}{(1+i)^n}$$

Where:
P = Present Value;
$\text{F}_\text{n}$ = Value in the n$^{\text{th}}$ year;
i = Interest Rate/Discount Rate.

### 6.2.4 Crash Cost Savings

As discussed in Chapter 4, the predicted yearly crash costs can be estimated with the methods in the *Highway Safety Manual* (HSM) (*4*). The difference of the crash costs between the standard design alternative and the design exception alternative is the user benefit for using the roadway with the design exception. Either IHSDM or HSM can be used to estimate the crash costs. The crash cost calculations with IHSDM and HSM are both based on Equations 4.1 through 4.13. As Table 6.3 shows, INDOT and FHWA recommend different values of the costs of different crashes. In this application example, both INDOT and FHWA crash cost values will be used in the benefit-cost analysis for comparison purpose.

### 6.2.5 Benefit-Cost Analysis Results

Following the methods discussed above, all the benefits and costs in Equation 6.1 can be computed with the Excel based computer program using the information in Table 6.4. In this benefit-cost analysis, a discount rate of money of 4% and an annual traffic growth rate of 4% are used. The standard design requires a lane width of 12 feet and a shoulder width of 6 feet. The design exception option proposes a lane width of 11 feet and a shoulder width of 2 feet and use of additional speed limit and warning signs. As Equation 6.1 shows, the net present value of total benefit is the summation of all benefits or savings:

$$\begin{aligned} NPV = {} & Agency\ Benefit + Travel\ Time\ Savings + \\ & Venicle\ Operating\ Savings + Crash\ Savings \end{aligned}$$

Using the current year (2012) as the base year and a service life of 20 years, the costs of the proposed design exception are compared to those of the standard design. If the difference between a cost of the standard design and a corresponding cost of the design exception is positive, it indicates that the design exception has a positive benefit. Otherwise, the design exception has a negative benefit. A negative benefit is actually a cost resulted from adoption of the design exception instead of the standard design.

The agency benefit in this example is given in Table 6.4 as:

$$\begin{aligned} Agency\ Benefit &= (Initial\ Cost\ of\ standard\ design) - \\ &\quad (Initial\ Cost\ of\ design\ exception) \\ &= \$243{,}250 \end{aligned}$$

That is, implementing the design exception project will save INDOT $243,250 of initial costs in terms of costs of design and engineering, land acquisition, and construction in comparison with the standard design option. Since this agency benefit incurs in the base year (year 0), the benefit is already the present value and there is no need to convert the value with discount rate.

With the Excel based computer program, the travel time cost savings, the vehicle operating cost savings, and the crash cost savings were calculated for a 20-year service life. Each of the cost savings is the difference between the corresponding costs of the standard design and the design exception. Table 6.5 lists the user benefit values of the design exception project in each of the 20 years of the service life. All the user benefit values for each year in Table 6.5 are expressed in present values, i.e., in the current (2011) dollar values. The crash cost savings were calculated based on the INDOT crash cost values as well as on the FHWA crash cost values listed in Table 6.3. The values of user benefits listed in Table 6.5 are all negative. This indicates that, compared to the standard design, the design exception will cost users more in the forms of longer travel time, higher vehicle operating expenses, and more estimated vehicle crashes.

The total benefits of the proposed design exception project can be calculated with Equation 6.1 using the agency benefit of $243,250 and the user benefits listed in

TABLE 6.5
**User Benefits of the Design Exception Project (Present Values)**

| | | | Crash Cost Savings | |
|---|---|---|---|---|
| Year | Travel Time Savings | Vehicle Operating Cost Savings | Based on INDOT Crash Cost Values | Based on FHWA Crash Cost Values |
| 2012 | -$19,261.58 | -$1,777.03 | -$3,532.17 | -$6,397.93 |
| 2013 | -$19,599.68 | -$1,808.22 | -$3,396.32 | -$6,151.85 |
| 2014 | -$19,883.28 | -$1,834.39 | -$3,382.32 | -$6,041.76 |
| 2015 | -$20,116.07 | -$1,855.86 | -$3,140.09 | -$5,687.74 |
| 2016 | -$20,301.54 | -$1,872.97 | -$3,019.32 | -$5,468.98 |
| 2017 | -$20,442.99 | -$1,886.02 | -$2,955.03 | -$5,314.87 |
| 2018 | -$20,543.52 | -$1,895.30 | -$2,841.38 | -$5,110.45 |
| 2019 | -$20,606.08 | -$1,901.07 | -$2,684.16 | -$4,861.90 |
| 2020 | -$20,633.44 | -$1,903.59 | -$2,580.93 | -$4,674.90 |
| 2021 | -$20,628.21 | -$1,903.11 | -$2,525.97 | -$4,543.17 |
| 2022 | -$20,592.86 | -$1,899.85 | -$2,386.21 | -$4,322.21 |
| 2023 | -$20,529.71 | -$1,894.02 | -$2,294.43 | -$4,155.97 |
| 2024 | -$20,440.96 | -$1,885.84 | -$2,284.98 | -$4,081.59 |
| 2025 | -$20,328.66 | -$1,875.48 | -$2,121.33 | -$3,842.43 |
| 2026 | -$20,194.77 | -$1,863.12 | -$2,039.74 | -$3,694.64 |
| 2027 | -$20,041.10 | -$1,848.95 | -$1,961.29 | -$3,552.54 |
| 2028 | -$19,869.38 | -$1,833.10 | -$1,919.53 | -$3,452.44 |
| 2029 | -$19,681.23 | -$1,815.74 | -$1,845.70 | -$3,319.65 |
| 2030 | -$19,478.15 | -$1,797.01 | -$1,743.58 | -$3,158.20 |
| 2031 | -$19,261.58 | -$1,777.03 | -$1,676.52 | -$3,036.73 |

TABLE 6.6
**Total Benefits of the Design Exception Project**

| Calendar Year | Service Year | Net Present Value of Total Benefit<br>Based on INDOT Crash Cost Values | Net Present Value of Total Benefit<br>Based on FHWA Crash Cost Values |
|---|---|---|---|
| 2011 | 0 | $243,250 | $243,250 |
| 2012 | 1 | $218,679 | $215,813 |
| 2013 | 2 | $193,875 | $188,254 |
| 2014 | 3 | $168,775 | $160,494 |
| 2015 | 4 | $143,663 | $132,835 |
| 2016 | 5 | $118,469 | $105,191 |
| 2017 | 6 | $93,185 | $77,547 |
| 2018 | 7 | $67,905 | $49,998 |
| 2019 | 8 | $42,714 | $22,629 |
| 2020 | 9 | $17,596 | -$4,583 |
| 2021 | 10 | -$7,462 | -$31,657 |
| 2022 | 11 | -$32,341 | -$58,472 |
| 2023 | 12 | -$57,059 | -$85,052 |
| 2024 | 13 | -$81,670 | -$111,460 |
| 2025 | 14 | -$105,996 | -$137,507 |
| 2026 | 15 | -$130,094 | -$163,260 |
| 2027 | 16 | -$153,945 | -$188,702 |
| 2028 | 17 | -$177,567 | -$213,857 |
| 2029 | 18 | -$200,910 | -$238,674 |
| 2030 | 19 | -$223,928 | -$263,107 |
| 2031 | 20 | -$246,643 | -$287,182 |

Table 6.5. The calculated total benefits are presented in Table 6.6. As can be seen from this table, in the beginning of the analysis period, Year 0, the total benefit is nothing but the agency benefit. That is, compared to the standard design, the design exception option would initially save INDOT $243,250 in terms of engineering, land acquisition, and construction costs. Because of the negative user benefits, the total benefit will decrease each year as motorists will endure negative impact of the roadway with design exceptions. As service time increases, the total benefit will eventually decrease from positive to negative. Therefore, use of the savings in initial costs alone to justify a design exception project may not be appropriate as this application example indicates.

To demonstrate the trends of the total benefits, Figure 6.1 displays the total benefits of the design exception project in different years. With the INDOT

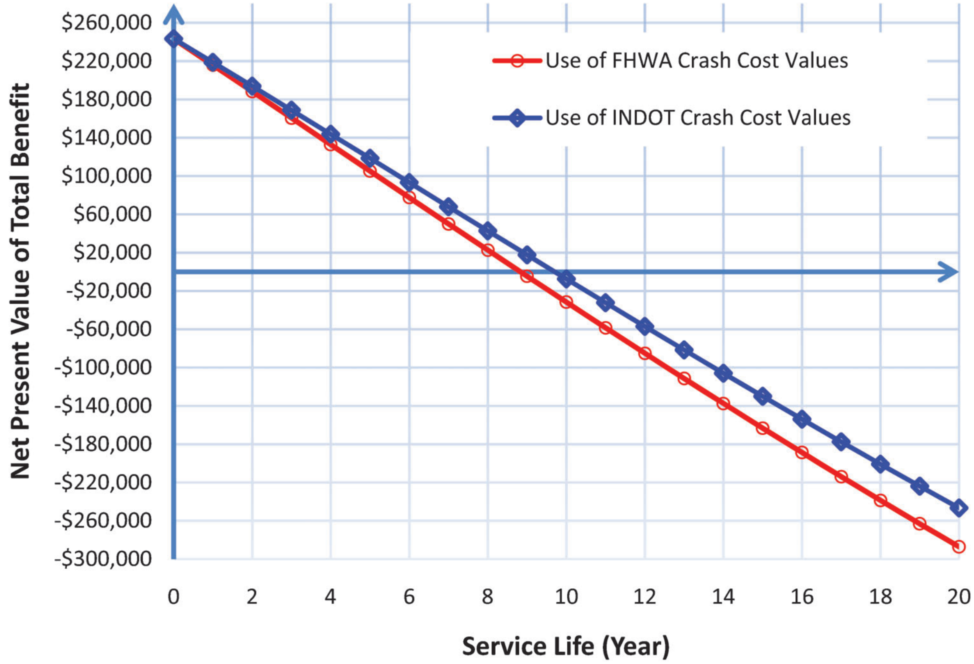


**Figure 6.1** Total benefits in different service years.

recommended crash cost values, the total benefit will become negative in the 10th service year. If the FHWA recommended crash cost values are used, the total benefit will change to negative in the 9th service year. Therefore, if the expected service life is longer than 10 years, the design exception project will not be justified in terms of the total benefit.

# 7. GUIDELINES FOR DEVELOPMENT AND ASSESSMENT OF DESIGN EXCEPTION PROJECTS

## 7.1 General Information

### *7.1.1 Design Exception*

A design exception is a design of a segment or an element of highway with justified rationale and need for a specific deviation from an established geometric value, criterion, or guideline. The need for such exceptions may be necessary when a design in full compliance with the established design criteria is unacceptable or unachievable under certain circumstances for one or more reasons. Justification for design exceptions should not only be based on cost considerations, but also on unusual or significant site-specific constraints that preclude the use of normal design values. The potential impacts of design exceptions on safety, user benefit and cost, and highway operations must be thoroughly analyzed and addressed. Appropriate safety measures should be included in the design to minimize the possible negative effects due to the exceptions to design criteria.

### *7.1.2 Main Reasons for Design Exceptions*

The main and common reasons for adopting design exceptions may include the following:

- Impacts to the natural environment
- Construction costs
- Right-of-way impacts
- Impact to adjacent properties
- Preservation of historic or cultural resources
- Sensitivity to context
- Sensitivity to community values
- Effects of existing conditions
- Temporary construction
- Delay of construction

In addition to these main reasons, there may be other reasons for design exceptions. It is possible that a design exception may be necessary for a combination of several reasons or factors. A design exception that includes one or more substandard design elements may be proposed and approved when it can be rationally verified to be the best practical alternative for the given location and specified time period. However, it should be emphasized that, compared to a standard design, a design exception may likely have the potential to adversely affect highway safety and operations. It is therefore essential to thoroughly analyze the possible social, economic and environmental impacts of using lesser design values before a final decision is made to construct a highway project with design exceptions.

### *7.1.3 Controlling Design Criteria*

Highway design standards include a wide range of geometric elements and design criteria. Among these criteria, FHWA identified 13 of them as the substantial important ones that should be treated with special attention in highway designs. The 13 controlling criteria are listed below:

1. Design speed
2. Lane width
3. Shoulder width
4. Bridge width
5. Horizontal alignment
6. Superelevation
7. Vertical alignment
8. Grade
9. Stopping sight distance
10. Cross slope
11. Vertical clearance
12. Lateral offset to obstruction
13. Structural capacity

A formal design exception is required if any of the 13 controlling criteria are not met on the NHS. Even though a formal approval is not required for exceptions to non-controlling criteria, they should also be identified and justified with appropriate analysis on safety effects.

In addition to the FHWA 13 controlling criteria, INDOT has identified eight additional design criteria which require formal documentation and INDOT approval. The INDOT controlling criteria are:

1. Physically-challenged individuals accessibility (ADA)
2. Bridge rail safety performance
3. Superelevation transition length and distribution
4. Curb offset
5. Intersection sight distance
6. Clear zone or obstruction free zone
7. Vertical clearance of a roadway over a railroad
8. Horizontal clearance at a railroad

### *7.1.4 Design Standards*

The standard design values for the controlling design criteria are contained in the following documents:

- INDOT publication, *Indiana Design Manual* (*2*)
- AASHTO publication, A Policy on Geometric Design of Highways and Streets
- AASHTO publication, A Policy on Design Standards Interstate System

## 7.2 Development and Assessment of Design Exception Projects

A designer shall always strive to design a highway project so that all the adopted design criteria are satisfied. However, under some circumstances, a design with substandard elements could be a more practical and economic alternative because of such factors as cost, right-of-way, and environmental issues. To adopt design exceptions, the effects of the substandard elements must be thoroughly analyzed and documented.

### *7.2.1 Project Information*

In order to perform safety analysis using the *Interactive Highway Safety Design Model* (IHSDM) (*3*) or the *Highway Safety Manual* (HSM) (*4*) for a design exception project, the following geometric design and traffic control features are needed:

- Length of segment (miles)
- AADT (vehicles per day)
- Lane width (feet)
- Shoulder width (feet)
- Shoulder type (paved/gravel/composite/turf)
- Presence or absence of horizontal curve (curve/tangent). If the segment has one or more curve:
    - Length of horizontal curve (miles), (this represents the total length of the horizontal curve and includes spiral transition curves, even if the curve extends beyond the limits of the roadway segment being analyzed);
    - Radius of horizontal curve (feet);
    - Presence or absence of spiral transition curve, (this represents the presence or absence of a spiral transition curve at the beginning and end of the horizontal curve, even if the beginning and/or end of the horizontal curve are beyond the limits of the segment being analyzed); and
    - Superelevation of horizontal curve and the maximum superelevation (emax).
- Grade (percent), considering each grade as a straight grade from Point of Vertical Intersection (PVI) to PVI (i.e., ignoring the presence of vertical curves)
- Driveway density (driveways per mile)
- Presence or absence of centerline rumble strips
- Presence or absence of a passing lane
- Presence or absence of a short four-lane section
- Presence or absence of a two-way left-turn lane
- Roadside hazard rating
- Presence or absence of roadway segment lighting
- Presence or absence of automated speed enforcement
- For all intersections within the study area, the following geometric design and traffic control features are identified:
- Number of intersection legs (3 or 4)
- Type of traffic control (minor road stop or signal control)
- Intersection skew angle (degrees departure from 90 degrees)
- Number of approaches with intersection left-turn lanes (0, 1, 2, 3, or 4), not including stop-controlled approaches
- Number of approaches with intersection right-turn lanes (0, 1, 2, 3, or 4), not including stop-controlled approaches
- Presence or absence of intersection lighting

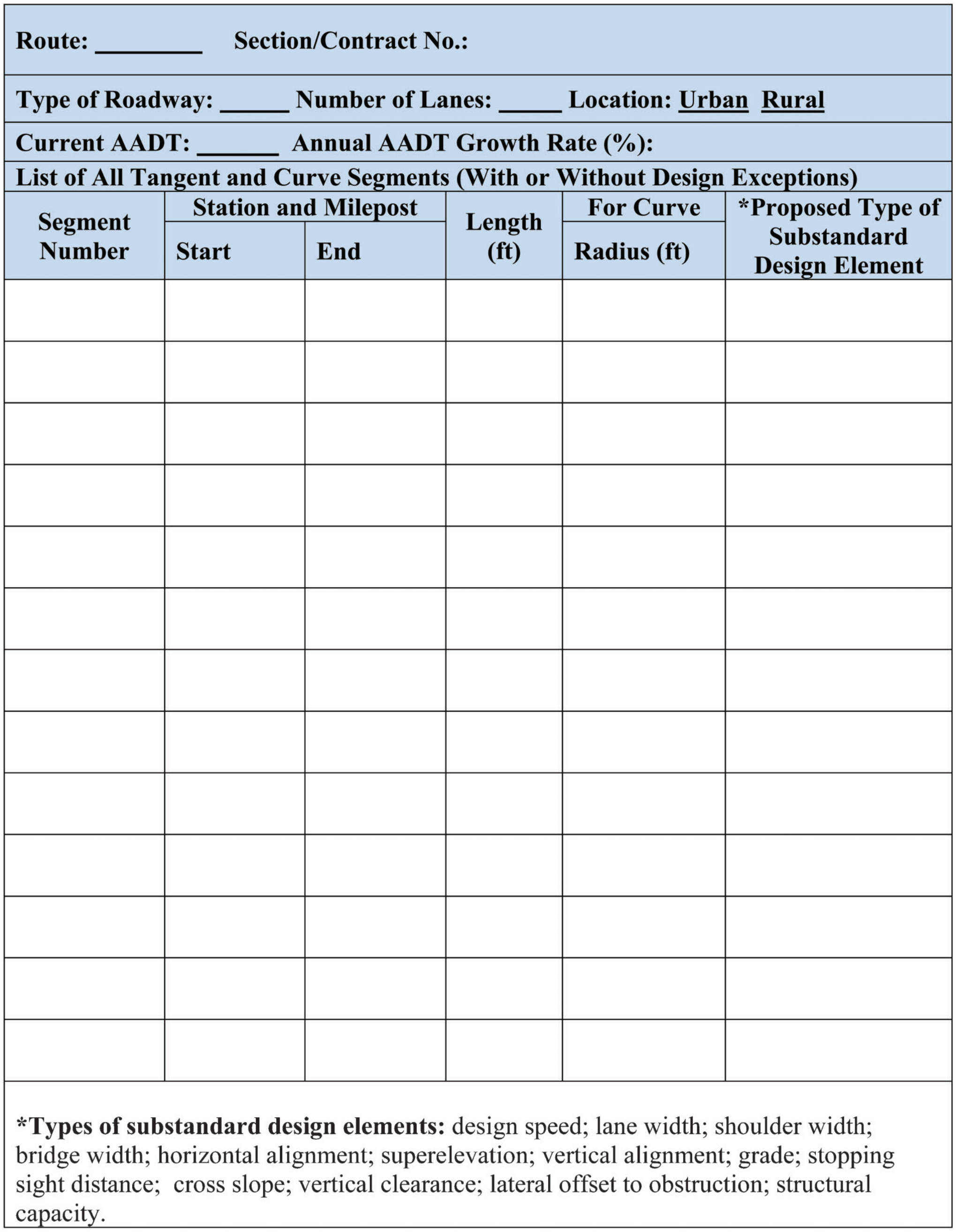
Figures 7.1 and 7.2 can be used to record main information on project and proposed design exceptions. The initial agency costs for both standard design and design exceptions should be estimated for benefit-cost analysis. Initial agency costs include design and engineering cost, land acquisition cost, construction cost, and any other costs needed for building a proposed highway project.

### *7.2.2 Development of Design Exception Alternatives*

The proposed design exceptions that would be identified in Figure 7.2 are only the initial considerations for the design exceptions. They should be refined to minimize the potential adverse impacts to highway safety and operations. In addition, alternative design exceptions may be developed for further evaluation and comparison. It is understandable that designs with lesser values than the established standards will affect roadway safety and traffic operations. The effects of the 13 controlling design criteria can be evaluated using the *Interactive Highway Safety Design Model* (IHSDM) (*3*) software or the HSM (*4*). Compared to a standard design, a design exception may influence the roadway's capacity, vehicle speed, and travel time. Roadway safety may also be affected in terms of expected crash rates and crash severities. In IHSDM and HSM, safety risks are expressed as expected cash frequencies and are estimated using the safety performance functions (SPFs) and crash modification factors (CMFs). SPFs describe the expected crash frequency for a condition or element as a function of traffic volume and other fundamental values. CMFs describe the expected change in crash frequency associated with incremental change in a design dimension. A CMF less than 1.0 indicates that the crash frequency would be lower than in a base condition and a CMF greater than 1.0 means that the crash frequency would be higher. Therefore, a CMF of 1.05 means the expected crash frequency will increase by 5% compared to a base condition.

To choose appropriate substandard design values, it is essential that a designer understands the potential effects of the substandard elements on highway safety and operations. The safety and operational effects of the 13 controlling design criteria are summarized and presented in the following. The Designers should refer to the information when designing substandard elements or developing alternatives of design exceptions.

**1. Design Speed.** In the HSM (*4*), design speed is defined as "a selected speed used to determine the various geometric design features of the roadway. The assumed design speed should be a logical one with respect to the topography, anticipated operating speed, the adjacent land use, and the functional classification of highway. The design speed is not necessarily equal to the posted speed." Design speed is a design control rather than a design element. The value of a design speed affects many geometric elements of the highway, such as the curvature, stopping sight distance, and superelevation.



**Route: ________ Section/Contract No.:**

**Type of Roadway: _____ Number of Lanes: _____ Location: Urban Rural**

**Current AADT: ______ Annual AADT Growth Rate (%):**

**List of All Tangent and Curve Segments (With or Without Design Exceptions)**

| **Segment Number** | **Station and Milepost** | | **Length (ft)** | **For Curve** | ***Proposed Type of Substandard Design Element** |
|---|---|---|---|---|---|
| | **Start** | **End** | | **Radius (ft)** | |
| | | | | | |
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***Types of substandard design elements:** design speed; lane width; shoulder width; bridge width; horizontal alignment; superelevation; vertical alignment; grade; stopping sight distance; cross slope; vertical clearance; lateral offset to obstruction; structural capacity.

**Figure 7.1** Data of project segments.

*Recommended Ranges for Design Speed.* The AASHTO Green Book (*1*) provides the recommended values for design speed as shown in Table 7.1. These values can be used by designers to choose appropriate design speed.

*Effects of Speed Differential.* It is most likely that a design exception will result in a lower speed limit. It is true that lower speeds are safer and lowering speed limits can decrease both crash frequency and severity. On the other hand, it is also true that crash risk increases with increasing differentials in speed. It is therefore essential to limit speed discrepancies to reasonable ranges along a roadway. Table 7.2 lists the safety risk levels associated with speed differential ranges.

### 2. Lane Width

*Recommended Ranges for Lane Width.* Lane width affects highway capacity, vehicle speed, traffic flow, and safety. Table 7.3 gives the ranges for lane width recommended by AASHTO in the Green Book (*1*).

*Safety Effects of Lane Width.* In the HSM (*4*), the average crash frequencies are predicted using SPFs and CMFs. The effect of traffic volume (AADT) on crash

| **Segment Number** | **Location and Direction (Station and Milepost)** | **Proposed Type of Design Exception** | **Ranges or Values of Standard Design** | **Proposed Values of Design Exception** | ***Estimated Initial Agency Cost ($) (Standard Design)** | ***Estimated Initial Agency Cost ($) (Design Exception)** |
|---|---|---|---|---|---|---|
| | | | | | | |
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| | | | | | | |
| | | | | | | |
| **Total Estimated Initial Agency Cost ($)** | | | | | | |
| ***Initial agency cost includes:** design and engineering cost, land acquisition cost, and construction cost. | | | | | | |

**Figure 7.2** Information on proposed substandard design elements.

frequency is incorporated through an SPF, while the effects of geometric design and traffic control features are incorporated through the CMFs. A CMF less than 1.0 indicates that the crash frequency would be lower than in a base condition and a CMF greater than 1.0 means that the crash frequency would be higher. Tables 7.4, 7.5, and 7.6 and Figures 7.3, 7.4, 7.5 and 7.6 are provided for designers to examine the impact of lane width on roadway safety related to design exceptions.

*Effects of Lane Width on Traffic Operations.* Lane widths less than 12 feet will reduce travel speeds and consequently affect highway capacity. A narrow lane in combination with a narrow shoulder will further affect traffic operations. The effects of lane width on free-flow speed are given in the following two tables from the *Highway Capacity Manual* (*23*).

*Potential Adverse Impacts of Reduced Lane Width.* See Table 7.9 for potential adverse impacts of narrow lane width to safety and operations.

### 3. Shoulder Width

*Functions of Shoulder.* Shoulders provide a number of important functions. The following functions are listed in the FHWA publication *Mitigation Strategies for Design Exceptions* (*13*):

- Shoulders provide space for emergency storage of disabled vehicles.
- Shoulders provide space for enforcement activities.
- Shoulders provide space for maintenance activities.
- Shoulders provide an area for drivers to maneuver to avoid crashes.
- Shoulders improve bicycle accommodation.

TABLE 7.1
**Ranges for Design Speed**

| | | Rural | | Urban | |
|---|---|---|---|---|---|
| **Type of Roadway** | **Terrain** | **US (mi/h)** | **Metric (km/h)** | **US (mi/h)** | **Metric (km/h)** |
| Freeway | Level | 70 | 110 | 50 min | 80 min |
| | Rolling | 70 | 110 | 50 min | 80 min |
| | Mountainous | 50-60 | 80-100 | 50 min | 80 min |
| Arterial | Level | 60-75 | 100-120 | 30-60 | 50-100 |
| | Rolling | 50-60 | 80-100 | 30-60 | 50-100 |
| | Mountainous | 40-50 | 60-80 | 30-60 | 50-100 |
| Collector | Level | 40-60 | 60-100 | 30+ | 50+ |
| | Rolling | 30-50 | 50-80 | 30+ | 50+ |
| | Mountainous | 20-40 | 30-60 | 30+ | 50+ |
| Local | Level | 30-50 | 50-80 | 20-30 | 30-50 |
| | Rolling | 20-40 | 30-60 | 20-30 | 20-30 |
| | Mountainous | 20-30 | 30-50 | 20-30 | 20-30 |

Source: (*1*).

- Shoulders increase safety by providing a stable, clear recovery area for drivers who have left the travel lane.
- Shoulders improve stopping sight distance at horizontal curves by providing an offset to objects such as barrier and bridge piers.
- On highways with curb and enclosed drainage systems, shoulders store and carry water during storms, preventing water from spreading onto the travel lanes.
- On high-speed roadways, shoulders improve capacity by increasing driver comfort.

*Recommended Ranges for Minimum Shoulder Width.* The ranges for minimum shoulder width are shown in Table 7.10.

*Safety Effects of Shoulder Width.* The following tables and figures are provided for designers to examine the impact of shoulder width on roadway safety related to design exceptions.

*Effects of Shoulder Width on Traffic Operations.* The effects of shoulder width on traffic operations are reflected by the reduction of free-flow speed in the *Highway Capacity Manual* (*23*). The interaction of shoulder width with lane width also affects operations. Table 7.14 presents shoulder width effects in combination with lane width for freeways and Table 7.15 lists effects for freeways. In Table 7.14, except for the last row of the table, all of the other values are for right side shoulders because of limited research on left side shoulders. In the last row of the table, it shows the safety effects of left side shoulder widths from a Texas study (*24*). That is, for roads with median, increasing left shoulder by 1 foot will result in a 12% reduction in crashes on 4-lane and 6-lane highways.

TABLE 7.2
**Relative Risk of Differential Speed Caused by Changes in Roadway Geometry**

| Speed Differential ($\Delta V$) | Safety Risk |
|---|---|
| $\Delta V<5$ mi/hr | Low |
| 5 mi/hr$<\Delta V<$15 mi/hr | Medium |
| $\Delta V>$15 mi/hr | High |

Source: (*13*).

*Potential Adverse Impacts of Reduced Shoulder Width.* See Table 7.15 for potential adverse impacts of narrow lane width to safety and operations.

**4. Bridge Width**. The FHWA publication, *Mitigation Strategies for Design Exceptions* (*13*), discusses the effects of bridge width as follows. Relatively short bridges represent a discontinuity that may affect driver behavior. The narrowed cross section can make some drivers uncomfortable and cause them to dramatically reduce speed, increasing the risk of rear-end crashes and degrading operations on high-speed, high-volume facilities. The bridge rail may be close enough to the travel lanes to cause drivers to shy towards the centerline or into adjacent lanes. The bridge infrastructure itself is closer to the edge of pavement and thus represents a roadside hazard. For long bridges, the safety and operational concerns at narrow bridges are similar to those on roads with narrow shoulders. There may be inadequate space for storage of disabled vehicles, enforcement activities, emergency response, and maintenance work. The lack of shoulder width on the bridge may make it impossible to avoid a crash or object on the roadway ahead.

*Potential Adverse Impacts of Narrow Bridge Width.* See Table 7.16 for potential adverse impacts of narrow bridge width to safety and operations.

**5. Horizontal Alignment**. In terms of the 13 controlling criteria, the term horizontal alignment refers only to the horizontal curvature of the roadway. Superelevation and stopping sight distance are considered separately.

*Safety Effects of Horizontal Alignment.* The base condition for horizontal alignment is a tangent roadway segment. A CMF has been developed to represent the manner in which crash experience on curved alignments differs from that of tangents. The CMF for horizontal alignment is calculated in terms of radius

TABLE 7.3
**Ranges for Lane Width**

| Type of Roadway | Rural | | Urban | |
|---|---|---|---|---|
| | US (feet) | Metric (meters) | US (feet) | Metric (meters) |
| Freeway | 12 | 3.6 | 12 | 3.6 |
| Ramps (1-lane) | 12-30 | 3.6-9.2 | 12-30 | 3.6-9.2 |
| Arterial | 11-12 | 3.3-3.6 | 10-12 | 3.0-3.6 |
| Collector | 10-12 | 3.0-3.6 | 10-12 | 3.0-3.6 |
| Local | 9-12 | 2.7-3.6 | 9-12 | 2.7-3.6 |

Source: (*1*).

TABLE 7.4
**CMF Values for Lane Width for Rural Two-Lane Two-Way Roads**

| Lane Width (ft) | AADT (vehicles per day) | | |
|---|---|---|---|
| | <400 | 400 to 2000 | >2000 |
| 9 or less | 1.05 | 1.05+0.000281 × (AADT-400) | 1.50 |
| 10 | 1.02 | 1.02+0.000175 × (AADT-400) | 1.30 |
| 11 | 1.01 | 1.01+0.000025 × (AADT-400) | 1.05 |
| 12 or more | 1.00 | 1.00 | 1.00 |

Source: (*4*).

TABLE 7.5
**CMF Values for Lane Width for Rural Undivided Multilane Highways**

| Lane Width (ft) | AADT (vehicles per day) | | |
|---|---|---|---|
| | <400 | 400 to 2000 | >2000 |
| 9 or less | 1.04 | 1.04+0.000213 × (AADT-400) | 1.38 |
| 10 | 1.02 | 1.02+0.000131 × (AADT-400) | 1.23 |
| 11 | 1.01 | 1.01+0.0000188 × (AADT-400) | 1.04 |
| 12 or more | 1.00 | 1.00 | 1.00 |

Source: (*4*).

TABLE 7.6
**CMF Values for Lane Width for Rural Divided Multilane Highways**

| Lane Width (ft) | AADT (vehicles per day) | | |
|---|---|---|---|
| | <400 | 400 to 2000 | >2000 |
| 9 | 1.03 | 1.04+0.000138 × (AADT-400) | 1.25 |
| 10 | 1.01 | 1.01+0.0000875 × (AADT-400) | 1.15 |
| 11 | 1.01 | 1.01+0.0000125 × (AADT-400) | 1.03 |
| 12 | 1.00 | 1.00 | 1.00 |

Source: (*4*).

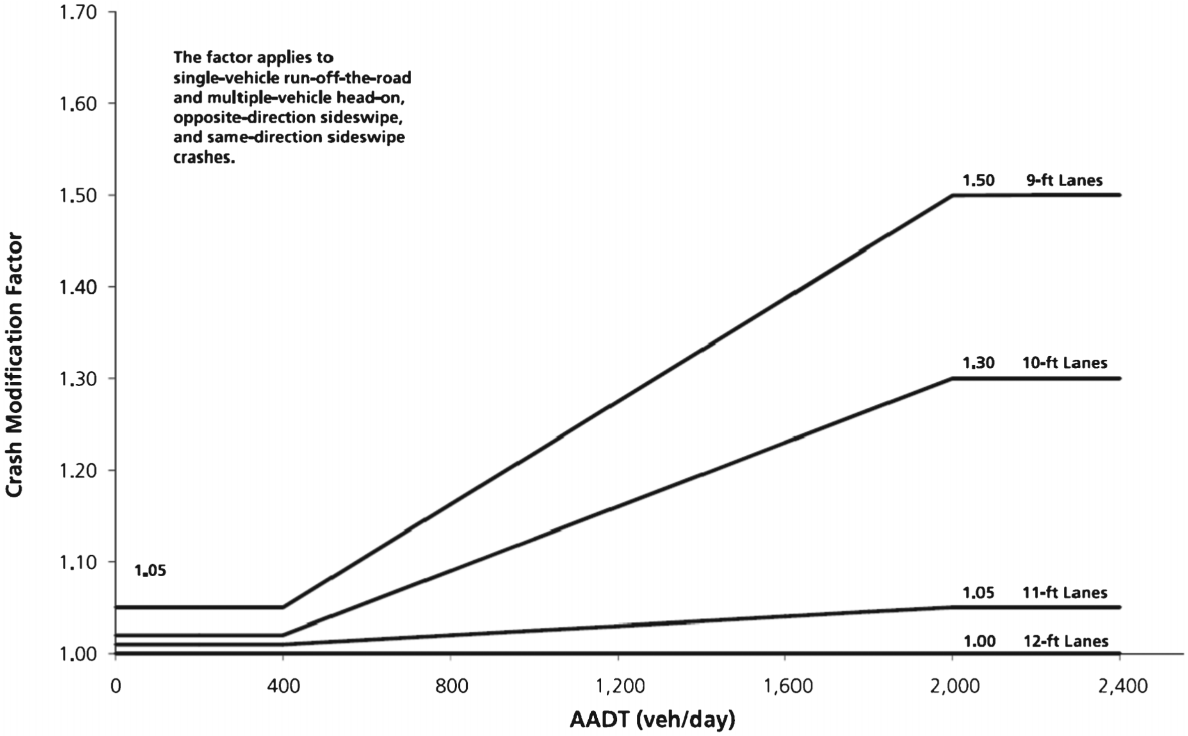


**Figure 7.3** CMF values for lane width for rural two-lane two-way roads. (Source: (*4*).)

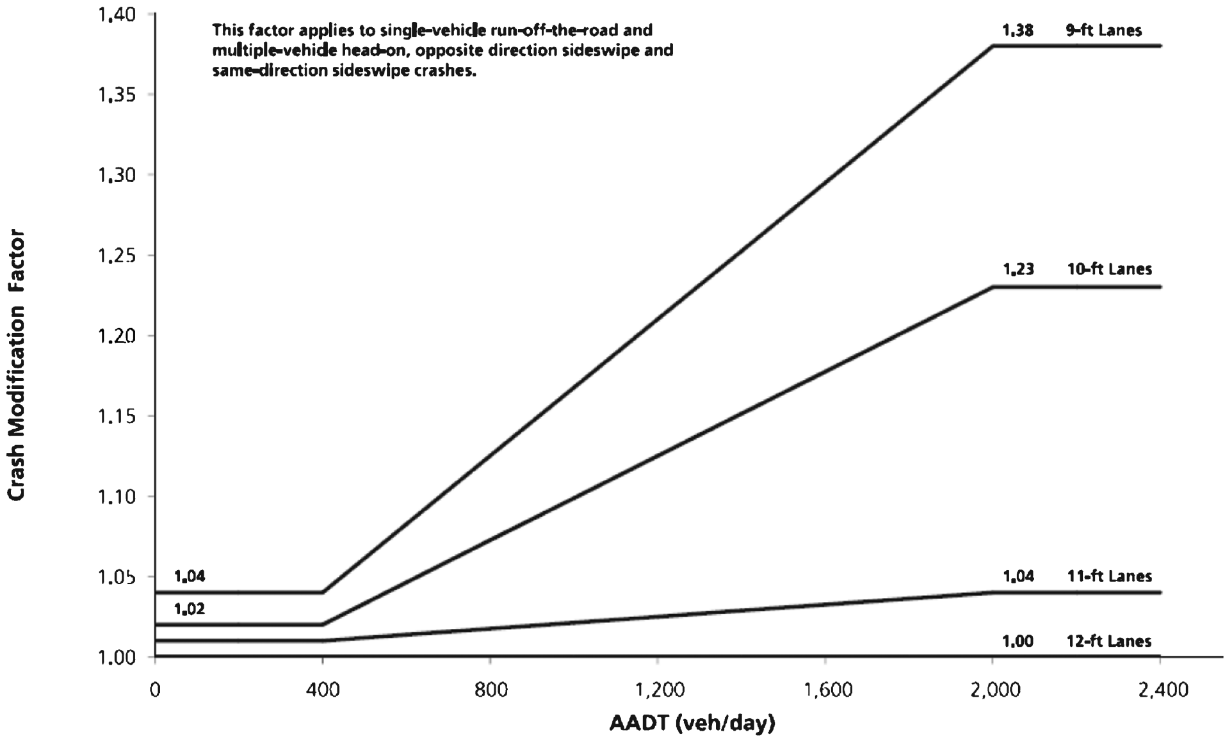


**Figure 7.4** CMF values for lane width for rural undivided multilane highways. (Source: (*4*).)

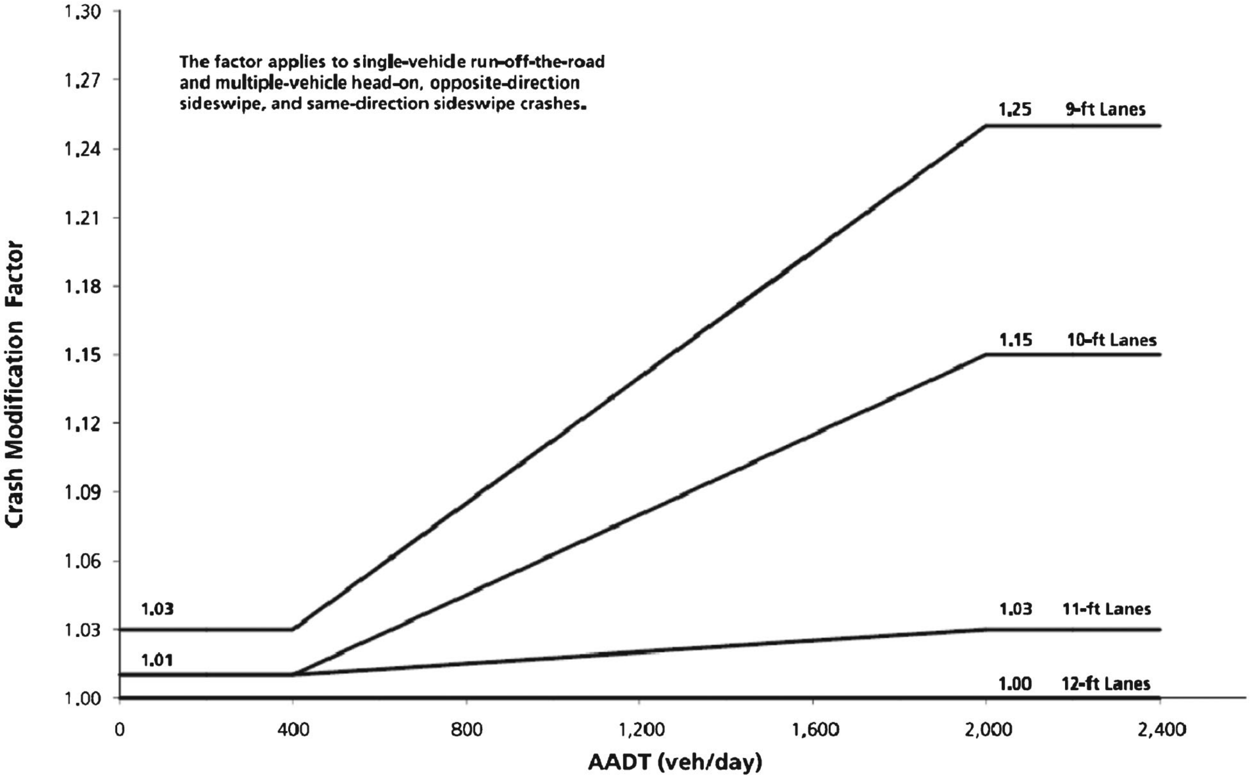


**Figure 7.5** CMF values for lane width for rural divided multilane highways. (Source: (*4*).)

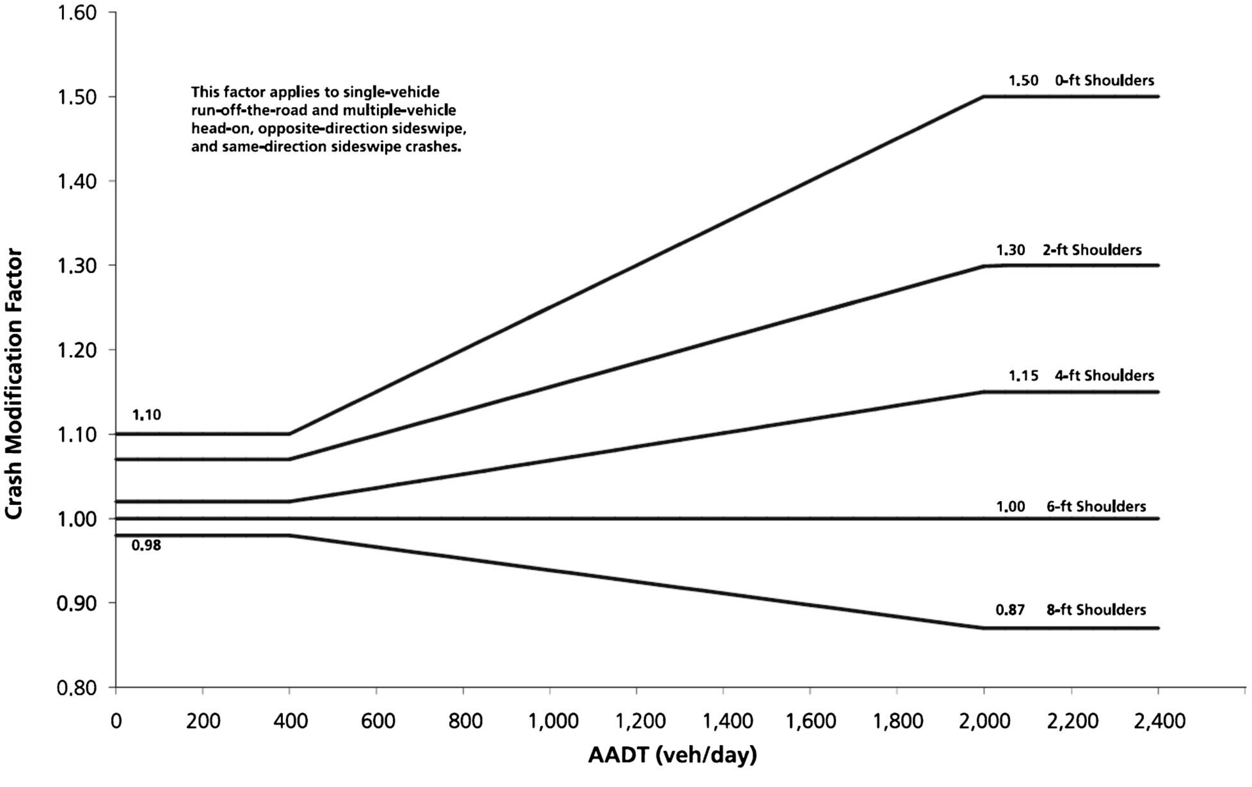


**Figure 7.6** CMF for shoulder width for rural undivided highways. (Source: (*4*).)

TABLE 7.7
**Operational Effects of Freeway Lane Widths**

| Lane Width (ft) | Reduction in Free-Flow Speed (mi/h) |
|---|---|
| 12 | 0.0 |
| 11 | 1.9 |
| 10 | 6.6 |
| **Lane Width (m)** | **Reduction in Free-Flow Speed (km/h)** |
| 3.6 | 0.0 |
| 3.5 | 1.0 |
| 3.4 | 2.1 |
| 3.3 | 3.1 |
| 3.2 | 5.6 |
| 3.1 | 8.1 |
| 3.0 | 10.6 |

Source: (*23*).

of curvature and length of horizontal curve. The equation for safety effects of horizontal alignment is provided in the HSM (*4*) as shown below:

$$CMF = \frac{(1.55 \times L_c) + \left(\frac{80.2}{R}\right) - (0.12 \times S)}{1.55 \times L_c}$$

Where:

CMF = crash modification factor for the effect of horizontal alignment on total crashes;

$L_c$ = length of horizontal curve (miles) which includes spiral transitions, if present;

R = radius of curvature (feet);

S = 1, if spiral transition curve is present;

0, if spiral transition curve is not present;

0.5, if a spiral transition curve is present at one but not both ends of the horizontal curve.

*Potential Adverse Impacts of Horizontal Alignment.* See Table 7.17 for potential adverse impacts of horizontal alignment to safety and operations.

### 6. Superelevation

*Safety Effects of Superelevation.* Superelevation is the rotation of the pavement on the approach to and through a horizontal curve. Superelevation is intended to assist the driver by counteracting the lateral acceleration produced by tracking the curve. The CMF for superelevation is based on the superelevation variance of a horizontal curve (i.e., the difference between the actual superelevation and the superelevation identified by AASHTO policy). When the actual superelevation meets or exceeds that in the AASHTO

TABLE 7.8
**Operational Effects of Lane and Shoulder Width on Two-Lane Highways**

| | Reduction in Free-Flow Speed (mi/h) | | | |
|---|---|---|---|---|
| | Shoulder Width (SW) (ft) | | | |
| **Lane Width (LW) (ft)** | **0≤SW<2** | **2≤SW<4** | **4≤SW<6** | **6≤SW** |
| 9≤LW<10 | 6.4 | 4.8 | 3.5 | 2.2 |
| 10≤LW<11 | 5.3 | 3.7 | 2.4 | 1.1 |
| 11≤LW<12 | 4.7 | 3.0 | 1.7 | 0.4 |
| 12≤LW | 1.2 | 2.6 | 1.3 | 0.0 |
| | **Reduction in Free-Flow Speed (km/h)** | | | |
| | **Shoulder Width (SW) (m)** | | | |
| **Lane Width (LW) (m)** | **0.0≤SW<0.6** | **0.6≤SW<1.2** | **1.2≤SW<1.8** | **1.8≤SW** |
| 2.7≤LW<3.0 | 10.3 | 7.7 | 5.6 | 3.5 |
| 3.0≤LW<3.3 | 8.5 | 5.9 | 3.8 | 1.7 |
| 3.3≤LW<3.6 | 7.5 | 4.9 | 2.8 | 0.7 |
| 3.6≤LW | 6.8 | 4.2 | 2.1 | 0.0 |

Source: (*23*).

TABLE 7.9
**Potential Adverse Impacts of Narrow Lane Width to Safety and Operations**

| Safety and Operational Issues | Freeway | Expressway | Rural Two-Lane | Urban Arterial |
|---|---|---|---|---|
| Run-off road crashes | × | × | × | |
| Cross-median crashes | × | × | | |
| Cross-centerline crashes | | | × | |
| Sideswipe (same direction) crashes | × | × | | × |
| Rear-end crashes if operations deteriorate (abrupt speed reduction) | × | × | × | |
| Reduced free-flow speed | × | × | × | × |
| Large vehicles off-tracking into adjacent lane or shoulder | × | × | × | × |

Source: (*13*).

TABLE 7.10
**Ranges for Minimum Shoulder Width**

| | Rural | | Urban | |
|---|---|---|---|---|
| **Type of Roadway** | **US (feet)** | **Metric (meters)** | **US (feet)** | **Metric (meters)** |
| Freeway | 4-12 | 1.2-3.6 | 4-12 | 1.2-3.6 |
| Ramps (1-lane) | 1-10 | 0.3-3.0 | 1-10 | 0.3-3.0 |
| Arterial | 2-8 | 0.6-2.4 | 2-8 | 0.6-2.4 |
| Collector | 2-8 | 0.6-2.4 | 2-8 | 0.6-2.4 |
| Local | 2-8 | 0.6-2.4 | | |

Source: (*1*).

TABLE 7.11
**CMF for Shoulder Width for Rural Undivided Highways**

| | AADT (vehicles per day) | | |
|---|---|---|---|
| **Shoulder width (ft)** | **<400** | **400 to 2000** | **>2000** |
| 0 | 1.10 | 1.10+0.00025 × (AADT-400) | 1.50 |
| 2 | 1.07 | 1.07+0.000143 × (AADT-400) | 1.30 |
| 4 | 1.02 | 1.02+0.00008125 × (AADT-400) | 1.15 |
| 6 | 1.00 | 1.00 | 1.00 |
| 8 or more | 0.98 | 0.98-0.00006875 × (AADT-400) | 0.87 |

Source: (*4*).

NOTE: The collision types related to shoulder width to which this CMF applies include single-vehicle run-off the-road and multiple-vehicle head-on, opposite-direction sideswipe, and same-direction sideswipe crashes.

TABLE 7.12
**CMF for Shoulder Type and Shoulder Width**

| | Shoulder Width (ft) | | | | | | |
|---|---|---|---|---|---|---|---|
| **Shoulder type** | **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 (50% width paved and 50% width turf) | 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 |

Source: (*4*).

NOTE: The base condition for shoulder type is “paved.” For a given shoulder width, the values should be compared vertically in each column in the table.

TABLE 7.13
**CMF for Right Shoulder on Rural Divided Multilane Highways**

| Average Shoulder Width (ft) | | | | |
|---|---|---|---|---|
| **0** | **2** | **4** | **6** | **8 or more** |
| 1.18 | 1.13 | 1.09 | 1.04 | 1.00 |

Source: (*4*).

NOTE: This CMF applies to paved shoulders only.

TABLE 7.14
**Operational Effects of Freeway Shoulder Widths**

| | Reduction in Free-Flow Speed (mi/h) Lanes in One Direction | | | |
|---|---|---|---|---|
| **Right-Shoulder Lateral Clearance (ft)*** | **2** | **3** | **4** | **≥5** |
| ≥6 | 0.0 | 0.0 | 0.0 | 0.0 |
| 5 | 0.6 | 0.4 | 0.2 | 0.1 |
| 4 | 1.2 | 0.8 | 0.4 | 0.2 |
| 3 | 1.8 | 1.2 | 0.6 | 0.3 |
| 2 | 2.4 | 1.6 | 0.8 | 0.4 |
| 1 | 3.0 | 2.0 | 1.0 | 0.5 |
| 0 | 3.6 | 2.4 | 1.2 | 0.6 |
| | **Reduction in Free-Flow Speed (km/h) Lanes in One Direction** | | | |
| **Right-Shoulder Lateral Clearance (m)*** | **2** | **3** | **4** | **≥5** |
| ≥1.8 | 0.0 | 0.0 | 0.0 | 0.0 |
| 1.5 | 1.0 | 0.7 | 0.3 | 0.2 |
| 1.2 | 1.9 | 1.3 | 0.7 | 0.4 |
| 0.9 | 2.9 | 1.9 | 1.0 | 0.6 |
| 0.6 | 3.9 | 2.6 | 1.3 | 0.8 |
| 0.3 | 4.8 | 3.2 | 1.6 | 1.1 |
| 0.0 | 5.8 | 3.9 | 1.9 | 1.3 |
| **Left Shoulder Width Effect on Crashes** | | | | |
| Roads with median, increasing left shoulder by 1 ft will result in 12% reduction in crashes at 4-lane and 6-lane highways. (Source: (*24*).) | | | | |

*Source of values listed: (*23*).

policy, the value of the superelevation CMF is 1.00. There is no effect of superelevation variance on crash frequency until the superelevation variance exceeds 0.01. The HSM (*4*) provides the following relationships in terms of superelevation variance:

$$CMF = 1.00 \; for \; SV < 0.01$$

$$CMF = 1.00 + 6 \times (SV - 0.01) \; for \; 0.01 \leq SV < 0.02$$

$$CMF = 1.06 + 3 \times (SV - 0.02) \; for \; 0.02 \leq SV$$

Where:

CMF = crash modification factor for the effect of superelevation variance on total crashes; and

SV = superelevation variance (ft/ft), which represents the superelevation rate contained in the AASHTO Green Book (*1*) minus the actual superelevation of the curve.

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

*Potential Adverse Impacts of Superelevation.* See Table 7.18 for potential adverse impacts of superelevation to safety and operations.

TABLE 7.15
**Potential Adverse Impacts of Narrow Lane Width to Safety and Operations**

| Safety and Operational Issues | Freeway | Expressway | Rural Two-Lane | Urban Arterial |
|---|---|---|---|---|
| Run-off road crashes | × | × | × | Assumed cross section with curb and gutter (no shoulders) |
| Cross-median crashes | × | × | | |
| Cross-centerline crashes | | | × | |
| Pavement edge dropoffs | × | × | × | |
| Rear-end crashes if operations deteriorate (abrupt speed reduction) | × | × | × | |
| Lane blockage from incidents | × | × | × | |
| Reduced free-flow speed | × | × | × | |
| Shying away from the edge of the roadway | × | × | × | |
| Inadequate space for enforcement activities and emergency response | × | × | × | |
| Lack of storage space for disabled lanes | × | × | × | |
| Bicyclists forced onto the travel lanes | × | × | × | |
| Inadequate space for maintenance activities | × | × | × | |

Source: (*13*).

TABLE 7.16
**Potential Adverse Impacts of Narrow Bridge Width to Safety and Operations**

| Safety and Operational Issues | Freeway | Expressway | Rural Two-Lane | Urban Arterial |
|---|---|---|---|---|
| Collision with bridge rail or approach guardrail | × | × | × | × |
| Rear-end crashes (abrupt speed reduction) | × | × | × | |
| Cross-centerline crashes | | | × | × |
| Degraded operations because of abrupt speed reduction as drivers approach bridge | × | × | | × |
| Inadequate space for enforcement activities and emergency response (long bridges) | × | × | × | × |
| Lane blockage from incidents (long bridges) | × | × | × | × |
| Shying away from bridge rail | × | × | × | × |
| Inadequate space for bicyclists | × | × | × | × |
| Inadequate space for emergency pullover (long bridges) | × | × | × | × |
| Inadequate space to avoid crashes or objects on the travel lanes | × | × | × | × |
| Lack of storage space for disabled vehicles (long bridges) | × | × | × | × |

Source: (*13*).

TABLE 7.17
**Potential Adverse Impacts of Horizontal Alignment to Safety and Operations**

| Safety and Operational Issues | Freeway | Expressway | Rural Two-Lane | Urban Arterial |
|---|---|---|---|---|
| Run-off-road crashes | × | × | × | |
| Cross-median crashes | × | × | | |
| Cross-centerline crashes | | | × | × |
| Large vehicle rollover crashes | × | × | × | |
| Large vehicle off-tracking into adjacent lane or shoulder | × | × | × | × |
| Skidding | × | × | × | × |
| Rear-end crashes if operations deteriorate (abrupt speed reduction) | × | × | × | |
| Reduced free-flow speeds | × | × | × | × |

Source: (*13*).

**7. Vertical Alignment.** Vertical alignment includes grade as well as vertical curvature (both crest and sag). However, in terms of the 13 controlling criteria, grade is considered separately. No crash modification factors are available at this time. The vertical alignment of a road is believed to affect crash occurrence in several ways. They are listed in the HSM (*4*):

Average speed: Vehicles tend to slow down going upgrade and speed up going downgrade. Speed is known to affect crash severity. As more severe crashes are more likely than minor crashes to be reported to the police and to be entered into crash databases, the number of reported crashes likely depends on speed and grade.

Speed differential: It is generally believed that crash frequency increases when speed differential increases. Because road grade affects speed differential, vertical alignment may also affect crash frequency through speed differentials.

Braking distance: This is also affected by grade. Braking distance may increase on a downgrade and decrease on an upgrade. A longer braking distance consumes more of the sight distance available before the driver reaches the object that prompted the braking. In other words, the longer braking distances associated with downgrades require the driver to perceive, decide, and react in less time.

TABLE 7.18
**Potential Adverse Impacts of Superelevation to Safety and Operations**

| Safety and Operational Issues | Freeway | Expressway | Rural Two-Lane | Urban Arterial |
|---|---|---|---|---|
| Run-off-road crashes | × | × | × | |
| Cross-median crashes | × | × | | |
| Cross-centerline crashes | | | × | |
| Skidding | × | × | × | × |
| Large vehicle rollover crashes | × | × | × | |

Source: (*13*).

TABLE 7.19
**CMF Values for Roadway Grade**

| Grade (%) | $CMF_{5r}$ |
|---|---|
| Level grade (grade ≤ 3%) | 1.00 |
| Moderate terrain (3%< grade ≤6%) | 1.10 |
| Steep terrain (grade > 6%) | 1.16 |

Source: (*4*).

Drainage: Vertical alignment influences the way water drains from the roadway or may pond on the road. A roadway surface that is wet or subject to ponding may have an effect on safety.

### 8. Grade

*Safety Effects of Grade.* The HSM (*4*) provides CMF values for rural two-lane, two-way highway grades in three ranges, i.e., grade≤3%, 3%<grade ≤6%, and grade>6%. The CMFs in Table 7.19 are applied to each individual grade segment on the roadway being evaluated without respect to the sign of the grade. The CMFs in Table 7.19 apply to total roadway segment crashes. The sign of the grade is irrelevant because each grade on a rural two-lane, two-way highway is an upgrade for one direction of travel and a downgrade for the other.

*Potential Adverse Impacts of Grade.* See Table 7.20 for potential adverse impacts of grade to safety and operations.

**9. Stopping Sight Distance.** Stopping sight distance (SSD) is the sight distance required to permit drivers to see a stationary object soon enough to stop for it under a defined set of worst-case conditions, without the performance of any avoidance maneuver or change in travel path; the calculation of SSD depends upon speed, gradient, road surface and tire conditions, and assumptions about the perception-reaction time of the driver.

*Safety Effects of Stopping Sight Distance.* See Table 7.21 for relative safety risk of various conditions in combination with non-standard stopping sight distance.

*Potential Adverse Impacts of Stopping Sight Distance.* See Table 7.22 for potential adverse

TABLE 7.20
**Potential Adverse Impacts of Grade to Safety and Operations**

| Safety and Operational Issues | Freeway | Expressway | Rural Two-Lane | Urban Arterial |
|---|---|---|---|---|
| Trucks losing control descending grade | × | × | × | |
| Risky passing maneuvers | | | × | × |
| Reduced speeds ascending grade | × | × | × | × |
| Reduced speeds descending grade | × | × | × | × |
| Run-off-road crashes, particularly where steep grades are combined with horizontal curves | × | × | × | |
| Rear-end crashes descending grade | × | × | × | |
| Slick pavement (flat grades) | × | × | × | × |
| Water ponding on the pavement surface (flat grades) | × | × | × | × |
| Water spreading onto travelled lanes (flat grades) | | | | × |

Source: (*13*).

TABLE 7.21
**Relative Safety Risk of Various Conditions in Combination with Non-Standard Stopping Sight Distance**

| Geometric Condition | Relative Safety Risk |
|---|---|
| Tangent horizontal alignment | Minor |
| Mild curvature, radius>2000 ft (600 m) | |
| Mild downgrade (<3%) | |
| Low volume intersection | Significant |
| Intermediate curvature, radius 1000 ft (300 m) to 2000 ft (600 m) | |
| Moderate downgrade (3%-5%) | |
| Structure | |
| High volume intersection | Major |
| Y-diverge on road | |
| Sharp curvature, radius<1000 ft (300 m) | |
| Steep downgrade (>5%) | |
| Narrow bridge | |
| Narrow pavement | |
| Freeway lane drop | |
| Exit or entrance downstream along freeway | |

Source: (*13*).

TABLE 7.22
**Potential Adverse Impacts of Non-Standard Stopping Sight Distance to Safety and Operations**

| Safety and Operational Issues | Freeway | Expressway | Rural Two-Lane | Urban Arterial |
|---|---|---|---|---|
| Collisions with vehicles stopped or slowed on the roadway | × | × | × | × |
| Collisions with objects on the roadway | × | × | × | × |
| Collisions with vehicles entering from intersecting roadways | | × | × | × |

Source: (*13*).

impacts of non-standard stopping sight distance to safety and operations.

**10. Cross slope.** Pavement cross slope is an important cross-sectional design element. The cross slope drains water from the roadway laterally and helps minimize ponding of water on the pavement. This prevents maintenance problems and also minimizes icing from occurring on poorly drained pavement. On roadways with curbed cross sections, the cross slope moves water to a narrower channel adjacent to the curb, away from the travel lanes, where it can be removed. Cross slopes that are too steep can cause vehicles to drift, skid laterally when braking, and become unstable when crossing over the crown to change lanes. These conditions are exacerbated by icy, snowy, or windy conditions. Both maximum and minimum criteria exist for cross slope. A formal design exception is required wherever either cannot be met.

*Potential Adverse Impacts of Cross Slope.* See Table 7.23 for potential adverse impacts of cross slope to safety and operations.

**11. Vertical clearance**

*Recommended Ranges for Vertical clearance.* The adopted criteria provide vertical clearance values for the various highway functional classifications (Table 7.17). These criteria are set to provide at least a 1-foot differential between the maximum legal vehicle height and the roadway, with additional allowances for future resurfacing. These clearances apply to the entire roadway width (traveled way and shoulders). A formal design exception is required whenever these criteria are not met for the applicable functional classification.

*Potential Adverse Impacts of Vertical Clearance.* See Table 7.25 for potential adverse impacts of vertical clearance to safety and operations.

**12. Lateral Offset to Obstruction.** The lateral offset to obstruction is defined as the distance from the edge of traveled way, shoulder, or other designated point to a vertical roadside element, such as curbs, walls, barriers, bridge piers, sign and signal supports, trees, and utility poles. The FHWA publication, Mitigation Strategies for Design Exceptions, suggest that lateral offset can be thought of as an operational offset – vertical roadside elements offset to the extent that they do not affect a driver's speed or lane position. Adequate clearance from these elements should be provided for mirrors on trucks and buses and for opening curbside doors where on-street parking is provided. The adopted criteria specify a minimum operational offset for all roadway conditions and classifications of 1.5 feet.

*Potential Adverse Impacts of Lateral Offset from Obstruction.* See Table 7.26 for potential adverse impacts of lateral offset from obstruction to safety and operations.

**13. Structural Capacity.** Structural capacity refers only to the load-carrying capacity of the bridge. No information on CMFs for structural capacities is available in the HSM (*4*) or any other publications. It should be emphasized that meeting structural capacity requirement is extremely important. A decision on design exception for structural capacity should not be made lightly.

### *7.2.3 Choose Safety Measures for Design Exceptions*

It is understandable that design exceptions may pose potential risk to highway safety because these projects contain features that do not meet the established design standards. To offset the negative effects of design exceptions, some safety measures can be applied to improve highway safety. There are many safety

TABLE 7.23
**Potential Adverse Impacts of Cross Slope to Safety and Operations**

| Safety and Operational Issues | Freeway | Expressway | Rural Two-Lane | Urban Arterial |
|---|---|---|---|---|
| Run-off-road crashes | × | × | × | |
| Skip pavement | × | × | × | × |
| Water ponding on the pavement surface | × | × | × | × |
| Water ponding onto the travelled lanes | | | | × |
| Lost control when crossing over a high cross-slope break | | × | × | |

Source: (*13*).

TABLE 7.24
**Ranges for Minimum Vertical Clearance**

| | Rural | | Urban | |
|---|---|---|---|---|
| **Type of Roadway** | **US (feet)** | **Metric (meters)** | **US (feet)** | **Metric (meters)** |
| Freeway | 14-16* | 4.3-4.9* | 14-16* | 4.3-4.9* |
| Arterial | 14-16 | 4.3-4.9 | 14-16 | 4.3-4.9 |
| Collector | 14 | 4.3 | 14 | 4.3 |
| Local | 14 | 4.3 | 14 | 4.3 |

*17 feet (5.1 meters) for sign trusses and pedestrian overpasses.
Source: (*1*).

measures that can be used to improve safety of design exception projects. The functions of these safety measures are to provide counter measures for the potential safety issues due to the substandard design elements and therefore to minimize the adverse impacts of design exceptions to highway safety and operations. Figure 7.7 and Figure 7.8 show possible safety measures for the 13 controlling criteria. These safety measures may not include every possible mitigation strategy for each controlling criterion. However, they include most of the commonly used counter measures for design exceptions. The list is provided for designers to consider during design process.

After the design exception alternatives are developed, effective safety measures should be selected for each of the alternatives if it is practical. It is possible and often necessary that more than one safety measures are utilized for a design exception. Most of the safety measures proved to be quite effective, even though they might not be expensive. The positive safety effects of some of the safety measures are reflected in terms of CMF reductions.

### *7.2.3 Safety Evaluation of Proposed Design Exceptions*

**1. Safety Evaluation with Historical Crash Data.** If crash data is available, an analysis of each substandard element shall be performed for the most recent 3 year period. The design exception request shall also include the crash detail report printout. For each location where the crashes for the substandard element exceed the statewide average, the designer shall provide a more detailed analysis of the crashes. The crash analysis should include the type of crash, severity, contributing circumstances, environmental conditions and time of day. The causes for the crashes shall be identified and countermeasures shall be selected and utilized to minimize possible adverse impacts of substandard elements.

**2. Safety Analysis Using IHSDM.** The *Interactive Highway Safety Design Model* (IHSDM) (*3*) is a power software package. It can be used to predict annual crashes based on highway geometric data and traffic

TABLE 7.25
**Potential Adverse Impacts of Vertical Clearance to Safety and Operations**

| Safety and Operational Issues | Freeway | Expressway | Rural Two-Lane | Urban Arterial |
|---|---|---|---|---|
| Collision with overhead structure | × | × | × | × |
| Rear-end crashes (vehicles following the vehicle that collided with structure) | × | × | × | × |
| Debris on the roadway | × | × | × | × |
| Long delays as a result of a closed roadway or lanes | × | × | × | × |

Source: (*13*).

TABLE 7.26
**Potential Adverse Impacts of Lateral Offset from Obstruction to Safety and Operations**

| Safety and Operational Issues | Freeway | Expressway | Rural Two-Lane | Urban Arterial |
|---|---|---|---|---|
| Shying away from obstructions | × | × | × | × |
| Reduced free-flow speed | × | × | × | × |
| Difficulty for parked vehicles | | | | × |

Source: (*13*).

|  | CONTROLLING CRITERIA |  |  |  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **SAFETY MEASURES** | **Design speed** | **Lane width** | **Shoulder width** | **Bridge width** | **Horizontal alignment** | **Superelevation** | **Vertical alignment** | **Grade** | **Stopping sight distance** | **Cross slope** | **Vertical clearance** | **Horizontal clearance** | **Structural capacity** |
| **Advanced warning signs** |  | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● |  | ● |
| **Advisory speed signs** | ● |  |  |  |  |  | ● | ● | ● |  | ● |  | ● |
| **Reduced speed signs** | ● |  |  | ● | ● | ● | ● | ● | ● |  |  |  |  |
| **Dynamic curve warning signs** |  |  |  |  | ● | ● |  |  | ● |  |  |  |  |
| **Stop and yield signs** |  |  |  |  |  |  |  |  | ● |  |  |  |  |
| **Narrow lane signs** |  | ● |  |  |  |  |  |  |  |  |  |  |  |
| **Narrow shoulder signs** |  |  | ● |  |  |  |  |  |  |  |  |  |  |
| **No turn on red sign** |  |  |  |  |  |  |  |  | ● |  |  |  |  |
| **Left turn lane** |  |  |  |  |  |  |  |  | ● |  |  |  |  |
| **Turning prohibitions** |  |  |  |  |  |  |  |  | ● |  |  |  |  |
| **Pavement markings** |  | ● | ● |  |  |  |  |  |  |  |  |  |  |
| **Slippery when wet sign** |  |  |  |  |  |  |  |  |  | ● |  |  |  |
| **Raised pavement markers** |  | ● | ● |  | ● | ● |  |  |  |  |  |  |  |
| **Enhanced pavement markings** |  | ● | ● | ● | ● | ● |  | ● |  |  |  | ● |  |
| **Object markers** |  |  |  | ● |  |  |  |  |  |  |  |  |  |
| **Chevrons** |  |  |  |  | ● | ● |  |  |  |  |  |  |  |
| **Centerline rumble strips** |  | ● |  |  | ● | ● |  | ● |  |  |  |  |  |
| **Shoulder rumble strips** |  | ● | ● |  | ● | ● |  | ● |  |  |  |  |  |
| **Remove or relocate fixed objects** |  | ● | ● | ● | ● | ● |  | ● | ● |  |  |  |  |
| **Traversable slopes** |  | ● | ● |  | ● | ● |  | ● |  | ● |  |  |  |
| **Shield fixed objects** |  | ● | ● |  | ● | ● |  | ● |  |  |  | ● |  |
| **Delineators** |  | ● | ● | ● | ● | ● |  | ● |  |  |  | ● |  |
| **Lighting** |  | ● | ● | ● | ● | ● |  |  | ● |  |  | ● |  |
| **Flashers or reflectors** |  |  |  | ● | ● | ● |  |  |  |  |  |  |  |
| **Shoulder widening** |  |  |  |  | ● | ● |  |  | ● |  |  |  |  |
| **Improved drainage system** |  |  |  |  | ● | ● | ● | ● |  | ● |  |  |  |
| **Skid-resistant pavement** |  |  |  | ● | ● | ● |  |  | ● | ● |  |  |  |
| **Pavement grooving** |  |  |  |  |  |  |  |  |  | ● |  |  |  |
| **Approach guardrail** |  |  |  | ● |  |  |  |  |  |  |  |  |  |

**Figure 7.7** Recommended safety measures for the controlling criteria.

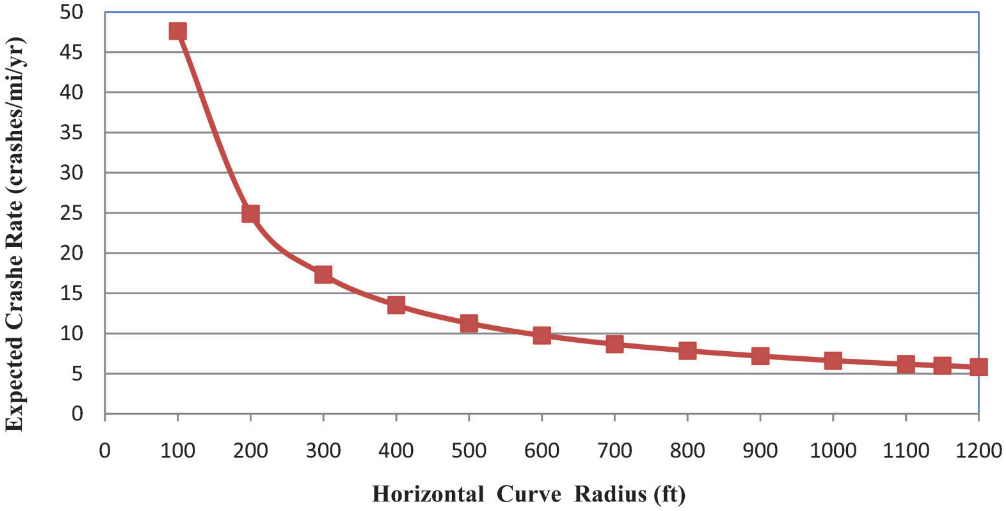


**Figure 7.8** Expected crash rates for different horizontal curve radii.

volume. Therefore, the safety effects can be analyzed for all of design exception alternatives as well as for a standard design option. In addition, sensitivity analysis can be conducted to examine the effects of selected substandard design values. For example, Figure 7.8 illustrates the safety effects of curve radius and Figure 7.9 displays the safety effects of different combinations of lane width and shoulder width. The two figures are plotted with IHSDM generated results from a demonstration project. Results in Figure 7.8 can be used to choose curve radius with respect to the potential safety impacts. Figure 7.9 would be useful for select the best combination of lane width and shoulder width.

### *7.2.4 Benefit-Cost Analysis of Proposed Design Exceptions*

To analyze and compare the benefits and costs of the standard design and the design exception, the standard design is used as the base and the design exception is used as an alternative. The initial costs and the user benefits/costs of the base and the alternative should be estimated in the benefit-cost analysis. The initial costs of a project include engineering cost, right-of-way cost, and construction cost. In addition to the agency benefit, the user benefits associated with highway operations after completion of the construction should also be considered in the benefit-cost analysis. These user

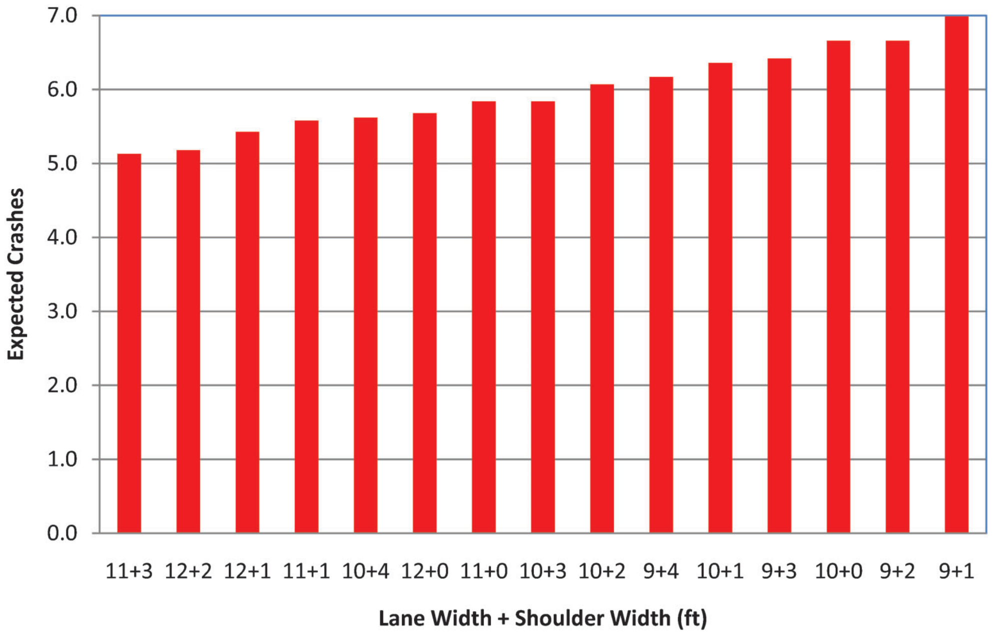


**Figure 7.9** Expected crashes for different lane and shoulder widths.

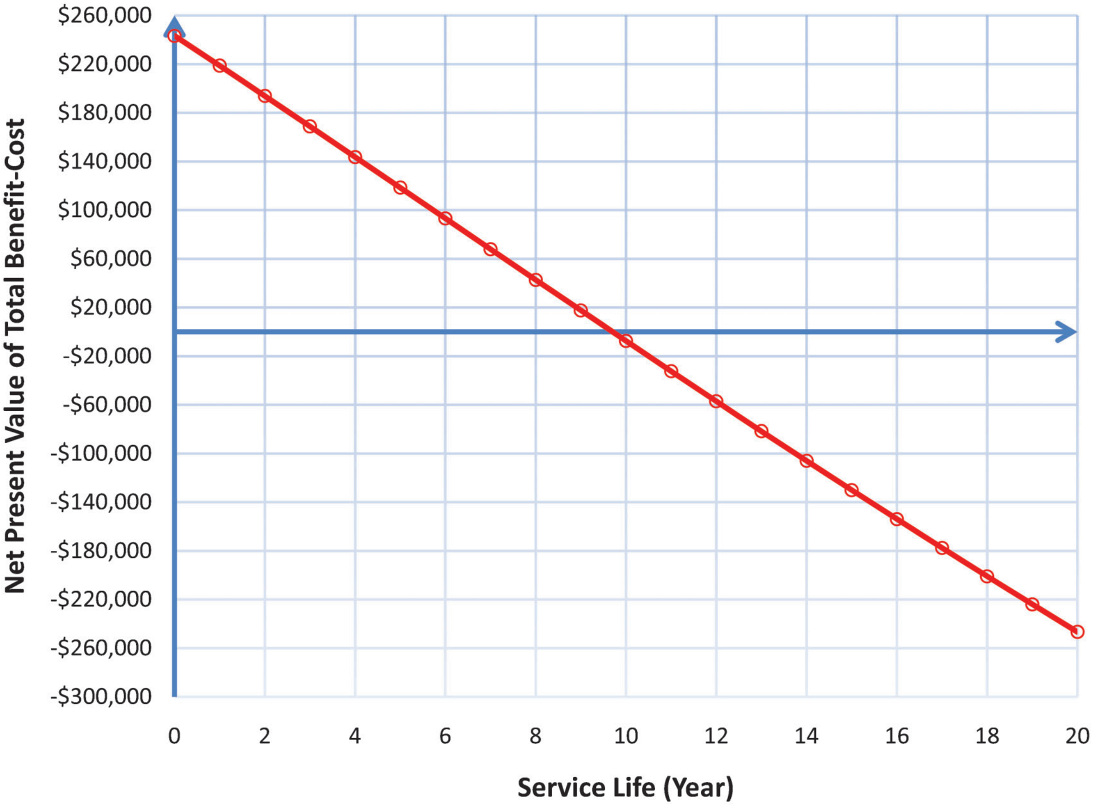


**Figure 7.10** Benefit-cost analysis for a design exception project.

benefits include the monetary values of travel time costs, vehicle operating costs, and crash costs. They are estimated by calculating the differences in the costs between the standard design and the design exception. When the difference in costs is positive, it means the design exception alternative reduces cost and thus a benefit is realized. If the difference in costs is negative, it means the design exception increases cost in comparison with the standard design. A negative user benefit can be considered a user cost. Since user benefits and costs are incurred annually, they are often converted to the present value with a discount rate to compare all the cost and benefit items in the same base year. The net present value (NPV) of the total benefit of a proposed design exception project can be expressed as:

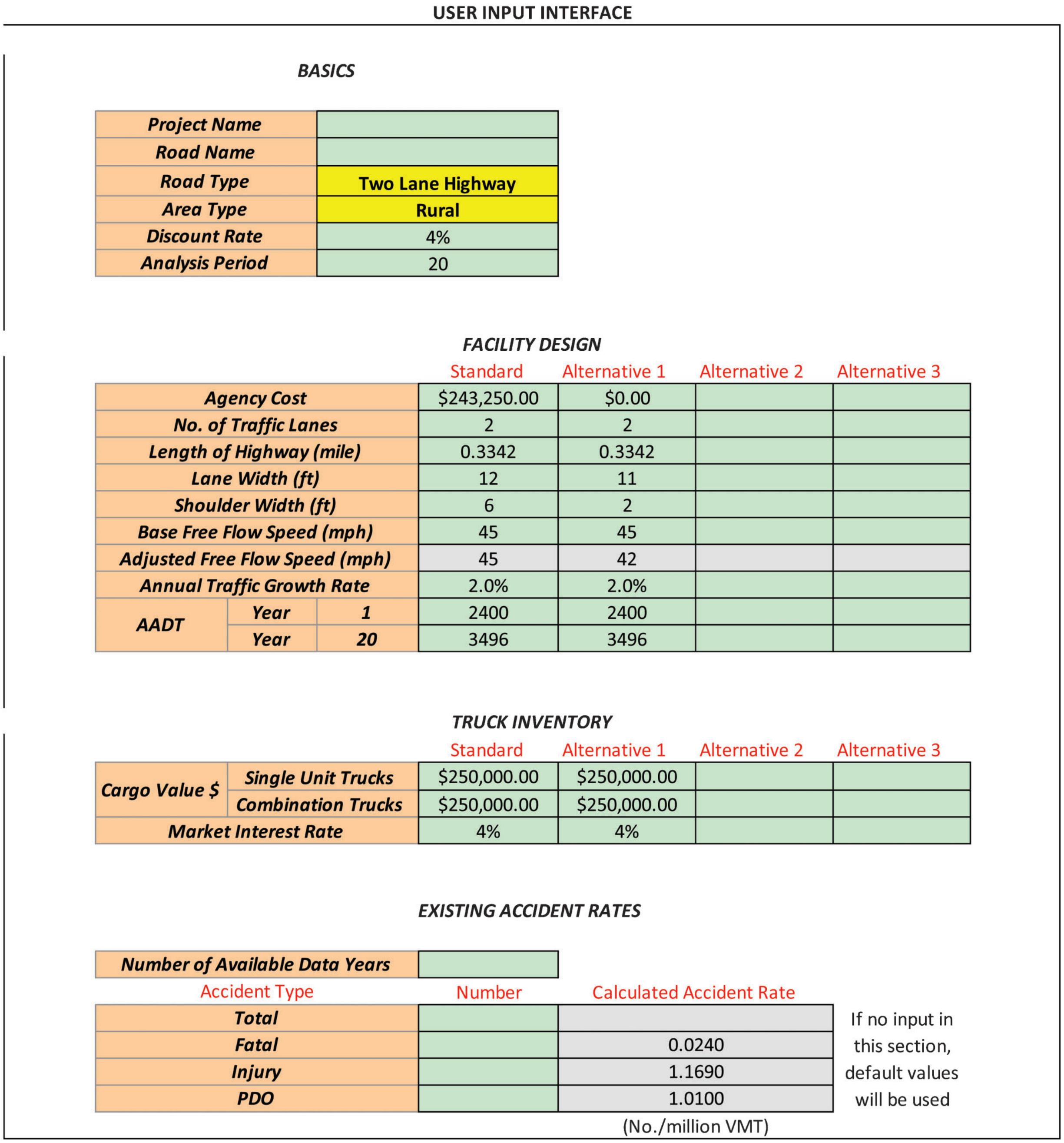
$$NPV = Agency\ Benefit + Travel\ Time\ Savings + Vehicle\ Operating\ Savings + Crash\ Savings \tag{7.1}$$

All the calculations of NPV are incorporated into an Excel based program. The program can calculate benefit and cost for 20 years. A designer can use it to produce NPV for each of the 20 years. A plot shown in Figure 7.10 can be drawn to identify the number of years of service life that would justify the design exception alternative in terms of benefit and cost. Figures 7.11 and 7.12 are two screen shots of an application example from the benefit-cost analysis program.

## 8. CONCLUSIONS

This study was conducted to develop a tool for INDOT to apply in the decision-making process for design exception projects. The tool developed in this study consists of the specified safety evaluation methods, the Excel-based benefit-cost analysis software, and the guidelines for development and assessment of design exception projects. The tool developed can be used for INDOT to evaluate design exception alternatives so that the best candidate alternative can be selected among them. To assure design exception projects meet a certain level of criteria, a set of goals should be specified by INDOT engineers in terms of expected crash rates and benefit-cost requirements. Once the goals are set, the method from this study can be used to evaluate the design exception alternatives and verify that the selected design exceptions meet the goals.

In order to identify available methodologies for design exceptions, a comprehensive literature review was conducted. The literature indicates that most design exceptions were conducted and evaluated in terms of the 13 controlling criteria recommended by FHWA. The 13 controlling criteria include following: design speed, lane width, shoulder width, bridge width, structural capacity, horizontal alignment, vertical alignment, grade, stopping sight distance, cross slope,



USER INPUT INTERFACE

BASICS

| | |
|---|---|
| Project Name | |
| Road Name | |
| Road Type | Two Lane Highway |
| Area Type | Rural |
| Discount Rate | 4% |
| Analysis Period | 20 |

FACILITY DESIGN

| | | | Standard | Alternative 1 | Alternative 2 | Alternative 3 |
|---|---|---|---|---|---|---|
| Agency Cost | | | $243,250.00 | $0.00 | | |
| No. of Traffic Lanes | | | 2 | 2 | | |
| Length of Highway (mile) | | | 0.3342 | 0.3342 | | |
| Lane Width (ft) | | | 12 | 11 | | |
| Shoulder Width (ft) | | | 6 | 2 | | |
| Base Free Flow Speed (mph) | | | 45 | 45 | | |
| Adjusted Free Flow Speed (mph) | | | 45 | 42 | | |
| Annual Traffic Growth Rate | | | 2.0% | 2.0% | | |
| AADT | Year | 1 | 2400 | 2400 | | |
| | Year | 20 | 3496 | 3496 | | |

TRUCK INVENTORY

| | | Standard | Alternative 1 | Alternative 2 | Alternative 3 |
|---|---|---|---|---|---|
| Cargo Value $ | Single Unit Trucks | $250,000.00 | $250,000.00 | | |
| | Combination Trucks | $250,000.00 | $250,000.00 | | |
| Market Interest Rate | | 4% | 4% | | |

EXISTING ACCIDENT RATES

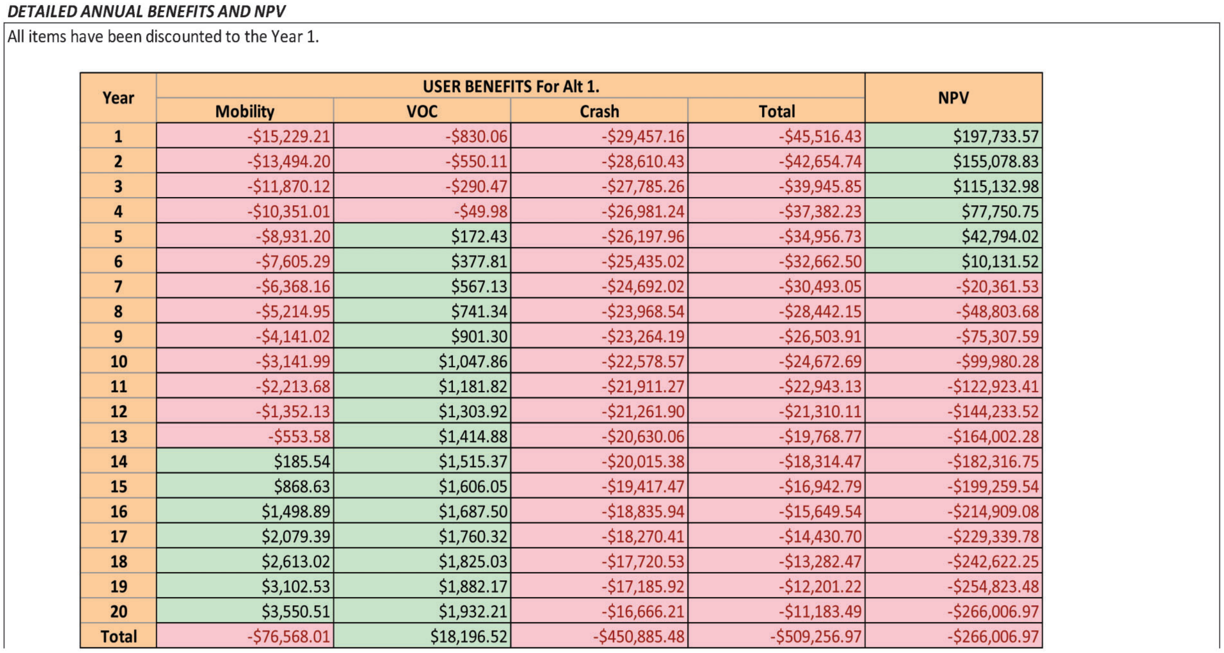
| | |
|---|---|
| Number of Available Data Years | |

| Accident Type | Number | Calculated Accident Rate |
|---|---|---|
| Total | | |
| Fatal | | 0.0240 |
| Injury | | 1.1690 |
| PDO | | 1.0100 |

(No./million VMT)

If no input in this section, default values will be used

**Figure 7.11** Input screen of the benefit-cost analysis program.



**DETAILED ANNUAL BENEFITS AND NPV**

All items have been discounted to the Year 1.

| Year | USER BENEFITS For Alt 1. | | | | NPV |
|---|---|---|---|---|---|
| | Mobility | VOC | Crash | Total | |
| 1 | -$15,229.21 | -$830.06 | -$29,457.16 | -$45,516.43 | $197,733.57 |
| 2 | -$13,494.20 | -$550.11 | -$28,610.43 | -$42,654.74 | $155,078.83 |
| 3 | -$11,870.12 | -$290.47 | -$27,785.26 | -$39,945.85 | $115,132.98 |
| 4 | -$10,351.01 | -$49.98 | -$26,981.24 | -$37,382.23 | $77,750.75 |
| 5 | -$8,931.20 | $172.43 | -$26,197.96 | -$34,956.73 | $42,794.02 |
| 6 | -$7,605.29 | $377.81 | -$25,435.02 | -$32,662.50 | $10,131.52 |
| 7 | -$6,368.16 | $567.13 | -$24,692.02 | -$30,493.05 | -$20,361.53 |
| 8 | -$5,214.95 | $741.34 | -$23,968.54 | -$28,442.15 | -$48,803.68 |
| 9 | -$4,141.02 | $901.30 | -$23,264.19 | -$26,503.91 | -$75,307.59 |
| 10 | -$3,141.99 | $1,047.86 | -$22,578.57 | -$24,672.69 | -$99,980.28 |
| 11 | -$2,213.68 | $1,181.82 | -$21,911.27 | -$22,943.13 | -$122,923.41 |
| 12 | -$1,352.13 | $1,303.92 | -$21,261.90 | -$21,310.11 | -$144,233.52 |
| 13 | -$553.58 | $1,414.88 | -$20,630.06 | -$19,768.77 | -$164,002.28 |
| 14 | $185.54 | $1,515.37 | -$20,015.38 | -$18,314.47 | -$182,316.75 |
| 15 | $868.63 | $1,606.05 | -$19,417.47 | -$16,942.79 | -$199,259.54 |
| 16 | $1,498.89 | $1,687.50 | -$18,835.94 | -$15,649.54 | -$214,909.08 |
| 17 | $2,079.39 | $1,760.32 | -$18,270.41 | -$14,430.70 | -$229,339.78 |
| 18 | $2,613.02 | $1,825.03 | -$17,720.53 | -$13,282.47 | -$242,622.25 |
| 19 | $3,102.53 | $1,882.17 | -$17,185.92 | -$12,201.22 | -$254,823.48 |
| 20 | $3,550.51 | $1,932.21 | -$16,666.21 | -$11,183.49 | -$266,006.97 |
| Total | -$76,568.01 | $18,196.52 | -$450,885.48 | -$509,256.97 | -$266,006.97 |

**Figure 7.12** Output screen of the benefit-cost analysis program.

superelevation, vertical clearance, and horizontal clearance. The literature also shows that, in reality, the most commonly adopted design exceptions included shoulder width, vertical alignment, lane width, grade, and horizontal alignment, while the least willingly considered design exception was structural capacity. The most significant advancement in highway safety evaluation is the publication of the HSM (*4*). HSM provides analytical tools and techniques for highway planner and engineers to evaluate the potential effects on crashes of proposed highway designs. In terms of design flexibility, HSM provides us a timely tool for this study to quantify the safety impacts of design exception projects. Also available is the *Interactive Highway Safety Design Model* (IHSDM) (*3*), which a suite of software analysis tools for evaluating safety and operational effects of highway projects with respect to geometric design characteristics. IHSDM was developed in coordination with HSM. Most of the HSM procedures and mathematic equations are incorporated into the IHSDM software package, so that the necessary and tedious computations are computerized.

To obtain the information on design exception practices in other states, a questionnaire survey was conducted. As the study advisory committee (SAC) of this study recommended, the questionnaire was distributed to the state DOTs of the neighboring states of Indiana. The state DOTs of Missouri, Ohio, Illinois, and Kentucky provided information on their design exception projects the recent years.

In order to find out the status of design exception projects in Indiana, the documents and records of 56 selected INDOT design exception projects were reviewed and examined. These design exception projects were proposed and approved between 2007 and 2010. On average, INDOT had about 50 design exception projects each year. Among the 56 design exception projects, the numbers of design exceptions related to superelevation and shoulder width were relatively higher than other types of design exceptions. Cost saving was the top reason for the design exception projects. In the reviewed 56 Indiana design exception projects, about 80% of them used safety measures to minimize the potential negative effects of the design exceptions on highway safety. The information in the table indicates that the safety measures were mainly uses of warning signs or advisory speed reduction signs.

A thorough evaluation of IHSDM and HSM was conducted to explore the feasibility of using the tools for safety assessment of design exception projects. A case study was performed to illustrate the process of safety evaluation. It was demonstrated that IHSDM can be used to generate quantitative measures of safety impacts of design exception projects. IHSDM is capable of analyzing safety impacts of an individual substandard element as well as combined effects of a number of substandard elements. With IHSDM, the sensitivity of substandard elements can be analyzed by changing the values of design criteria. Using different combinations of substandard elements, such as lane width and shoulder width combinations, designers can choose the best alternative that would minimize the negative safety impacts. It is therefore recommended that INDOT use IHSDM in design exception projects for safety impact assessment. IHSDM has incorporated most of the methods and calculations in HSM, but there are still some of the items in HSM that are not included in IHSDM. It is possible that designers may need to use HSM in addition to IHSDM for design exceptions, such as in evaluating safety impacts of roundabout intersections.

One of the commonly used methods for justifying design exception projects is to use the savings in construction cost. However, this method is not a reasonable one because it does not include the impacts of a substandard highway section to the highway safety and operations. In this study, benefit-cost analysis method was used to evaluate the effectiveness of design exceptions. An Excel based computer program was developed to conduct benefit-cost analysis for design exceptions. This method includes not only the savings in construction cost and other initial costs, but also the user benefits in terms of travel time, vehicle operation, and safety. The computer program will be a useful and convenient tool for INDOT to evaluate design exception projects.

Based on the results of the efforts discussed above, the guidelines for development and evaluation of design exception projects were developed and presented. The guidelines recommend the steps for developing and evaluating design exception projects. The potential impacts of design exception elements to highway safety and operations are listed for the 13 controlling criteria to provide designers with important and easy to use information. The possible counter measures for each of the controlling criteria are listed in a one-page table for easy reference. It is recommended that IHSDM be used to analyze safety effects and the Excel based computer program be used to conduct benefit-cost analysis for design exception projects.

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