JOINT TRANSPORTATION RESEARCH PROGRAM

INDIANA DEPARTMENT OF TRANSPORTATION
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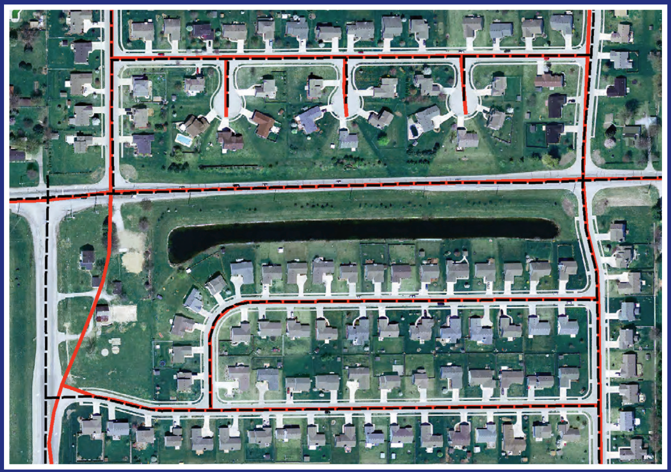
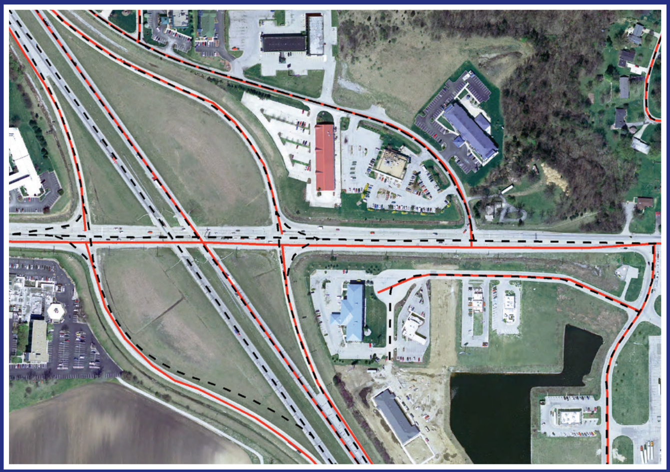
Performance Measure That Indicates Geometry Sufficiency of State Highways

Volume I—Project Scoring and Network Screening





Andrew P. Tarko, Aveedibya Dey, Mario A. Romero

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AUTHORS

Andrew P. Tarko, PhD
Professor of Civil Engineering
Lyles School of Civil Engineering
Purdue University
(765) 494-5027
tarko@purdue.edu
Corresponding Author

Aveedibya Dey
Graduate Research Assistant
Lyles School of Civil Engineering
Purdue University

Mario A. Romero
Research Scientist
Lyles School of Civil Engineering
Purdue University

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16. Abstract

The Indiana Department of Transportation (INDOT) selects projects for implementation by taking into account several criteria related to cross-section, alignment and safety to evaluate various geometry improvements to be carried out as a part of projects. The existing practice uses an intuitive point allocation method to score these individual categories. The current study proposes a methodology to evaluate these projects considering the safety and mobility impacts of the improvements which lie in the scope of each project. This methodology is also used to screen roads based on existing geometry deficiencies with respect to a desirable design standard. The road screening process and the project evaluation process form two steps that support the asset management process. The road screening process helps in filtering road segments based on geometry deficiencies and identifies the least adequate road segments. Projects may be further developed with estimated improvements to be carried out on such segments using detailed information regarding these improvements.

The asset management components discussed here rely on the evaluation of safety and mobility benefits corresponding to geometry changes. To develop an up-to-date method, the safety performance functions used in this method have been calibrated based on the latest crash data available for 2009-2011. Safety performance functions have been developed for rural two-lane, rural multi-lane, urban two-lane and urban multi-lane roads in the state of Indiana. The crash modification factors derived from these safety performance functions and speed adjustments from earlier studies, supplemented with data available in Highway Capacity Manual are used to calculate the safety and mobility benefits.

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EXECUTIVE SUMMARY

PERFORMANCE MEASURE THAT INDICATES GEOMETRY SUFFICIENCY OF STATE HIGHWAYS: VOLUME I—PROJECT SCORING AND NETWORK SCREENING

Introduction

The Indiana Department of Transportation uses a point-based method of scoring projects. The evaluated components include alignment, cross-section, safety, compliance with ADA guidelines, and drainage. High-scoring projects are selected for implementation. The scoring method is simple and measures the geometry improvements at only two levels: (1) the improved geometry partly satisfies the design standards and (2) the improved geometry fully satisfies the design standards. The current scoring method disregards the initial and final geometry parameters.

In this study we replaced the geometry-scoring component with a more precise method that estimates the safety (reduced crashes) and mobility (increased speed) benefits of improving cross-sectional and alignment elements. The new component was integrated with other method components without changing the relative importance of the other scoring criteria. One of the important considerations was data availability—using data currently available in Indiana.

Another important component of the research was conducting a feasibility study to determine whether the current information technology and data processing techniques would allow additional data elements to be extracted from existing high-resolution maps and ortho-images in a practical manner to better support asset management in Indiana. This component is presented in a separate Volume II of this report.

Findings

The developed methodology for evaluating geometry improvements to score and rank projects relies on safety performance functions and average speed equations. Crash modification factors and speed adjustments derived from these equations were used to evaluate various geometry treatments. The safety performance functions were estimated in the current study based on Indiana data. These functions were then supplemented with results obtained from previous studies to develop the project scoring methodology. The proposed evaluation methodology is for improvements carried out on rural two-lane, rural multi-lane, urban two-lane, and urban multi-lane roads in the state of Indiana.

The method has been developed to facilitate a two-step scoring process: (1) screening the Indiana road network for segments that have the highest needs for geometry improvement and (2) scoring projects developed for the roads selected in the first step.

Implementation

The project scoring method developed was implemented with the help of an Excel-based application. The application allows the user to enter various data corresponding to estimated geometry improvements on different road segments in the scope of a project. The output from the spreadsheet application includes the safety and mobility benefits corresponding to every segment for which data has been provided to the application. Furthermore, the total project benefit is calculated and the benefit-cost ratio obtained. The re-scaled benefit-cost ratio is added to the ADA and drainage point to obtain an output on the desired 0–10 scale, which can be further used in the project scoring process utilized by the INDOT roadway asset management team.

The method was implemented in Excel VB. The project documentation includes a user manual to support the method application.

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1. INTRODUCTION

1.1 Background

The project selection process of the Indiana Department of Transportation (INDOT) involves evaluating roads in Indiana to identify various road segments which need to be improved or upgraded. These road segments are identified by evaluating the effect of possible improvements on the road segment, taking into account various factors such as pavement, geometry, traffic, and road class, among other criteria. The evaluation is done using a set of guidelines available to the roadway asset team which utilizes a discrete point-based scoring system to allocate points to each road segment based on the effect of estimated improvements. Once the road segments have been identified and the improvements applicable to each segment have been evaluated, various projects may be formed and subsequently ranked using the scoring system. The purpose of scoring is to prioritize projects for implementation based on estimated or proposed improvements on various roads. Preliminary information regarding the existing road conditions, including current geometry and pavement conditions, is gathered in such an evaluation. Needless to say, there are various sources through which such information can also be obtained. These include GIS-based road inventories, video logs, and image repositories.

To make the project evaluation more efficient and meaningful, it should be preceded by a road screening process which can help narrow down the "least adequate segments" from the entire road network. Inadequate segments are those that depart from the desirable geometric design standards applicable to these roads. Improving geometry of the least adequate segments can give the most benefits. Thus, the road screening process provides a preliminary set of target road segments that should be the subject of detailed analysis to develop relevant road improvement projects.

1.2 Problem Description, Research Objectives, and Research Scope

The evaluation method used in the project identification process is based on intuitive allocation of points. There are several drawbacks. The discrete point-based method relies on subjective decision making and includes neither quantifying the benefits nor even levels of benefits associated with certain types of improvements. Thus, the point allocation currently in use may lead to erroneous results. The current method is also imprecise in that it allows only two distinguishable levels of geometry adequacy: standard and substandard.

The aim of the current research is to replace the intuitive scoring method with a robust methodology that relies on predicting the safety and mobility benefits in a defensible manner. Although the proposed methodology should preserve the road evaluation factors considered by the roadway asset team of INDOT, the current three-value scoring scale should be replaced with a more precise continuous scale. In addition to this, the proposed methodology should not affect various other factors taken into account in the road scoring process, leaving their relative importance unchanged. The scope of research is thus narrowed down to establishing a method that quantifies the impact of road geometry improvements. The quantified benefits should be rescaled to obtain an appropriate input that can be used in the existing scoring process without affecting the evaluation of other factors.

The project evaluation process is a detailed analysis of various geometry improvements applicable to different road sections. The geometry improvements can accrue most benefits when it is applied to the most deficient (or the least adequate) segments. In other words, projects should ideally be formed using road segments identified by a well-defined screening process. This justifies the need to develop a road screening process consistent with the project evaluation methodology. The method for road screening should identify road segments based on the geometry deficiencies and benefits that can be obtained from improvements carried out to remove them.

The focus of the current study is to develop a methodology for quantification of safety and mobility benefits. Mobility benefits are travel time savings associated with the increase in speeds due to improvements in the road section. Since rural and sub-urban roads are of major concern, the changes in the free-flow speed can be used as a good estimate to calculate the travel time savings. This can be corroborated by the fact that the focus is on evaluating relatively low and medium congested roads, mostly without signalization. The scope of the study includes two-lane and four-lane roads, and hence the conversion of two-lane road sections to four lanes needs to be considered in the evaluation method. Among the geometry improvements, only the evaluation of cross-sectional elements is possible due to the limitations of the data available.

1.3 Structure of Report

This report presents the project identification process within asset management that includes the proposed road screening and project evaluation methodologies. The report begins with an extensive literature study on the safety and speed models developed in the past and are shown and discussed in Chapter 2.

The research approach is discussed in Chapter 3, which highlights the need for the proposed methodology in the asset management process, describes the purpose of developing new and updated safety models for Indiana, and summarizes the use of various sources of data in the presented study.

The two-steps for project identification in the asset management process are described in Chapter 4, which includes highlights of the steps involved in the proposed road screening and project evaluation process.

As a part of this research, safety performance functions for the state of Indiana have been developed from crash record and road inventory database available at the Center for Road Safety, Purdue University. The safety models developed from the recent crash data and the discussion of the results for these statistical models is presented in Chapter 5.

The safety component in the project scoring process is discussed in Chapter 6. This chapter also includes a list of tables and equations compiled from the developed models and previous research, relevant to the scope of this thesis, which are necessary for the evaluation of safety benefits. Similarly, the mobility component is discussed in Chapter 7 and contains relevant tables and equations for evaluation of mobility benefits. The design standards for the proposed road screening process are shown in Chapter 8. The tables and equations from Chapters 6 to 8 are used extensively in the evaluation of benefits for both road screening and project evaluation processes that follow in Chapters 9 and 10. These chapters describe in detail the methodologies adopted with proper equations and tables and consist of an elaborated version of the summarized steps of Chapter 4. The conclusions and scope of future research are discussed in Chapter 11. Finally, Appendix A provides an overview and explanation of the project scoring application.

2. ASSET MANAGEMENT PRACTICE

2.1 Existing Asset Management Methods

The need to identify several performance measures and to allocate the available budget based on the benefits acquired from improvements has been discussed in the U.S. Department of Transportation's Asset Management Primer (USDOT, 1999). In context of asset management practice, it clearly states that "technical information is needed to support the decision making process." This asset management primer also identifies the steps needed to improve the asset management process. Project identification or selection is one of several aspects of the asset management process. The Asset Management Primer also emphasizes the need to collect and update inventory information and to implement analytical methods to allocate funds to cost-effective strategies. The information collected should help agencies evaluate the future system requirements and performance expectations, keeping in mind the budget available, future goals, and policies. The Transportation Asset Management Guide (AASHTO, 2002) summarizes the prevailing practice. It points out the scope for improvement:

- "Projects are evaluated largely in terms of initial cost and judgment to potential benefit."
- "Programming is based mainly on intuitive judgment."
- "Management systems are used only to rank the condition of assets; needs are programmed based on 'worst first.'"
- "The identification and analysis of options, evaluation of candidate projects and tradeoffs is strategic, interdisciplinary, and integrated. It potentially encompasses a number of modes and their associated infrastructure, rather than focusing solely on individual classes of assets (as in pavement or bridge management, for example)."

Different agencies have their own project identification processes using different evaluation criteria and methodologies. The Ulster County Transportation Council (UCTC, 2006) has a two-step project evaluation method based on: (1) Screening and (2) Merit Evaluation. Similar to many other agencies, it uses a point based system on a 0-10 scale to evaluate 16 different criteria. The point based system adopted by UCTC has three different levels with specific improvements defined for each of these levels. Various evaluation criteria used by UCTC are: Economic viability, security, accessibility and mobility, environment, integration and connectivity, system management and operations, safety, preservation of the existing transportation system, air quality, social impacts and environmental justice, congestion management programs, statewide transportation plans, land use plans, sponsor's priorities, planning study recommendations, and bridge and paving projects only.

The Federal Highway Administration's (FHWA) Highway Safety and Asset Management guidelines emphasize identification of the highest need areas, including the highest priority safety program areas in order to allocate resources in these places. It also states that the asset management team should focus on developing methods to analyze data, quantify system performance, and identify appropriate improvements with emphasis on safety strategies. The Transportation Asset Management Expert Task Group has pointed out this need to develop techniques and quantify system performance. Furthermore, it states that the asset management decisions, both short and long-term, should be based on current and future performance requirements.

The Minnesota Department of Transportation (MnDOT, 2015) uses the safety benefits calculated from crash rates and travel time benefits calculated from Vehicle-Miles Traveled (VMT) in their project ranking and selection process. The difference in the base case and each alternative is used to obtain the change in number of crashes and VMT for that alternative. The change in number of crashes is obtained for different severity types. Further, the Net Present Value, B/C ratio, and incremental B/C ratio are utilized for the purpose of evaluation. This process results in a better approach to quantification of the system performance and determination of benefits from future improvements. A sample spreadsheet that shows the details of the evaluation method is also available from MnDOT.

The Indiana Department of Transportation (INDOT) uses a set of guidelines known as the Roadway Scoring Rules (INDOT, 2011) to evaluate projects on three broad factors: cost-effectiveness (40 points), condition (40 points), and other factors (20 points). The cost-effectiveness component takes into account various criteria such as alignment, cross-section, safety, drainage and compliance with the American Disability Act (ADA). The "condition factor" takes into account the pavement conditions through PCR and IRI score, while the "other factors" include traffic volume, truck traffic volume, roadway functional class, and system classification.

The benefit from geometry improvements is obtained on the 0-10 scale, with a maximum of 2 points allocated to each of the 5 criteria included in the cost-effectiveness factor. Discrete points are allocated to each of these criteria, with a change from "substandard" to "standard" allowing 2 points, "substandard" to "improved but substandard" allowing 1 point, and "no change" allowing 0 points. The three-value scoring system is nonetheless an intuitive allocation of points with no specific measure for system performance. The total of these points in the 0-10 scale represents the benefit from the estimated geometry improvements, also known as the "Geometry Raw Score." The "Geometry Raw Score" is used to calculate the "Geometry Multiplier," which is further used to calculate the "Geometry Benefit." The "Raw CE" score representing the cost-effectiveness is obtained from the "Geometry Benefit." The equations used for these calculations are shown below:

$$\text{Geometry Multiplier} = 100{,}000 \times \sqrt{\text{Geometry Raw Score}} \quad (2.1)$$

$$\text{Geometry Benefit} = \text{Geometry Multiplier} \times \text{Geometry Raw Score} \quad (2.2)$$

$$\text{Raw CE} = \frac{\text{Cost}}{(\text{Pavement Benefit}) + (\text{Geometry Benefit})} \quad (2.3)$$

$$\text{Factor 1 Score} = (1 - \left(\frac{\text{Raw CE}}{7.5}\right)) \times 40 \quad (2.4)$$

The existing roadway scoring method utilizes a three-value discrete scoring system for each of the criteria used for evaluating the geometry raw score. The three-value scoring system is based on the intuitive judgment and decision of the asset team to assign points to each criterion.

Apart from the errors associated with subjective decision making, the scoring system may over or under-represent the benefits in several cases. It is easy to see how the categorical scoring system may show ambiguous results in comparison to the performance-based scoring system. An improvement in a geometric feature results in a corresponding safety and travel time improvement. The absolute value of the change in any geometry element can be used to determine this benefit, if any. It is possible that a very small change in geometry might cause it to be categorized as a "Sub-standard to Standard change," thus showing an improvement of 2 points using the existing scoring system. However, this absolute change in geometry may not yield significant benefit in terms of safety and travel time benefits, or in some cases, no benefit at all. The existing scoring system has hence over-represented the benefit from the expected geometry improvement. Similarly, an under-representation of the benefits may occur when a significantly large change in a geometric feature fails to get acknowledged by the existing scoring method. In such cases, although the scoring system allocates the change as "No improvement," it gets 0 points, whereas the absolute change in the geometry can result in sufficient safety and travel time benefits. This is demonstrated in the following example:

Example:

Consider two different shoulder width treatments on rural two-lane segments:

- **Case 1:** Increase in shoulder width from 2 feet to 5 feet.
- **Case 2:** Increase in shoulder width from 5 feet to 6 feet.

From the Indiana Design Manual 2013, the desirable shoulder width standard for a rural two-lane with AADT $<$ 400 veh/day is 6 feet (see Table 8.1). Using this information, the existing scoring method would give the following results:

- **Case 1:** 2 feet to 5 feet: Substandard to improved but substandard change (1 point).
- **Case 2:** 5 feet to 6 feet: Substandard to standard change (2 points).

Using crash frequency models, it can be shown that the crash reduction in the two cases will be as follows (using Equation 6.1 and values from Table 6.5):

- **Case 1:** 2 feet to 5 feet: Change of 3 feet: 8% crash reduction in fatal/injury crashes.
- **Case 2:** 5 feet to 6 feet: Change of 1 foot: 3% crash reduction in fatal/injury crashes.

***

The current study focuses on replacing the three-value scoring system with a robust performance-based evaluation of various criteria specified by the INDOT asset management team. These safety and mobility benefits are then summed up and rescaled in the scoring system to obtain the new "Geometry Raw Score." The utilization of this score remains unchanged in the rest of the process and the new methodology also doesn't affect the relative importance of other factors in the scoring process. The three categories, (1) Alignment, (2) Cross-Section, and (3) Safety (along with various criteria within these categories) are used in the new scoring process which gives an output on the 0-6 point scale. The points allocated in this range are in a continuous scale, unlike the discrete three-valued scoring system present originally. The other two sub-criteria, (4) Drainage and (5) ADA, are out of the scope of the current study. Hence, an input is expected for these two criteria from the asset management team based on their evaluations.

2.2 Safety Models

The use of safety models and speed models are predominant in the road screening and project evaluation methodology developed for the purpose of asset management. The current section gives an overview of the safety models developed in the past with an emphasis on the safety performance functions developed for Indiana. Several of the models developed for Indiana have been used directly for the purpose of evaluating the safety benefits from various geometry improvements in the asset management methodology presented in this study. The discussion of speed models is presented in the next section.

Several research studies provide insight regarding the effect and influence of road geometry, traffic volumes, and other factors that affect crash frequency and severity of crashes. In a study by Karlaftis and Golias (2002) concerning the accident rates on rural roadways in the state of Indiana, several factors such as Average Annual Daily Traffic (AADT), Lane Width, Serviceability Index, Friction, Pavement Type, and Access Control were found to significantly affect the accident rates on rural two-lane and rural multi-lane roads. The hierarchical tree-based regression used in this study was justified by its ease of implementation in safety management. In the study by Rengarasu, Hagiwara, and Hirasawa (2009), the effect of road geometry and cross-section was investigated using both homogeneous segments and fixed length segments. The negative binomial model was used for modeling of accidents. Several variables, including the number of lanes, AADT, shoulder width, number of truck lanes, indicators for built-up areas, and weather variables, were found significant.

An extensive study was undertaken by Labi (2006) investigating the effect of various geometry elements on safety for rural two-lane roads in Indiana. Several safety performance functions were developed as a part of this study, which showed that factors such as segment length, AADT, pavement condition, lane width, shoulder width, horizontal curvature, vertical grade, driveway density, shoulder type, and presence of posted speed limits have a significant influence in predicting the number of expected crashes on different types of road segments. Besides this, the study also discusses in-depth the existing geometry deficiencies in various rural two-lane roads in Indiana and the huge monetary requirements to address this issue. The study by Anastasopoulos, Tarko, and Mannering (2008) looked into the vehicle accident rates on the interstate highways of Indiana from data obtained from INDOT for the period of 1995–1999. Several factors related to pavement characteristics, road geometrics, and traffic variables were found to affect the crash rates in a significant manner. Among the road geometry variables, median width, presence of medians, inside and outside shoulder width, presence of rumble-strips, number of vertical curves per mile, degree of horizontal curves, and the number of ramps per mile were found significant in the left-censored tobit model. The effect of different types of medians on rural freeway safety was investigated by Tarko, Villwock, and Blond (2008) using data collected from several states including Indiana. The crash frequency models for depressed median types showed that variables such as AADT, average horizontal curvature, off-ramp frequency, and shoulder width affected the frequency of crashes. The absence of barriers in medians resulted in higher number of opposite-direction crashes. An increase in speed limit also increased the frequency of such crashes. The lane and shoulder width combination and their resulting safety effectiveness were studied by Gross, Jovanis, and Eccles (2009). The case-control, conditional logistic regression method was used with the data comprising of rural two-lane roads in Pennsylvania. The models suggested that wider lanes are safer as compared to wider shoulders, given the total paved width remains unchanged. Other factors remaining the same, an increase in lane width and increase in shoulder width both reduce the crash risk.

An extensive safety study for the state of Indiana was undertaken by Tarko et al. (2006) which looked into the existing safety performance functions from various sources and re-calibrated them to obtain better results. Further, a set of safety performance functions were developed for different facility types, categorized by crash severity. For the road segments, negative binomial models were developed for rural interstates, rural two-lane, rural multi-lane, urban two-lane, urban multi-lane, and urban interstates. Various factors such as AADT, segment length, lane width, left/inside shoulder width, right shoulder width, average longitudinal grade, average degree of horizontal curvature, number of through lanes, and two-way left-turn lane presence were found to be significant in these models. Similarly, models were also developed for different types of intersections. The safety performance functions provide an excellent source from which crash modification factors (CMFs) can be derived corresponding to various geometry improvements. Since the data used was obtained from INDOT regarding crashes in the state of Indiana, the CMFs derived shall be applicable specifically to Indiana. The data used to develop these equations correspond to the crashes from 2003–2005.

The effect of design element trade-offs on crash severity and number of crashes was studied by Stamatiadis et al. (2011). The data used in the study was obtained from the FHWA's Highway Safety Information System for multi-lane rural highways in California, Minnesota and Kentucky. Accident Modification Factors (AMFs) were developed in the study using the negative binomial modeling approach. It was evident from the study that shoulder width affects the frequency of all crash types except for single-vehicle crashes. The median width was shown to affect multi-vehicle crashes: an increase in median width decreases this type of crash. The use of accident modification factors in the highway design process is presented in a study by Lord and Bonneson (2006).

TABLE 2.1
List of safety models developed in the past showing model type, equation and variables used.

Reference	Model/Equations	Variables Used
Stamatiadis et al. (2011)	Generalized linear modeling procedure	*Models: (1) Divided and Undivided Highways (2) Single-Vehicle (SV), Multi-Vehicle (MV), All-Vehicle (AV)* Average Shoulder Width, ADT, Median Width, Median Barrier, Right Shoulder Paved, Functional Class Arterial, Left-Turn Presence, Segment Length • Undivided Highways—Shoulder width significant for MV and AV crashes only • Median width is significant for MV crashes onlycrashes.
Findley et al. (2012)	Collisons/year $= \text{HSM}[0.116 + (0.637 \times D) + (0.122 \times P) + (-0.255 \times D \times P)]$	*HSM Model is multiplied with a factor accounting for spatial relationship of horizontal curves* Distance to distal adjacent curve (D), Distance to proximal adjacent curve (P)
Geedipally et al. (2010)	Poisson-gamma Models for Crash Types; MNL and Fixed Proportion Models for All-Crash Types	*Crash type models: (1) Head-on, (2) Rear-end, (3) Passing direction sideswipe, (4) Opposite sideswipe and (5) Single-vehicle* AADT, Percentage of Trucks, Segment Length, Lane Width and Shoulder Width
Rengarasu et al. (2009)	Negative binomial regression model	*Homogeneous Road Segment Model (Min 200 m segments)* Bendiness, Hilliness, Tunnel, Bridge, Max. Shoulder, Lane Width, Number of Lanes, AADT, Densely Inhabited Districts (DID), Railway Stations, Winter, Log(Segment Length), Combination of Adjacent Segments, Combination of Cross-Section Variables, Combination of Road Geometry Variables *1-km Road Segment Model (Fixed length segments)* Bendiness, Hilliness, Max. Grade, Number of Lanes, AADT, DID, Winter
Gross et al. (2009)	Case-control, conditional logistic regression	Confounding Variables – AADT and Segment Length. *Pennsylvania Model* Covariates - Lane Width, Shoulder Width, Posted Speed, Unpaved Shoulder Width and District
Anastasopoulos et al. (2008)	Tobit Model	*Accidents per 100-million VMT* Interstate Indicator, Pavement Characteristics (High Friction Indicator, Smooth-Pavement Indicator, Rutting Indicator, PCR Indicator), Median Width, Median Presence, Inside-Shoulder Width, Outside-Shoulder, Number of Bridges, Rumble Strips Indicator, Number of Vertical Curves, Ratio of Vertical Curve Length Over Roadway Segment Length, Horizontal Curve's Degree Curvature Indicator, Number of Ramps in the Driving Direction, AADT, Avg. Daily Percent of Combination Trucks *Washington Model* Covariates – Lane Width, Shoulder Width, Speed Limit, Horizontal and Vertical Curve Indicator
Tarko et al. (2008)	Negative Binomial Model	*Crash Frequency Model for Depressed Medians without Barriers* Segment Length, AADT, State Indicator, Average Horizontal Curvature, Frequency of Horizontal Curves, Frequency of Off-Ramps, Frequency of Ramps, Inside-Shoulder Width, Frequency of Bridges, Posted Speed Limit *Crash Severity Models* Indicator variables for different median types, State Indicator variables, Number of Lanes, Presence of Outside Barrier, AADT, Posted Speed Limit, Percentage of Trucks, Frequency of Bridges, Frequency of Off-ramps, Frequency of On-Ramps, Presence of Vertical Curves and Horizontal Curves

TABLE 2.1
(Continued)

Reference	Model/Equations	Variables Used
Labi (2006)	Negative Binomial Model $a = \exp(\beta o + \Sigma \beta i\ Xi)$	*Rural Minor Arterials, Principal Arterials and Major Collectors* *(1) Total Crash Model, (2) Property Damage Only Model and (3) Fatal/Injury Model* Section Length, AADT, Lane Width, Shoulder Width, Pavement Friction, Pavement Condition, Average Horizontal Curve Radius, Average Vertical Grade *Rural County Roads* *(1) Total Crash Model, (2) Property Damage Only Model and (3) Fatal/Injury Model* Section Length, AADT, Lane Width, Shoulder Width, Horizontal Curve Density, Posting of Speed Limit
Lamptey, Labi, & Sinha (2005)	Negative Binomial Model $a = \exp(\beta o + \Sigma \beta i\ Xi)$	*Rural Two- Lane Model* *(1) Total Crash Model, (2) Property Damage Only Model and (3) Fatal/Injury Model* Section Length, AADT, Lane Width, Right Shoulder Width, Skid Resistance Factor, Avg. Radius of Curvature for Horizontal Curves, Avg. Grade for Vertical Curves *Rural Multi-Lane Model* *(1) Total Crash Model, (2) Property Damage Only Model and (3) Fatal/Injury Model* Section Length, AADT, Lane Width, Access Control, Left Shoulder Width, Median Width *Urban Two-Lane Model* *(1) Total Crash Model, (2) Property Damage Only Model and (3) Fatal/Injury Model* Section Length, AADT, Lane Width, Right Shoulder Width, Shoulder Type (No Shoulder/Earth/Stabilized/Paved), Presence of Turning Lane, Presence of Curb *Urban Multi-Lane Model* *(1) Total Crash Model, (2) Property Damage Only Model and (3) Fatal/Injury Model* Section Length, AADT, Lane Width, Access Control, Presence of Curbed Shoulder, Presence of Left-Turning Lane, Friction Factor
Ng & Sayed (2004)	Generalized Linear Regression Modeling $Accidents/5year = \exp(-3.369)\ L^{0.8858} V^{0.5841} \times \exp[0.0049(V_{85} - V_d) + 0.0253\ \Delta V_{85} - 1.77 \Delta f_R]$ (2) $Accidents/5year = \exp(-2.338)\ L^{0092} V^{0.4629} \times \exp[IC\ (0.022\ \Delta V_{85} - 1.189 \Delta f_R]$	*Models: (1) Horizontal Curve only (2) Horizontal Curve and Tangent* Section Length, AADT, Difference between Operating and Design Speed of a Single Element, Change in 85th Percentile Speed and Change in Friction *Models relating individual design consistency measure to safety for:* Difference between Operating and Design Speed (V_{85} – V_d), Speed Reduction (ΔV), Difference between Side Friction and Assumed Friction (Δf_R), Ratio of the Radius of Individual Section to Average Radius of the Alignment, Visual Demand of Unfamiliar Drivers and Visual Demand of Familiar Drivers
Wang, Hughes, & Stewart McLean (1998)	Poisson Model $a = \exp(\Sigma \beta i\ Xi)$	*Rural Multi-Lane Model* *(1) Total Crash Model, (2) Property Damage Only Model and (3) Fatal/Injury Model* Avg. Roadside Hazard Rating, Access Control (Indicator), Driveways/Mile, Intersection with Turns (per mile), Intersections without Turns (per mile), Functional Class (Indicator for Rural Principal Arterial),Outside-Shoulder Width, Median + Inside-Shoulder Width, Area Location (Indicator for Rural Municipal), Daily Vehicle Miles Traveled
Karlaftis & Golias (2002)	Hierarchical Tree-Based Regression Methodology	*Rural Two-Lane Model (Variables in decreasing order of importance)* AADT, Lane Width, Serviceability Index, Friction, Pavement Type and Access Control. *Rural Multi-Lane Model* AADT, Median Width, Access Control, Friction, Lane Width, Serviceability Index, Pavement Type

TABLE 2.1
(Continued)

Reference	Model/Equations	Variables Used
USDOT (2002)	Crashes = 132.2AADT$^{0.073}$ × exp(0.131RHR – 0.151AC + 0.034DD + 0.078INT – 0.572RPA + 0.0082(12-LW) – 0.094SHLDW – 0.003MEDW + 0.429(DEVEL-1)	*Rural Multi-Lane Model* *Crashes per 100 million VMT* Roadside Hazard Rating, Access Control, Driveway Density, Intersections (per mile), Principal Arterial Indicator, Lane Width, Shoulder Width, Median Width, Type of Development (Rural/Dense)
Tarko et al. (2007)	Negative Binomial Model a = exp(βo +Σβi Xi)	*Rural Two-Way Lane Model* *Total Crash Model* Section Length, AADT, Lane Width, Skid Resistance Factor, Pavement Serviceability Index, Pavement Type (Indicator variable for Concrete) *Property Damage Only* Section Length, AADT, Lane Width, Skid Resistance Factor, Pavement Serviceability Index, Pavement Type (Indicator variable for Concrete) *Fatal/Injury Crash Model* Section Length, AADT, Lane Width, Pavement Serviceability Index, Pavement Type (Indicator variable for Concrete), Shoulder Type (Indicator for Paved Type)
Tarko et al. (2007)	Poisson Model a = exp(βo +Σβi Xi)	*Rural Multi-Lane Model* *(1) Total Crash Model* Section Length, AADT, Median Width, Access Control, Skid Resistance *(2) Property Damage Only Model* Section Length, AADT, Median Width, Access Control *(3) Fatal/Injury Model* Section Length, AADT, Median Width, Access Control, Skid Resistance, Inside Shoulder Width
Tarko et al. (2007)	Negative Binomial Model a = exp(βo +Σβi Xi)	*Urban Two-Lane Model* *(1) Total Crash Model* Section Length, AADT, Lane Width, Presence of Turning Lane, Presence of Continuous Turning Lane *(2) Property Damage Only Model* Section Length, AADT, Skid Resistance Factor, Presence of Turning Lane *(3) Fatal/Injury Model* Section Length, AADT, Lane Width, Skid Resistance Factor *Urban Multi-Lane Model* *(1) Total Crash Model, (2) Property Damage Only Model* Section Length, AADT, Number of Lanes, Access Control, Friction Number, Serviceability Index (0-5 scale), Paved Shoulder Type Indicator, Number of Parking Lanes, Continuous Turn Lane on Section Indicator *(3) Fatal/Injury Model* Section Length, AADT, Number of Lanes, Access Control, Friction Number, Inside Shoulder Width, Continuous Turn Lane on Section Indicator
Brown & Tarko (1999)	Negative Binomial Model a = exp(βo +Σβi Xi)	*Urban Two-Lane Model* *(1) Total Crash Model, (2) Property Damage Only Model and (3) Fatal/Injury Model* Section Length, Number of Years, AADT, Lane Width, Access Points (per km), Outside-Shoulder Presence Indicator, Presence of Two-Way Left Turn, No Median Opening between Signalized Intersections

TABLE 2.1
(Continued)

Reference	Model/Equations	Variables Used
Vogt & Bared (1998)	Negative Binomial Model a = exp(βo +Σβi Xi)	*Rural Two-Way Lane Model* *Washington Model (Total Crashes)* ADT, Total (Lane + Shoulder) Width, Roadside Hazard Rating, Driveway Density, Degree of Horizontal Curve, Crests VC (sum of crest % grade changes per hundred feet weighted by relative crest curve lengths), Absolute Grade *Minnesota Model (Total Crashes)* Lane Width, Shoulder Width, Driveway Density, Degree of Horizontal Curve, Crests (Vertical Curve), Absolute Grade *Washington Model (Injury Crashes):* Lane Width, Shoulder Width, Degree of Horizontal Curve *Minnesota Model (Injury Crashes):* Total (Lane + Shoulder) Width, Driveway Density, VMC (number of crests per mile), Degree of Horizontal Curve, Absolute Grade

In broad terms, the AMFs can be used in evaluating safety at the preliminary design stage or where a design exception occurs and also for evaluating design consistency. These applications closely represent the safety benefit evaluation methodology wherein the AMFs are used in conjunction with the base conditions to obtain the current conditions. Different AMFs are used for every specified change in road characteristics, which are then combined in a multiplicative manner. The difference of the current and the base conditions then gives an estimate of the safety change.

The use of the multinomial logit model to predict crash types was presented in a study by Geedipally, Patil, and Lord (2010). The study was conducted for two-lane rural highways of Minnesota, which included operational characteristics as well as segment characteristics. The variables used to predict the crash counts included AADT, percentage of trucks, segment length, lane width, and shoulder width. Further, Poisson-gamma models were also used to predict the total number of crashes for each collision type. Although the MNL model was outperformed, it showed realistic trends for single-vehicle and rear-end crashes.

Besides the road geometry, pavement characteristics, and traffic volumes, other studies have included factors like the geometric design consistency and road safety inspection. These too have shown to affect the crash frequency. The study by Cafiso, Cava, and Montella (2007) looks into the effect of the safety index on rural two-lane highways. The safety index factor takes into account three major components: exposure factor, accident frequency factor, and accident severity factor. The accident frequency factor takes into account the road safety inspection and the geometric design factors which are combined in a multiplicative manner. The roadside safety inspection factor defined by the IASP research program includes subjective ranking of roadside items, such as accesses, cross-section, delineation marking, pavement, sight distance, and signs. This is based on inspections. The study by Ng and Sayed (2004) showed the impact of geometric design consistency on road safety using two different models, one with horizontal curves only, and the other with horizontal curves and tangent. These models showed that the difference between operating and design speed and change in 85th percentile speed was significantly related to road safety. These models also included the AADT and change in friction variable. This study showed that a reduction in the accident frequency was observed if the radius of a section is larger than the average radius, whereas higher visual demand implied higher accident rates. The generalized linear regression modeling approach was used in the study focused on two-lane rural highways only.

The models and equations discussed above have been summarized in Table 2.1. Several of these equations shall be used to derive crash modification factors to evaluate the safety benefit further in the study. The Indiana specific models are extremely relevant for the scope of the current study and shall be used throughout the methodology.

2.3 Speed Models

Similar to the safety performance functions, speed models of interest in this study are those that predict the speed on a roadway segment, curve section, and tangent sections or transition zones as a function of road characteristics and operating conditions. The speed predicted might be average speed, 85th percentile speed, or the operating speed depending on the model developed. The following section discusses the different types of speed models developed in the past. The use of average speed is most relevant to the current study. As such, an emphasis has been laid on the equations predicting average speed.

The study conducted by Figueroa-Medina and Tarko (2004) developed speed equations for two-lane and four-lane highways in the state of Indiana. Different models were developed for curves and tangent sections. For each of these, two model specifications were presented: the ordinary least squares panel data

TABLE 2.2
List of speed models developed in the past showing model type, equation and variables used.

Reference	Model/Equations	Variables Used
Himes & Donnell (2010)	Three-stage least squares method (3SLS)	*Right Lane Mean Speed Model* Left Lane Mean Speed, Right Lane Speed Deviation, Commercial Land/Golf Course Indicator, Signalized Intersection Indicator, Posted Speed Limit of 35mph, Right-Lane Heavy Vehicle Percentage, Number of Access Points within 500ft and Clear-Zone Width Indicator *Left Lane Mean Speed Model* Right Lane Mean Speed, Left Lane Speed Deviation, Two-Way Left-Turn Lane Indicator, Horizontal Curve Length, Horizontal Curve Indicator (0 If Horizontal Tangent), Posted Speed Limit of 55mph, Segment Access Density and Signalized Intersection Indicator *Right Lane Speed Deviation Model* Right Lane Mean Speed, Left Lane Speed Deviation, Segment Access Density, Degree of Curve, Posted Speed Limit (55mph), Posted Speed Limit (50mph), Posted Speed Limit (35mph) and Vertical Curve Length *Left Lane Speed Deviation:* Left Lane Mean Speed, Right Lane Speed Deviation, Depressed Earth Median Indicator, Inverse Rate of Vertical Curvature, Number of Access Points within 500ft and Clear Zone Width Indicator (1 if >20ft)
Cruzado & Donnell (2010)	Multi-level model (Linear regression with clustered data)	*Linear Regression Model (For speed in transition zone)* Operating Speed Prior to Transition Zone, Change in speed limit, Lane Width, Paved Shoulder Width, Lateral Clearance, Total Driveways, Curb/Gutter in Transition Zone, Intersection Ahead Warning Sign, School/ Children Warning Sign, Curve Ahead Warning Sign, Transition Length, Curve with/without Warning Sign *Multi-Level Model (For speed in transition zone)* Operating Speed Prior to Transition Zone, Change in speed limit, Paved Shoulder Width, Total Driveways, Intersection Ahead Warning Sign, School/Children Warning Sign, Curve Ahead Warning Sign, Transition Length, Curve with/without Warning Sign
Figueroa-Medina & Tarko (2007)	85th Percentile Speed Model *Speed on Tangents,* $V_T = 58.994 - 1.470PSL_{50} - 0.030TR - 0.087GRA - 1.004RES + 0.005SD - 2.770 \times 10^{-6}(SD^2) + 0.032TW + 0.015PSW + 0.554GSW + 0.034USW$ *Speed on Curves,* $V_C = 51.973 + 0.003SD - 2.639RES - 2.296DC + 7.748SE - 0.624SE^2$	*85th Percentile Speed on Tangents* Posted Speed Limit Indicator, Percentage of Trucks, Roadway Grade, Residential Development Indicator, Sight Distance, Traveled Way Width, Paved Shoulder Width, Gravel Shoulder Width, Un-treated Shoulder Width *85th Percentile Speed on Curves* Sight Distance, Residential Development Indicator, Degree of Curvature, Super-elevation Rate *Speed on Transition Section* Speed on Tangent, Speed on Horizontal Curve, Position of the speed measurement spot in relation to starting/ ending of curve *Observed Road Characteristics* Posted Speed Limit, Curve Advisory Speed, Percent Trucks, Sight Distance, Roadway Grade, Travel Way Width, Paved Shoulder Width, Gravel Shoulder Width, Untreated Shoulder Width, Degree of Curvature, Curve Radius, Super-elevation Rate, Curve Length, Mean Speed, 85th Percentile Speed

TABLE 2.2
(Continued)

Reference	Model/Equations	Variables Used
Schurr et al. (2002)	$V_{Mean,T}$ = 51.7+0.51PSL $V_{85,T}$ = 70.2+0.43PSL-0.001ADT $V_{Mean,C}$ = 67.4-0.11CD+0.022LC+0.28PSL $V_{85,C}$ = 103.3-0.12CD+0.024LC-1.04G	*Mean Speed, 85th Percentile Speed and 95th Percentile Speed Model* Traffic Volume (ADT), Posted Speed Limit(PSL), Curve Deflection Angle(CD), Arc Length of Curve(LC) and Approach Grade (G)
Poe & Mason (2000)	$V_{Mean,PC}$ = 51.1-0.01DC-0.24G-0.01LW-0.57RD $V_{Mean,\ MID}$ = 48.8-0.14DC-0.75G-0.01LW-0.12RD	*Site Specific Model* Degree of curve, Lane Width and Hazard Rating *Single Comprehensive Model* Degree of curve(DC), Absolute Grade(G), Lane Width(LW) and Hazard Rating(RD)

model and the random effects model. Each of these models was capable of generating any percentile speed (i.e., 5th percentile to 95th percentile). Parameters such as driveway density, intersection density, sight distance, clear zone, presence of guardrails, presence of ditches, and two-way left-turn lanes were found to be significant for the four-lane model. Indicator variables were used to distinguish between rural and sub-urban areas. For the two-lane highways, variables such as gravel shoulder width, untreated shoulder width, posted speed limit, segment grade, super-elevation rate, intersection density, and traveled way width were found significant in the model.

Speed models using the simultaneous equations approach were developed by Himes and Donnell (2010). They predicted the right and left lane mean speed and right and left lane speed deviation. Variables such as signalized intersection indicator, posted speed limit, heavy vehicle percentage, number of access points, horizontal curve length, rate of vertical curvature, and clear-zone width were found significant in these equations. Since a simultaneous equations approach was used, the right lane mean speed used left lane mean speed and right lane speed deviation as independent variables. Similarly, two other independent variables were present in each of the four equations developed (see Table 2.2). It can also be concluded from these models that the mean speed is positively associated with the adjacent lane mean speed and negatively associated with the in-lane speed deviation.

The effect of various roadway features on the operating speed in tangent sections was studied by Fitzpatrick et al. (2005). Linear regression models were used to establish a relationship between posted speed limit and 85th percentile speed based on roadway functional class. The importance of other variables was also investigated, which showed that access density, pedestrian activity, median type, and two-way left-turn lane presence were significant. Similarly, the effect of various factors on operating speed in transition zones present on two-lane rural highways was shown by Cruzado and Donnell (2010). A multi-level modeling approach is considered in which the driver speed data (lower level) is nested in data collection sites (higher level). Data was obtained for near free-flow speed and ideal weather conditions in various transition zones in central Pennsylvania. From the models developed, it was shown that reduction in lane width, reduction in paved shoulder width, reduction in lateral clearance, increase in total driveways, and increase in transition length reduced the mean speed in the transition zone. Presence of warning signs associated with intersections, schools, or curves also caused a reduction in the mean speed of vehicles. However, several variables related to horizontal alignment, vertical profile, and cross-sectional elements could not be considered in the model due to the lack of available data with respect to these variables.

The effect of geometric design on operating speed in a low-speed environment (urban collectors) was studied by Poe and Mason (2000) by taking into account roadway, cross-sectional, roadside, land-use, and traffic characteristics. From the site specific analysis, variables found significant in the model were degree of curve, lane width, and hazard rating. A site specific binary variable was also found to be significant in few of the models. From the multi-point comprehensive analysis, degree of curve, absolute grade, lane width, and hazard rating variables were found to be significant. It was observed that an increase in degree of curve, absolute grade, and hazard rating decreased speed, whereas an increase in lane width before the curve and while exiting the curve increased speed.

The Highway Capacity Manual (TRB, 2010) provides several equations for estimating the free-flow speed from the known (or measured) base average speed adjusted for different geometric elements. The base average speed can be assumed for each facility type or measured from the field. Thereafter, separate equations are available for two-lane and multi-lane highways which estimate the free-flow speed using average speed and various adjustment factors. For two-lane highways, adjustment factors for lane width, shoulder width, and access point density are used. For multi-lane highways, adjustment factors for lane width, total lateral clearance, median type, and access point density are used. A base case is assumed for each of these equations for which the adjustment factor or the reduction in free-flow speed is 0.

Several of the models discussed above can be used to derive relevant speed adjustment factors, which shall be used further in the study to evaluate the mobility benefits from geometry improvements. The equations and variables used in these studies have been summarized in Table 2.2.

3. RESEARCH APPROACH

The safety and speed models form the backbone of the project identification process. The existing safety and speed models lay the foundation for a robust, performance-based methodology for the scoring process used for identifying projects as a part of asset management. The safety models help to quantify the crash reduction benefits from different types of geometry improvements; similarly, speed models help to quantify the travel time benefits. The models developed specifically for Indiana are deemed more useful than general models or those developed for other states. These models are used directly, as well as indirectly, through use of derived parameters such as crash modification factors (CMFs) and speed adjustments (SAs). In cases where CMFs and SAs are unavailable for specific geometry improvements, other relevant sources of data may be used to obtain these factors (which can represent the effect of improvements or changes as accurately as possible).

3.1 Using Data from Various Sources

Based on the models available so far, the concept of Road Screening and Project Evaluation shall be developed and discussed in detail in the next few chapters. For the purpose of developing an up-to-date method for evaluation of benefits, the safety performance functions for the state of Indiana shall be developed using the latest crash data, available for the 2009–2011 period. In the case that the effects of some of the geometry elements are not reflected in the models due to lack of data availability or other reasons, appropriate alternate sources of data shall be readily used. Using several sources of data for CMFs and SAs helps us quantify different types of improvements in the road scoring process. However, caution must be exercised while using the absolute value of these benefits, as it might differ from the actual safety and mobility benefit achievable for a road segment when it is analyzed in isolation. The purpose of the scoring process is to look at the relative impact of different combinations of geometry improvements on different road segments, which is a good way of ranking the projects. In the case a single source of data were used for the ranking process, it is possible that due to the lack of knowledge of the effects of several geometry improvements that the ranking process would yield results that may not be useful.

The methodology adopted in the current study uses data from different data sources that are relevant and expected to be of good quality and integrates it into a single methodology. This method of combining various sources of data (especially CMFs and SAs) is also reflected in the methodologies adopted in the latest versions of the Highway Capacity Manual (TRB, 2010) and Highway Safety Manual (AASHTO, 2010). As mentioned before, there might be ambiguity in dealing with the absolute benefits that shall be calculated using this approach with possible over-estimation of benefits. However, the absolute benefits are not of concern in the current methodology and the benefits are used purely in relative terms to compare a set of geometry improvements applicable to different road segments. The screening of roads and prioritization of projects using this approach is thus well-justified.

3.2 Need for New Models

The need for developing new safety models arises for the following reasons:

1. To develop an up-to-date method.

From the literature review, it is evident that there are several statistical equations which predict crash frequency depending on geometry, traffic, and other factors. However, as more data becomes available with the improvement of the road inventory and the availability of newer and better data collection capabilities, an up-to-date set of models are needed to develop better models. These updated models can provide a better idea about the effect of various geometry improvements on crashes and speed on various types of roads, thus letting us evaluate the safety and speed components better.

2. To incorporate more parameters in the model.

The availability of more reliable data gives information related to different features associated with the road segments. This information might not have been available in the models developed previously. As a result, the effect of those additional variables on crash frequency and average speed can now be analyzed. For example, the models that have been developed for Indiana take into account intersection density classified in several categories. This type of intersection density information is not available from the Indiana safety models developed in previous research studies. Only binary indicator variables showing the presence or absence of signalization in a road segment have been used previously.

3. To meet the specific requirements of the project scoring process.

The models developed from the recent crash data shall not only reflect the current conditions, but also meet several requirements of the proposed project identification process. The road network selected for the purpose of developing the model comprises of road segments in the state of Indiana and specifically only take into account state-administered roads. Thus, the statistical models estimated from the data are specific to the road segments in the scope of the study. Furthermore, the data-set comprises of long, homogeneous segments (uniform cross-sectional geometry) which have been formed by combining shorter homogeneous road segments. This is considering the project evaluation approach, wherein similar geometry improvements typically apply throughout the road segment.

4. CONCEPT OF TWO-STEP ASSET MANAGEMENT

4.1 Introduction

The project identification process in asset management comprises of a performance based screening of roads followed by a more detailed ranking of projects. The objective of the two-step process is to identify the "geometry inadequacy" in the road segments and to rank them on the basis of the benefits that can be derived using geometry improvements in the scope of the project. These geometry improvements are pre-defined by the asset management team, and the benefits derivable from each segment shall vary with the project scope.

Broadly, the project identification process within asset management comprises the following two steps:

1. Road Screening
2. Project Evaluation

The road screening process serves as a filtering process (Table 4.1) which narrows down the road segments to the ones which are the most deficient in terms of geometry standards. This step is used to screen roads prior to the formation of projects. Hence, information regarding possible geometry improvements corresponding to each road segment is unavailable during this process. To address this gap, the road screening process uses the minimum geometry standards. The geometry deficiency in every road segment is determined by comparing the actual geometry of the road segment to the minimum geometry standard for this segment. In other words, the road screening process searches for the *least adequate* road segments in the entire network using the minimum/desirable geometry standard as the reference. The output of the road screening process is a sorted list of segments, with the most deficient segments being on the top.

To proceed from the road screening process to the project evaluation process, a certain number of segments need to be chosen from the sorted list. This is usually a user defined input, such as "X percentile" ("X%") of the most deficient segments. Once these segments are chosen, the target segments from the entire road network have been narrowed down. This is also why the road screening process is essential prior to the project evaluation process because it is not possible to carry out a detailed evaluation of the vast number of segments present in the entire Indiana road network using detailed estimates for geometry improvements for each and every segment. The road screening process is fully automated, as it uses a pre-defined set of road standards (Indiana Design Manual, 2013) and available information in the road inventory to generate a sorted list. The only input from the user is to determine the number of segments to be carried forward to the project evaluation process.

The project evaluation process is more detailed than the road screening process. This is because the project evaluation process needs more detailed information regarding estimated benefits for each road segment. This is provided by the user. The road screening process, on the other hand, uses a predefined set of standards. Usually, the road screening process evaluates each segment based on a lesser number of features. This is another reason why the road screening process can be used more efficiently for evaluating the extraneously larger number of road segments in its scope.

4.2 Road Screening

The proposed road screening process can be divided into several steps. These steps are briefly discussed below. In Chapter 9, these steps are elaborated in more detail by showing the required equations, tables and calculations.

1. Obtain the list of road segments present in the entire network. Longer road sections should be divided into smaller segments between intersections. Typically, this information is available in the road inventory database.
2. Obtain the minimum standard requirement for various geometry elements from the Indiana Design Manual. The user may also choose to use the desirable standards or any other set of standards to screen roads.
3. The information regarding the geometry elements present in the minimum/desirable standard requirements should be also present in the inventory. Information regarding other geometry elements may be disregarded at this point.

TABLE 4.1
Summary of the inputs, decision criteria, and output of the two steps in the asset management process.

Step	Input	Decision Criteria	Output
Road Screening	All road segments in the network	Minimum/Desirable Design Standards	"X%" or percentile or number of most deficient road segments
Project Evaluation	Selected road segments from the output of the road screening process	Estimated Geometry Improvements	List of road segments ranked based on estimated benefit

4. Using the information about the existing conditions on the road segments, calculate the geometry deficiency corresponding to each geometry element. The deficiency is calculated with respect to the standards chosen in Step b. In the screening process, only the deficient geometry elements are taken into account; hence, those elements which exceed the standards chosen should be considered as non-deficient elements.
5. Determine the Crash Modification Factors and Speed Adjustments corresponding to each deficient geometry element. The non-deficient geometry elements should yield a CMF = 1 and SA = 0. The CMFs are obtained for different crash severities: CMF(FI) for fatal injury crashes and CMF(PD) for property damage crashes.
6. The CMFs and SAs determined in the previous step should be combined for each road segment to obtain the Combined Crash Modification Factor (CCMF) and Combined Speed Adjustment (CSA) respectively. The CCMF is also obtained for two different crash severities since the CMFs across different severities cannot be combined together. The CMFs are combined in a multiplicative manner and SAs are combined in an additive fashion.
7. The existing conditions on each road segment should be used to determine the Base Crash Frequency (BCF) and the Base Average Speed (BAS) using the base safety performance functions and the mean speed equations.
8. The CCMFs obtained in Step f should be used with the BCF and BAS obtained in Step g to calculate the crashes saved for both the crash severities. The SAs obtained in Step f give the change in the average speed for every road segment. The SA should be used with the BAS to calculate the improved average speed for each segment.
9. The annual safety benefit BS and the annual mobility benefit BM for each segment can be calculated using the information available. The safety and mobility benefit should be expressed in dollar amounts saved annually.
10. Calculate the total annual benefit for each segment B for the improvements in the scope of the project by summing up the annual safety benefit and the mobility benefit obtained in the previous step.
11. Sort the segments in a decreasing order based on the total annual benefit for each segment. The user can select "X%" or percentile or number of segments from the top. These shall be the most deficient segments in the network.

The above steps describe the road screening process in a summarized manner. Several steps in the road screening process (Step f to Step j) are similar to the project evaluation process that is described in Section 4.3. The input from the user of the road screening process is required only in Step k to determine the number of segments to be used in the project evaluation process.

4.3 Project Evaluation

The following sub-criteria are currently used in the project evaluation method to score the five major categories:

1. *Alignment:* Stopping Sight Distance, Decision Sight Distance, Passing Sight Distance, Intersection Sight Distance, Minimum Radius, Superelevation Rate, Horizontal Sight Distance, Vertical Curvature, Maximum Grade, and Minimum Grade.
2. *Cross-Section:* Travel Lane, Shoulder, Cross Slope, Auxiliary Lane, Median Width, Side Slope, Median Slopes, TWTL Width, Parking Lane Width, Sidewalk Width, Bicycle Lane Width, and Typical Curbing.
3. *Safety:* Guardrail, Side Slopes, and Obstruction Removal/Relocation.
4. *Drainage:* Ditch Grading/Ditch Lining, Structure and/or Pipe Replacement, and Channel Relocation/Overflow Channel.
5. *Compliance with Americans with Disabilities Act (ADA):* Curb Ramps and Sidewalk.

The current methodology takes into account the first three categories mentioned above: Alignment, Cross-Section, and Safety. These categories and their corresponding sub-criteria are used in the proposed method to evaluate the safety and mobility benefits on a road segment. The other two categories, Drainage and Compliance with ADA, are taken into account by using an input from the roadway asset management team based on their evaluation. This is because of the lack of knowledge of the effect of these factors on safety and mobility. Each of these categories is evaluated by INDOT on a discrete 0–2 scale, adding up to a maximum of 10 points. Although the scale used for scoring these individual categories is kept the same, a continuous scoring system is used in the described methodology to score the first three categories, whereas the discrete scoring system is used for the other two categories.

The road segments chosen from the road screening process are the most deficient segments. However, a more detailed analysis of the effect of geometry improvements on these segments is required to prioritize them for the purpose of projects. These segments are evaluated one by one, using detailed input from the user regarding the estimated geometry improvements for each segment. The following steps summarize the proposed project evaluation process. In Chapter 10, these steps are elaborated in more detail, showing the required equations, tables, and calculations.

1. Divide the road section into segments of similar traffic volume and geometry. The list of road segments from the output of the road screening process can be directly used for project evaluation. However, it is advisable to combine consecutive short segments with similar cross-section and traffic volume to form longer segments. This reduces the amount of input required from the user. For each segment, input is required from the user regarding the estimated geometry improvements to be carried out in that segment.
2. Identify the geometry improvements to be carried out in each segment. The estimated change corresponding to several geometry improvements are also required. The geometry changes accounted for in the evaluation process are shown in Chapter 10.

The following steps (c to h) are similar to the road screening process.

1. For every road segment, determine the CMFs for both severities: CMF(FI) and CMF(PD), as well as the SAs corresponding to each geometry change in the project. In the project evaluation, the estimated geometry change is

entered as an input from the user and is used to calculate the CMFs and SAs instead of the geometry deficiency that is used in the road screening process.

2. The CMFs and SAs obtained for various geometry improvements applicable to each segment should be combined to determine the CCMF for both crash severities, CCMF(FI) and CCMF(PD), as well as CSA.
3. Calculate the BCF and BAS from the existing conditions in each segment using the base safety performance function and the mean speed equation.
4. Using the BCF and BAS values calculated in the previous step and the CMFs and SAs obtained in Step d, calculate the annual crashes saved for each crash severity and the improved average speed in the road segment.
5. Calculate the total safety benefit BS from the annual crashes saved and the total mobility benefit BM from the total travel time savings.
6. Calculate the total benefit for the segment by summing up the annual safety benefit and the annual benefit for each segment. The total project benefit B is obtained by summing up the total safety benefit and mobility benefit across all segments.
7. Calculate the Benefit-Cost Ratio for the project using the annualized capital cost of the project. The annualized capital cost is obtained as an input from the user. This is an additional input, as opposed to the road screening process, which did not require cost as an input.
8. Re-scale the Benefit-Cost ratio obtained in the previous step to calculate the *Geometry B/C Score*. The *Ref B/C Score* is required as an input (or needs to be predefined) for this step. The *Ref B/C Score* is a theoretical maximum achievable or desired B/C score for any project. The *Geometry B/C Score* is obtained on the 0-6 scale, and the points corresponding to the Drainage (0-2 scale) and ADA (0-2 scale) should be added by the user. The sum of the *Geometry B/C Score* and the points corresponding to Drainage and ADA gives the *Geometry Raw Score*.

The *Geometry Raw Score* obtained as the output of the Project Evaluation process is used as an input in to the roadway scoring process. The further steps remain the same as it is shown in the Roadway Scoring Rules (INDOT, 2011). The Geometry Raw Score is obtained on the 0–10 scale and doesn't affect the relative importance of any other factor in the overall scoring process.

It should be also noted that the sorted segments from the road screening are not necessarily needed as an input to the project evaluation process. The project evaluation steps can be used for evaluating projects on pre-selected segments.

5. INDIANA SAFETY MODELS

5.1 Data Description

The crash records used for modeling the safety performance functions were obtained from police recorded crashes that occurred during the 2009–2011 period in the state of Indiana. The crashes are assigned to the closest road segment that lies within 250 feet from the recorded location of the crash. This includes crashes occurring on both road segments as well as intersections. Using this approach results in crashes that occur on intersections being assigned to the closest road segment. This process is justified, since we include intersection density information to develop the models and no separate models are estimated solely for intersections.

Considering the scope of the study, 8 different models are developed, with two separate models corresponding to different crash severities for each of the 4 segment types. The following crash frequency models have been developed:

- Rural Two-Lane Model for Fatal/Injury Crashes
- Rural Two-Lane Model for Property Damage Crashes
- Rural Multi-Lane Model for Fatal/Injury Crashes
- Rural Multi-Lane Model for Property Damage Crashes
- Urban Two-Lane Model for Fatal/Injury Crashes
- Urban Two-Lane Model for Property Damage Crashes
- Urban Multi-Lane Model for Fatal/Injury Crashes
- Urban Multi-Lane Model for Property Damage Crashes

Models corresponding to interstate highways were not developed because they were out of the scope of the current study. Similarly, all local roads were also discarded from the dataset. Only the state-administered non-interstate roads in Indiana were considered.

The road inventory contains the information regarding various geometry features of each segment. The relevant information, which was available in the road inventory and used in the form of independent variables to build the model, is discussed below. The descriptive statistics of these variables are presented in Table 5.1.

- *Segment Length:* The length of the road segment expressed in miles. Short, consecutive road segments with similar cross-section are combined to form longer segments. Usually, the segments begin and end at intersections and may also contain several intersections along the entire length. The minimum length of the segment was restricted to 500 feet. All segments shorter than this length were removed from the dataset.
- *Annual Average Daily Traffic (AADT) or Traffic Volume:* The traffic volume expressed in vehicles/day is used for every segment in the dataset. The average traffic volume for rural road segments is lower than for urban segments.
- *Lane Width:* This is the width of the traveled way expressed in feet corresponding to each lane. The lane width is obtained indirectly from the information regarding the total surface width, shoulder width, and the number of lanes. All the segments with lane width less than or equal to 8.00 feet are removed from the dataset, while the lane widths greater than 13.00 feet are set to 0.00 feet and the "Lane Width missing indicator" set to a value of 1. This is because lane widths greater than 13.00 feet are speculated to be present due to an error in recording one of the following variables: surface width, shoulder width, median type, or number of lanes.
- *Lane Width Missing Indicator:* The lane width missing indicator is used to indicate an erroneously recorded lane width variable. This variable takes the value '1' whenever the Lane Width of a segment is found to be greater than 13.00 feet.

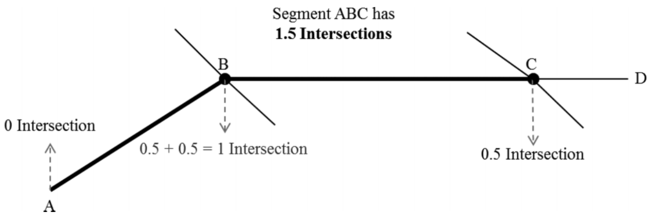

Figure 5.1 Schematic diagram showing the counting of the total number of intersections for each road segment.

- *Left/Inside Shoulder Width:* The left shoulder, or the inside shoulder width, is expressed in feet and includes the predominant width of the inside shoulder including rumble strips and gutter pans. It does not include bike and parking lanes.
- *Shoulder Width:* This is the right shoulder, or the outside shoulder width, expressed in feet and measured from the outer edge of the traveled way lane. It does not include bike and parking lanes.
- *Median Width:* The median width is expressed in feet and includes the inside shoulder, measured between the inside edges of the through lanes. Several categorical variables were created for median width and used in the crash frequency model:

a. MW_10: Binary variable indicating median width less than 10 feet.
b. MW_20: Binary variable indicating median width less than 20 feet and greater than or equal to 10 feet.
c. MW_30: Binary variable indicating median width less than 30 feet and greater than or equal to 20 feet.
d. MW_50: Binary variable indicating median width less than 50 feet and greater than or equal to 30 feet.
e. MW_L: Binary variable indicating median width greater than or equal to 50 feet.

One or more of these categorical variables were combined together wherever it seemed appropriate and yielded better results. The discussion of the significant variables can be found in Sections 5.2 and 5.3.

- *Paved Shoulder:* The paved shoulder indicator is a binary variable indicating the presence of a paved shoulder in the segment. The paved shoulder variable takes a value of 1.00 when there is a paved shoulder present; otherwise, it is 0.00.
- *Border Zone:* The border zone is expressed in feet. It is the region between the outside edge of the outermost shoulder and the boundary of the right-of-way. The boundary zone is calculated from the surface width and the right of way width information. The boundary zone is represented by categorical variables as defined below:

a. *BRDR_min20:* Binary variable indicating that the border zone is greater than or equal to 20 feet.
b. *BRDR_min50:* Binary variable indicating that the border zone is greater than or equal to 50 feet.

- *Curb on Both Sides Indicator:* The curb on both sides indicator variable takes a value of '1' if a curb is present on both sides of the road segment; otherwise, it takes a value of '0'. This variable is used only for urban road segments.
- *Continuous Turn Lane indicator:* The continuous turn lane indicator is a binary variable which takes the value '1' if there is a continuous turn lane present in the road segment; otherwise it takes the value '0'.
- *Principal Arterial Indicator:* The principal arterial indicator is a binary variable which takes the value '1' if the road segment is classified as a principal arterial; otherwise, it takes the value '0'.
- *Minor Arterial Indicator:* The minor arterial indicator is a binary variable which takes the value '1' if the road segment is classified as a minor arterial; otherwise, it takes the value '0'.
- *Major Collector Indicator:* The major collector indicator is a binary variable which takes the value '1' if the road segment is classified as a major collector; otherwise, it takes the value '0'. Only the rural road segments were classified as "Major Collector" and "Minor Collector" functional classes.
- *Collector Indicator:* The collector indicator is a binary variable which takes a value '1' if the road segment is classified as a collector; otherwise, it takes the value '0'. This classification is used only for the urban system.
- *Number of Intersections:* The total number of intersections present in the road segment is counted as shown in Figure 5.1. Any intersection present in the beginning/end of the segment is counted as 0.5 intersections, whereas all lying within the road segment are counted as a complete intersection. The intersections are classified into different types, and different variables are used representing the number of each type of intersection. The intersections were classified as:

a. *Unsignalized 3-Legged Intersection:* Total number of intersections which are unsignalized and have 3 legs.
b. *Unsignalized 4-Legged Intersection:* Total number of intersections which are unsignalized and have 4 or more legs. Since, only a small number of intersections had more than 4 legs, they were counted together with the 4-legged intersections.
c. *Signalized 3-Legged Intersection:* Total number of intersections which are signalized and have 3 legs.
d. *Signalized 4-Legged Intersection:* Total number of intersections which are signalized and have 4 or more legs.

The descriptive statistics of the variables available to the model are shown in Tables 5.1, 5.2, 5.3, and 5.4.

5.2 Model Development

5.2.1 Modeling Approach

The negative binomial model has been used to develop crash frequency models for Indiana. This is the most commonly used count data model for developing safety performance functions. The functional form of the negative binomial model (Washington Karlaftis, & Mannering, 2003) is given as:

$$a = \exp\left(\beta_o + \sum_{i=1}^{n} \beta_i x_i\right) \quad (5.1)$$

Where, β_o is the intercept or the constant;

x_i is the i^{th} independent variable in the model;

β_i is the coefficient for the i^{th} variable x_i and

n is the number of independent variables in the model.

TABLE 5.1
Descriptive statistics for rural two-lane road segments.

Variable	Mean	Std. Dev	Min	Max
Segment length, in miles	1.3287	1.4156	0.0950	15.5408
Annual Average Daily Traffic (AADT), in vehicles/day	3935	2924	60	28880
Lane width,* in ft	11.2345	1.0737	8.5000	13.0000
Lane width missing indicator	0.1033	0.3043	0.0000	1.0000
Left/inside shoulder width, in ft	3.2995	2.6735	0.0000	14.0000
Shoulder width, in ft	3.5124	2.7661	0.0000	16.0000
Median width, in ft	0.0665	2.0703	0.0000	97.0000
Paved shoulder indicator	0.2598	0.4385	0.0000	1.0000
Border zone, in ft	20.7205	16.7048	0.5000	424.0000
Continuous turning lane indicator	0.0024	0.0492	0.0000	1.0000
Principal Arterial indicator	0.1531	0.3601	0.0000	1.0000
Minor Arterial indicator	0.2411	0.4278	0.0000	1.0000
Major Collector indicator	0.6019	0.4896	0.0000	1.0000
Number of un-signalized 3-legged intersections per mile	3.2110	4.2504	0.0000	32.1550
Number of un-signalized 4-legged intersections per mile	2.0285	3.2674	0.0000	33.4711
Number of signalized 4-legged intersections per mile	0.0349	0.3422	0.0000	9.7282
Number of road segments	**5355**			

*Based on 4802 non-zero observations.

To develop the crash frequency models, every road segment is used as an observation, where "a" is the number of crashes (for each crash severity) occurring on the road segment in three years. The independent variables "x_i" are the geometry features and attributes of the road segments discussed in the previous section. The estimation of these models gives us the values of the coefficients associated with each dependent variable. The estimation process also tells us whether the coefficient of a dependent variable is significantly different from 0 at a certain significance level. These models have been estimated in SAS 9.2 (2010), and the models estimated are discussed in Section 5.3.

The crash frequency models not only show the effect of different geometry features and attributes on crashes, but also can be used to derive crash modification factors. These factors can tell us the percentage change in the number of crashes associated with the change in a particular geometry feature. This can help us determine the safety effect of estimated geometry changes on different road segments.

5.2.2 *Crash Modification Factors from Crash Frequency Models*

The safety performance functions are negative binomial models which have the exponential functional form shown in Equation 5.1. Crash modification factors are derived from these safety performance functions and are defined as the ratio of the crashes after change to the crashes before change. The change in one or more of the dependent variables (or geometry features) causes the expected number of crashes to change. The crash modification factors can be derived in the following manner:

$$\text{Crash Modification Factor (CMF)} = \frac{\text{Expected crashes after change}}{\text{Expected crashes before change}} = \frac{C_{after}}{C_{before}} \quad (5.2)$$

Assuming that only the k^{th} geometry feature is changed and the model takes into account n variables, we have:

$$C_{before} = \exp(\beta_o + \beta_1 x_1 + \ldots + \beta_k x_k + \ldots + \beta_n x_n) \quad (5.3)$$

$$C_{after} = \exp(\beta_o + \beta_1 x_1 + \ldots + \beta_k (x_k + \Delta x_k) + \ldots + \beta_n x_n) \quad (5.4)$$

Therefore, the CMF for the k^{th} variable or geometry feature is:

$$\Rightarrow CMF_k = \frac{C_{after}}{C_{before}}$$

$$= \frac{\exp(\beta_o + \beta_1 x_1 + \ldots + \beta_k (x_k + \Delta x_k) + \ldots + \beta_n x_n)}{\exp(\beta_o + \beta_1 x_1 + \ldots + \beta_k x_k + \ldots + \beta_n x_n)}$$

$$= \exp(\beta_k \Delta x_k) \quad (5.5)$$

The CMF for a geometry change depends on the coefficient $\hat{a}_k$ estimated in the model, as well as the actual geometry change Δx_k. Some properties of the CMF based on the above equation are shown below:

- If $\Delta x_k = 0$, then there is no geometry change $\Rightarrow CMF_k = \exp(0) = 1 \Rightarrow$ no effect on the number of crashes.
- If $\beta_k \times \Delta x_k > 0 \Rightarrow CMF_k = \exp(+ve) > 1 \Rightarrow$ crashes have increased due to the geometry change.
- If $\beta_k \times \Delta x_k < 0 \Rightarrow CMF_k = \exp(-ve) < 1 \Rightarrow$ crashes have decreased due to the geometry change.

TABLE 5.2
Descriptive statistics for rural multi-lane road segments.

Variable	Mean	Std. Dev	Min	Max
Segment length, in miles	1.2951	1.3450	0.0971	9.5621
Annual Average Daily Traffic (AADT), in vehicles/day	11945	6763	2220	33450
Lane width,* in feet	11.8902	0.4232	9.0000	13.0000
Lane width missing indicator	0.0241	0.1535	0.0000	1.0000
Left/inside shoulder width, in ft	3.4664	1.8591	0.0000	13.0000
Shoulder width, in ft	8.5680	3.2975	0.0000	14.0000
Median width, in ft	40.7969	21.3811	0.0000	99.0000
Paved shoulder indicator	0.7332	0.4427	0.0000	1.0000
Border zone, in ft	42.8787	28.3077	0.5000	232.0000
Continuous turning lane indicator	0.0327	0.1780	0.0000	1.0000
Principal Arterial indicator	0.6265	0.4841	0.0000	1.0000
Minor Arterial indicator	0.1738	0.3793	0.0000	1.0000
Major Collector indicator	0.1997	0.4001	0.0000	1.0000
Number of un-signalized 3-legged intersections per mile	2.1711	2.7757	0.0000	19.1951
Number of un-signalized 4-legged intersections per mile	1.2261	1.8700	0.0000	13.4462
Number of signalized 4-legged intersections per mile	0.0225	0.2034	0.0000	2.7603
Number of road segments	**581**			

*Based on 567 non-zero observations.

Since different models are developed for different road types and crash severities, the CMF for a geometry change shall be different for different road types and crash severities, even if the value of the change remains the same. For the geometry changes indicated as binary variables in the model, a specific CMF can be derived since Δx_k can only take the value of 1. In such a case:

$$\Rightarrow \mathrm{CMF_k} = \exp(\beta_k \times 1) = \exp(\beta_k) \tag{5.6}$$

Where, the k^{th} variable is a binary variable (or rather a geometry change indicated by a binary variable).

From the above equation, it can be shown that if m number of independent variables are changed, starting with the k^{th} variable, then the resulting CMF is obtained as follows.

$$\Rightarrow \mathrm{CMF} = \frac{\mathrm{C_{after}}}{\mathrm{C_{before}}} = \exp\left(\sum_{j=k}^{k+m} \beta_j \Delta x_j\right) \tag{5.7}$$

Where, $1 \leq j \leq n$ and m can take only non-negative integer values.

$$\Rightarrow \mathrm{CMF} = \prod_{j=k}^{k+m} \exp(\beta_j \Delta x_j) \tag{5.8}$$

$$\Rightarrow \mathrm{CMF} = \mathrm{CMF_k} \times \mathrm{CMF_{k+1}} \times \ldots \times \mathrm{CMF_{k+m-1}} \times \mathrm{CMF_{k+m}} \tag{5.9}$$

TABLE 5.3
Descriptive statistics for urban two-lane road segments.

Variable	Mean	Std. Dev	Min	Max
Segment length, in miles	0.4231	0.4245	0.0948	6.6838
Annual Average Daily Traffic (AADT), in vehicles/day	9121	4963	400	31049
Lane width,* in feet	11.7762	0.7884	9.0000	13.0000
Lane width missing indicator	0.3963	0.4892	0.0000	1.0000
Left/inside shoulder width, in ft	2.7186	3.0826	0.0000	14.0000
Shoulder width, in ft	3.0177	3.2911	0.0000	14.0000
Median width, in ft	0.3945	4.2626	0.0000	97.0000
Paved shoulder indicator	0.2706	0.4444	0.0000	1.0000
Border zone, in ft	18.1382	13.9463	0.5000	178.0000
Curb on both sides indicator	0.3913	0.4881	0.0000	1.0000
Continuous turning lane indicator	0.0227	0.1491	0.0000	1.0000
Principal Arterial indicator	0.5964	0.4907	0.0000	1.0000
Minor Arterial indicator	0.2621	0.4399	0.0000	1.0000
Collector indicator	0.0389	0.1935	0.0000	1.0000
Number of un-signalized 3-legged intersections per mile	6.2312	5.5965	0.0000	40.4945
Number of un-signalized 4-legged intersections per mile	4.1123	4.4173	0.0000	32.3432
Number of signalized 4-legged intersections per mile	0.0721	0.5595	0.0000	9.6366
Number of road segments	**2594**			

*Based on 567 non-zero observations.

TABLE 5.4
Descriptive statistics for urban multi-lane road segments.

Variable	Mean	Std. Dev	Min	Max
Segment length, in miles	0.4981	0.4640	0.0949	4.0282
Annual Average Daily Traffic (AADT), in vehicles/day	20390	9852	1610	72700
Lane width,* in ft	11.8788	0.6600	9.0000	13.0000
Lane width missing indicator	0.1340	0.3408	0.0000	1.0000
Left/Inside shoulder width, in ft	2.4278	2.8884	0.0000	13.0000
Shoulder width, in ft	5.6107	4.7264	0.0000	15.0000
Median width, in ft	21.7039	22.5336	0.0000	99.0000
Paved shoulder indicator	0.5263	0.4995	0.0000	1.0000
Border zone, in ft	30.6229	28.5613	0.5000	218.0000
Curb on both sides indicator	0.3479	0.4765	0.0000	1.0000
Continuous turning lane indicator	0.1273	0.3334	0.0000	1.0000
Principal Arterial indicator	0.8113	0.3915	0.0000	1.0000
Minor Arterial indicator	0.0666	0.2495	0.0000	1.0000
Collector indicator	0.0015	0.0385	0.0000	1.0000
Number of un-signalized 3-legged intersections per mile	4.4481	4.4957	0.0000	33.2153
Number of un-signalized 4-legged intersections per mile	2.7185	3.4218	0.0000	19.8956
Number of signalized 4-legged intersections per mile	0.0711	0.4891	0.0000	8.3126
Number of road segments	**1351**			

*Based on 1170 non-zero observations.

The above equation shows that several crash modification factors can be combined together in a multiplicative manner to obtain the single combined crash modification factor reflecting the effect of all the changes combined. This *CMF* has been referred to as the "Combined Crash Modification Factor" in Chapter 4. This equation for combining several CMFs to obtain a combined CMF shall be used extensively in the evaluation of safety benefits.

5.3 Results Discussion

Crash frequency models for different types of roads have been developed that predict the expected number of crashes for 3 years. These models are shown in Table 5.5. The values of the estimated coefficients for different variables and their corresponding *t*-statistics are shown in these tables. The discussion of the values and signs of the estimated coefficients for different models are presented in the following sections.

5.3.1 Crash Frequency Models for Rural Two-Lane Roads

The fatal/injury crash model for rural two-lane is shown in Table 5.5, while the property damage crash model is shown in Table 5.6. For both the crash severities, the variables found significant include *Segment Length, AADT, Lane Width, Lane Width missing indicator, Number of Unsignalized 3-Legged Intersections,* and *Number of Unsignalized 4-Legged Intersections.*

The traffic volume and the segment length have an almost similar effect on the models for rural two-lane

TABLE 5.5
Negative binomial model for rural two-lane roads predicting number of fatal/injury crashes for 3 years.

Variable Description	Coefficient	*t*-statistic
Intercept	–5.5700	–22.09
Logarithm of segment length, in miles	0.9299	44.75
Logarithm of Annual Average Daily Traffic (AADT), in vehicles/day	0.8165	29.56
Lane width, in feet	–0.0772	–4.04
Lane width missing indicator (1-if lane width for the road segment is not available, 0-otherwise)	–1.1868	–5.06
Shoulder width, in feet	–0.0279	–4.01
Border zone minimum 20 feet (1-if border zone is greater than or equal to 20 feet, 0-otherwise)	–0.1780	–5.26
Number of un-signalized 3-legged intersections per mile	0.0300	4.76
Number of un-signalized 4-legged intersections per mile	0.0216	2.74
Minor Arterial indicator (1-if functional class of road segment is Minor Arterial, 0-otherwise)	0.3488	7.35
Major Collector indicator (1-if functional class of road segment is Major Collector, 0-otherwise)	0.2708	5.37
Over-dispersion Parameter, Alpha	**0.4283**	**17.79**
Number of observations	**5355**	
Log-likelihood at convergence	**–7835**	

TABLE 5.6
Negative binomial model for rural two-lane roads predicting number of property damage crashes for 3 years.

Variable Description	Coefficient	*t*-statistic
Intercept	–4.3598	–20.24
Logarithm of segment length, in miles	0.9116	51.13
Logarithm of Annual Average Daily Traffic (AADT), in vehicles/day	0.7843	32.48
Lane width, in feet	–0.0853	–4.99
Lane width missing indicator (1-if lane width for the road segment is not available, 0-otherwise)	–1.2096	–5.80
Paved shoulder (1-if shoulder is paved, 0-otherwise)	–0.0559	–1.60
Border zone minimum 50 feet (1-if border zone is greater than or equal to 50 feet, 0-otherwise)	0.1306	1.77
Number of un-signalized 3-legged intersections per mile	0.0420	8.59
Number of un-signalized 4-legged intersections per mile	0.0302	5.07
Minor Arterial indicator (1-if functional class of road segment is Minor Arterial, 0-otherwise)	0.4024	9.08
Major Collector indicator (1-if functional class of road segment is Major Collector, 0-otherwise)	0.3439	7.42
Over-dispersion Parameter, Alpha	**0.6789**	**32.07**
Number of observations	**5355**	
Log-likelihood at convergence	**–12512**	

roads. The segment length is almost linearly related to the number of crashes, indicating a higher number of crashes for longer segments. The lane width variable has a negative coefficient, indicating a decrease in number of both types of crashes with an increase in lane width of the road segment. The lane width missing indicator gives the average effect of the lane widths of road segments with missing lane width information. The negative sign shows that most of the road segments with missing lane width information have lower crashes.

The number of unsignalized intersections, irrespective of the number of legs, increases the number of both types of crashes for rural two-lane roads. This can be explained by the fact that an increase in number of intersections increases the possibility of conflict between vehicles, thus raising the expected number of crashes. It can also be observed that 3-legged intersections seem to have a stronger effect on crashes than those with 4 or more legs. The reason behind this is speculated to be the conspicuity associated with 3-legged intersections, making them less obvious and detectable by drivers. 4-legged intersections are easy to detect, and drivers might take appropriate caution beforehand when approaching such intersections. The minor arterial indicator and the major collector indicator also have positive coefficients indicating that road segments which are classified as minor arterial or major collector have the highest number of crashes. The road classification accounts for variables that are not present in the model (for example, the posted speed limit). The posted speed limit varies depending on the functional class of the road.

For the fatal/injury crash model, the additional variables found significant are *Shoulder Width* and the *Border Zone minimum 20 feet indicator.* Both these variables have negative coefficients, indicating that an increase in shoulder width decreases fatal/injury crashes on rural two-lane roads and a border zone greater than 20 feet also causes a reduction in fatal/injury crashes. Larger shoulder width and border zone provide more recovery zone for drivers, thus causing a decrease in fatal/injury crashes.

For property damage crashes, the additional variables found significant are *Paved Shoulder indicator* and the *Border Zone minimum 50 feet indicator.* The negative coefficient of the paved shoulder indicator shows that paved shoulder presence reduces property damage crashes, as it acts as a stable recovery zone for vehicles. On the other hand, an increase in the border zone beyond 50 feet causes an increase in property damage crashes. Very large border zones might cause an increase in the average speed of vehicles, resulting in a higher number of property damage crashes.

5.3.2 Crash Frequency Models for Rural Multi-Lane Roads

The fatal/injury crash model for rural multi-lane roads is shown in Table 5.7 and the property damage crash model is shown in Table 5.8. For both the crash severities, the variables found significant included *Segment Length, AADT, Number of Unsignalized 3-Legged Intersections*, and *Number of Unsignalized 4-Legged Intersections.* All these variables have a positive coefficient, thus indicating an increase in the number of crashes with an increase in these variables. Similar to rural two-lane roads, the 3-legged unsignalized intersections have a stronger effect on crashes than 4 or more legged intersections.

For fatal/injury crashes, the additional variables found to be significant were *Lane Width, Lane Width missing indicator, Shoulder Width*, and *Border Zone minimum 50 feet indicator*. All these variables have negative coefficients, indicating that an increase in lane width or shoulder width causes a decrease in crashes. Border zones greater than 50 feet also reduce crashes. Again, the negative coefficient of the lane

TABLE 5.7
Negative binomial model for rural multi-lane roads predicting number of fatal/injury crashes for 3 years.

Variable Description	Coefficient	*t*-statistic
Intercept	–3.4477	–1.88
Logarithm of segment length, in miles	0.8979	14.41
Logarithm of Annual Average Daily Traffic (AADT), in vehicles/day	0.7885	8.52
Lane width, in feet	–0.2384	–1.58
Lane width missing indicator (1-if lane width for the road segment is not available, 0-otherwise)	–2.9755	–1.65
Shoulder width, in feet	–0.0412	–1.84
Border zone minimum 50 feet (1-if border zone is greater than or equal to 50 feet, 0-otherwise)	–0.2104	–1.78
Number of un-signalized 3-legged intersections per mile	0.1240	4.52
Number of un-signalized 4-legged intersections per mile	0.0665	1.74
Over-dispersion Parameter, Alpha	**0.8884**	**9.45**
Number of observations	**581**	
Log-likelihood at convergence	**–1137**	

width missing indicator tells us that many of the road segments with wide lanes have missing lane width information.

For property damage crashes, the additional variables found significant are *Left/Inside Shoulder Width* and *Continuous Turning Lane indicator.* Both these variables have negative coefficients, indicating that an increase in the left/inside shoulder width reduces property damage crashes. Also, the presence of a continuous turning lane reduces property damage crashes. The negative signs are justified since higher shoulder widths reduce crashes. The presence of a continuous turn lane increases the separation between two opposite lanes, thus making them safer and reducing crashes as well.

5.3.3 Crash Frequency Models for Urban Two-Lane Roads

The fatal/injury crash model for urban two-lane roads is shown in Table 5.9, and the property damage crash model is shown in Table 5.10. For both the crash severities, the variables found significant are *Segment Length, AADT, Border Zone minimum 50 feet indicator, Curb on both sides indicator, Number of Unsignalized 3-Legged Intersections, Number of Unsignalized 4-Legged Intersections, Principal Arterial indicator*, and *Minor Arterial indicator.*

As discussed in the previous models, the increase in segment length has an almost linear effect on the crashes, suggesting that longer segments would have more crashes. Increase in traffic volume also increases the number of crashes. It can be observed that the coefficient of AADT has a stronger effect for urban roads as compared to rural roads. The number of unsignalized intersections, both 3-legged and 4 or more than 4-legged intersections increases the number of fatal/injury and property damage crashes. For urban roads, it can be seen that the effect of intersections on crashes is approximately the same, irrespective of the number of legs. The principal arterial indicator and the minor arterial indicator have positive coefficients, indicating that such road segments have a higher number of crashes.

For fatal/injury crashes, the only additional variable found to be significant is the *Continuous Turning Lane indicator* variable. This variable has a positive coefficient, unlike that in the rural multi-lane model, which indicates that the presence of a continuous turning lane increases the number of fatal/injury crashes on urban two-lane roads. For urban roads, the continuous

TABLE 5.8
Negative binomial model for rural multi-lane roads predicting number of property damage crashes for 3 years.

Variable Description	Coefficient	*t*- statistic
Intercept	–5.9705	–7.32
Logarithm of segment length, in miles	0.9424	16.91
Logarithm of Annual Average Daily Traffic (AADT), in vehicles/day	0.8409	9.60
Left/Inside shoulder width, in feet	–0.0443	–1.42
Continuous turning lane indicator (1-if continuous turning lane is present in the road segment, 0-otherwise)	–0.9659	–3.08
Number of un-signalized 3-legged intersections per mile	0.1066	4.69
Number of un-signalized 4-legged intersections per mile	0.0550	1.60
Principal Arterial indicator (1-if functional class of road segment is Principal Arterial, 0-otherwise)	–0.2322	–1.72
Major Collector indicator (1-if functional class of road segment is Major Collector, 0-otherwise)	0.2538	1.54
Over-dispersion Parameter, Alpha	**0.9572**	**12.24**
Number of observations	**581**	
Log-likelihood at convergence	**–1561**	

TABLE 5.9
Negative binomial model for urban two-lane roads predicting number of fatal/injury crashes for 3 years.

Variable Description	Coefficient	*t*-statistic
Intercept	–7.2920	–17.36
Logarithm of segment length, in miles	0.8446	22.51
Logarithm of Annual Average Daily Traffic (AADT), in vehicles/day	0.9124	18.87
Border zone minimum 50 feet (1-if border zone is greater than or equal to 50 feet, 0-otherwise)	–0.4436	–2.77
Curb on both sides indicator (1-if curb is present on both sides, 0-otherwise)	–0.1336	–1.91
Continuous turning lane indicator (1-if continuous turning lane is present in the road segment, 0-otherwise)	0.3242	2.16
Number of un-signalized 3-legged intersections per mile	0.0198	3.38
Number of un-signalized 4-legged intersections per mile	0.0196	2.70
Principal Arterial indicator (1-if functional class of road segment is Principal Arterial, 0-otherwise)	0.4464	4.49
Minor Arterial indicator (1-if functional class of road segment is Minor Arterial, 0-otherwise)	0.3467	3.36
Over-dispersion Parameter, Alpha	**0.8162**	**18.09**
Number of observations	**2594**	
Log-likelihood at convergence	**–4509**	

turning lane is associated with a high number of turning maneuvers which results in more crashes, as indicated by the positive sign.

For property damage crashes, the additional variables found significant are *Lane Width, Lane Width missing indicator, Shoulder Width*, and *Number of Signalized 4-Legged Intersections.* The lane width, lane width missing indicator, and shoulder width have negative coefficients similar to the models discussed before. An increase in lane width and shoulder width reduces property damage crashes, and the negative sign of the lane width missing indicator implies that the lane width information is missing for road segments with wider lanes. This explains the reduction in property damage crashes on urban two-lane roads with missing lane width information. On the other hand, an increase in the number of signalized 4 or more than 4-legged intersections increases the number of property damage crashes. It can also be observed that the effect of signalized intersections on property damage crashes is much higher than that of unsignalized crashes.

5.3.4 Crash Frequency Models for Urban Multi-Lane Roads

The fatal/injury crash model for urban multi-lanes is shown in Table 5.11, and the property damage crash model is shown in Table 5.12. For both the crash severities, the variables found significant were *Segment Length, AADT, Number of Unsignalized 3-Legged Intersections, Number of Unsignalized 4-Legged Intersections, Principal Arterial indicator*, and *Minor Arterial indicator.* All these variables have positive coefficients, implying that an increase in segment length, AADT, number of unsignalized intersections, or signalized intersections causes an increase in the number of fatal/injury and property damage crashes.

TABLE 5.10
Negative binomial model for urban two-lane roads predicting number of property damage crashes for 3 years.

Variable Description	Coefficient	*t*-statistic
Intercept	–5.1322	–10.34
Logarithm of segment length, in miles	0.8199	23.92
Logarithm of Annual Average Daily Traffic (AADT), in vehicles/day	0.9100	21.93
Lane width, in feet	–0.0678	–1.88
Lane width missing indicator (1-if lane width for the road segment is not available, 0-otherwise)	–0.7190	–1.64
Shoulder width, in feet	–0.0176	–1.79
Border zone minimum 50 feet (1-if border zone is greater than or equal to 50 feet, 0-otherwise)	–0.7170	–4.79
Curb on both sides indicator (1-if curb is present on both sides, 0-otherwise)	–0.1920	–2.22
Number of un-signalized 3-legged intersections per mile	0.0233	4.53
Number of un-signalized 4-legged intersections per mile	0.0276	4.45
Number of signalized 4-legged intersections per mile	0.1007	2.59
Principal Arterial indicator (1-if functional class of road segment is Principal Arterial, 0-otherwise)	0.1901	2.40
Minor Arterial indicator (1-if functional class of road segment is Minor Arterial, 0-otherwise)	0.1625	1.98
Over-dispersion Parameter, Alpha	**0.9554**	**27.41**
Number of observations	**2594**	
Log-likelihood at convergence	**–6966**	

TABLE 5.11
Negative binomial model for urban multi-lane roads predicting number of fatal/injury crashes for 3 years.

Variable Description	Coefficient	*t*-statistic
Intercept	–7.4788	–10.66
Logarithm of segment length, in miles	0.8754	18.26
Logarithm of Annual Average Daily Traffic (AADT), in vehicles/day	0.9378	13.03
Paved shoulder (1-if shoulder is paved, 0-otherwise)	–0.1112	–1.41
Median width minimum 20 feet (1-if median width is greater than or equal to 20 feet, 0-otherwise)	–0.1207	–1.39
Border zone minimum 50 feet (1-if border zone is greater than or equal to 50 feet, 0-otherwise)	–0.2208	–2.15
Number of un-signalized 3-legged intersections per mile	0.0478	5.40
Number of un-signalized 4-legged intersections per mile	0.0420	3.88
Number of signalized 4-legged intersections per mile	0.1288	1.94
Principal Arterial indicator (1-if functional class of road segment is Principal Arterial, 0-otherwise)	0.3440	2.84
Minor Arterial indicator (1-if functional class of road segment is Minor Arterial, 0-otherwise)	0.4451	2.54
Over-dispersion Parameter, Alpha	**1.0869**	**18.73**
Number of observations	**1351**	
Log-likelihood at convergence	**–3364**	

TABLE 5.12
Negative binomial model for urban multi-lane roads predicting number of property damage crashes for 3 years.

Variable Description	Coefficient	*t*-statistic
Intercept	–7.3443	–11.17
Logarithm of segment length, in miles	0.8309	16.52
Logarithm of Annual Average Daily Traffic (AADT), in vehicles/day	1.0520	15.50
Lane width, in feet	–0.0205	–2.22
Shoulder width, in feet	–0.0160	–1.80
Border zone minimum 20 feet (1-if border zone is greater than or equal to 20 feet, 0-otherwise)	–0.1342	–1.59
Number of un-signalized 3-legged intersections per mile	0.0473	5.13
Number of un-signalized 4-legged intersections per mile	0.0552	4.75
Number of signalized 4-legged intersections per mile	0.1662	2.22
Principal Arterial indicator (1-if functional class of road segment is Principal Arterial, 0-otherwise)	0.3157	2.73
Minor Arterial indicator (1-if functional class of road segment is Minor Arterial, 0-otherwise)	0.5679	3.34
Over-dispersion Parameter, Alpha	**1.3789**	**23.80**
Number of observations	**1351**	
Log-likelihood at convergence	**–4668**	

For fatal/injury crashes, the only additional variables found to be significant were *Paved Shoulder indicator, Median Width minimum 20 feet*, and *Border Zone minimum 50 feet.* All these variables have a negative coefficient, which implies that presence of a paved shoulder, median width greater than 20 feet, and border zone greater than 50 feet reduces fatal/injury crashes. Thus, the signs are logical since paved shoulder and border zone increase the recovery zone for vehicles, hence reducing crashes. Also, a larger median width implies that the opposite lanes are further apart, which shall reduce the probability of severe crashes. Thus, a median width greater than 20 feet reduces fatal/injury crashes on urban multi-lane roads.

For property damage crashes, the additional variables found significant are *Lane Width, Shoulder Width*, and *Border Zone minimum 20 feet indicator.* All the three variables have negative coefficients, implying that an increase in them reduces property damage crashes for urban multi-lane roads. The lane width missing indicator was found to be insignificant in this model, although the lane width variable was significant.

6. SAFETY COMPONENT

6.1 Base Crash Rate

The base crash rate is the expected number of crashes occurring on the current road segment. This can be obtained from base safety performance functions by using the known traffic volume and the segment length. The base safety performance functions represent an average road segment, since it is obtained by using the average values of the geometry features in the safety performance functions. The safety performance functions developed in the current study are summarized in Table 6.1 and Table 6.2, and the base safety performance functions derived from these equations are shown in Table 6.3. It should be noted that the crashes predicted by these safety performance functions are the number of crashes every 3 years. The list of variables used in the safety performance functions is shown in Table 6.4.

To calculate the existing number of crashes on a road segment with known geometry features, the safety performance functions can be used directly. Using the current values of the geometry elements, the safety performance function shall give the expected number of crashes on the road segment corresponding to each crash severity. However, if the information regarding the current geometry elements is not available, then the average value of the geometry elements corresponding to the road type gives us the closest estimate of the expected crash frequency. The base crash rate is often used as a good estimate of the existing safety conditions in the project evaluation process.

6.2 Crash Modification Factors

Crash modification factors for various geometry changes can be derived from safety performance functions. The coefficients (or the Betas, β) estimated in the negative binomial models are used to derive CMFs corresponding to different geometry changes given the estimated value of the changes are known. These coefficients are shown in Table 6.5 for rural roads and Table 6.6 for urban roads. Coefficients estimated in the current models and those obtained from previous models are shown in these tables. These coefficients can be used to derive CMFs for desired geometry changes. A positive coefficient indicates an increase in the number of expected crashes, while a negative coefficient indicates a reduction in the number of expected crashes, thus corresponding to a positive geometry change.

Using equation 5.5, CMFs can be derived from the coefficients shown in Table 6.5 in the following manner:

$$\mathrm{CMF(FI)_k} = \exp[(\mathrm{b(FI)_k} \times \Delta \mathrm{x_k}] \quad (6.1)$$

$$\mathrm{CMF(PD)_k} = \exp[(\mathrm{b(PD)_k} \times \Delta \mathrm{x_k}] \quad (6.2)$$

Where,

$\mathrm{CMF(FI)_k}$ and $\mathrm{CMF(PD)_k}$ are the crash modification factors obtained for fatal/injury and property damage crashes corresponding to the k^{th} geometry improvement;

$\mathrm{b(FI)_k}$ and $\mathrm{b(PD)_k}$ are the coefficients corresponding to the k^{th} geometry improvement obtained from Table 6.5, and

$\Delta \mathrm{x_k}$ is the value of the change corresponding to the k^{th} geometry improvement.

Example: CMF for a Geometry Change.

Consider a geometry improvement of 2 feet applicable to the shoulder width (SW) of a rural multi-lane road. The CMF corresponding to this change can be obtained as follows:

From Table 6.5,

$$b(FI)_{SW} = -0.0412; b(PD)_{SW} = 0; \Delta x_k = +2$$

$$\Rightarrow CMF(FI)_{SW} = \exp(-0.0412 \times 2) = 0.92$$

***

Specific CMFs can be derived for geometry changes represented by binary variables in the SPFs developed. CMFs are also available from various other studies corresponding to specific geometry improvements. Parameters used to determine these specific CMFs are shown in Table 6.7 for rural and urban roads, respectively. The parameters shown are essentially the Crash Reduction Factors (CRF) for the geometry changes. The CMF can be derived from these tables in the following manner:

$$\mathrm{CMF(FI)_k} = 1 - \mathrm{b(FI)_k} \quad (6.3)$$

$$\mathrm{CMF(PD)_k} = 1 - \mathrm{b(PD)_k} \quad (6.4)$$

Where,

$CMF(FI)_k$ and $CMF(PD)_k$ are the crash modification factors obtained for fatal/injury and property damage

TABLE 6.1
Safety performance functions (SPF) developed for rural roads.

Crash Severity	Rural Two-Lane Roads
Fatal/Injury	$\mathrm{Length}^{0.9299} \times \mathrm{AADT}^{0.8165} \times \exp(-5.5700 - 0.0772 \times \mathrm{LW} - 1.1869 \times \mathrm{LW_{missing}} - 0.0279 \times \mathrm{SW} - 0.1780 \times \mathrm{BRDR_{min20}} + 0.0300 \times \mathrm{Unsig_{3leg}} + 0.0216 \times \mathrm{Unsig_{4leg}} + 0.3488 \times \mathrm{Arterial_{minor}} + 0.2708 \times \mathrm{Collector_{major}}$
Property Damage	$\mathrm{Length}^{0.9116} \times \mathrm{AADT}^{0.7843} \times \exp(-4.3598 - 0.0853 \times \mathrm{LW} - 1.2096 \times \mathrm{LW_{missing}} - 0.0559 \times \mathrm{ST_{Paved}} + 0.1306 \times \mathrm{BRDR_{min50}} + 0.0420 \times \mathrm{Unsig_{3leg}} + 0.0302 \times \mathrm{Unsig_{4leg}} + 0.4024 \times \mathrm{Arterial_{minor}} + 0.3439 \times \mathrm{Collector_{major}})$
Crash Severity	**Rural Multi-Lane Roads**
Fatal/Injury	$\mathrm{Length}^{0.8979} \times \mathrm{AADT}^{0.7885} \times \exp(-3.4477 - 0.2384 \times \mathrm{LW} - 2.9755 \times \mathrm{LW_{missing}} - 0.0412 \times \mathrm{SW} - 0.2104 \times \mathrm{BRDR_{min50}} + 0.1240 \times \mathrm{Unsig_{3leg}} + 0.0665 \times \mathrm{Unsig_{4leg}})$
Property Damage	$\mathrm{Length}^{0.9424} \times \mathrm{AADT}^{0.8409} \times \exp(-5.9705 - 0.0443 \times \mathrm{LSW} - 0.9659 \times \mathrm{CTL} + 0.1066 \times \mathrm{Unsig_{3leg}} + 0.0550 \times \mathrm{Unsig_{4leg}} - 0.2322 \times \mathrm{Arterial_{minor}} + 0.2538 \times \mathrm{Collector_{major}}$

Note: The crashes predicted are the number of crashes every 3 years. Variable description is provided in Table 6.4.

TABLE 6.2
Safety performance functions (SPF) developed for urban roads from 2009–2011 crash data.

Crash Severity	Urban Two-Lane Roads
Fatal/Injury	$Length^{0.8466} \times AADT^{0.9124} \times \exp(-7.920 - 0.4436 \times BRDR_{min50} - 0.1336 \times CRB + 0.3242 \times CTL + 0.0198 \times Unsig_{3leg} + 0.0196 \times Unsig_{4leg} + 0.4464 \times Arterial_{principal} + 0.3467 \times Arterial_{minor}$
Property Damage	$Length^{0.8199} \times AADT^{0.9100} \times \exp(-5.1322 - 0.0678 \times LW - 0.7190 \times LW_{missing} - 0.0176 \times SW - 0.7170 \times BRDR_{min50} - 0.1920 \times CRB + 0.0233 \times Unsig_{3leg} + 0.0376 \times Unsig_{4leg} + 0.1901 \times Arterial_{principal} + 0.1625 \times Arterial_{minor})$
Crash Severity	**Urban Multi-Lane Roads**
Fatal/Injury	$Length^{0.8754} \times AADT^{0.9378} \times \exp(-7.4788 - 0.1112 \times ST_{Paved} - 0.1207 \times MW_{min20} - 0.2208 \times BRDR_{min50} + 0.0478 \times Unsig_{3leg} + 0.0420 \times Unsig_{4leg} + 0.1288 \times Sig_{4leg} + 0.3440 \times Arterial_{principal} + 0.4451 \times Arterial_{minor})$
Property Damage	$Length^{0.8309} \times AADT^{1.0520} \times \exp(-7.3443 - 0.0205 \times LW - 0.0160 \times SW - 0.1342 \times BRDR_{min20} + 0.0473 \times Unsig_{3leg} + 0.0552 \times Unsig_{4leg} + 0.1662 \times Sig_{4leg} - 0.3157 \times Arterial_{principal} + 0.5679 \times Arterial_{minor}$

Note: The crashes predicted are the number of crashes every 3 years. Variable description is provided in Table 6.4.

crashes corresponding to the k^{th} geometry improvement and

$b(FI)_k$ and $b(PD)_k$ are the parameters corresponding to the k^{th} geometry improvement obtained from Table 6.7.

The CMFs and specific CMFs obtained using these equations and parameters shown in the tables can be further utilized along with the base safety performance functions to estimate the number of crashes saved on a road segment due to a geometry improvement. This method is very useful in evaluating the safety impacts of the one or more geometry improvements in the road screening and project evaluation process which shall be discussed in Chapters 9 and 10.

6.3 CMFs for Partial Improvements

The equations used to derive crash modification factors assume that the geometry change is applicable to the entire road segment. It can be speculated that the effect of a geometry change for only a portion of the road segment shall be lesser in terms of the number of expected crashes saved as compared to the geometry change applicable to the entire road segment. Thus, Equations 6.1 and 6.4 should be used to calculate the CMF for a geometry improvement only when it is applicable to the entire road segment.

To calculate the CMF for the k^{th} geometry change, applicable only for a certain length l_k of the road segment which has a total length L, the equations required are derived below.

From Equation 5.2,

$$\text{Crash Modification Factor (CMF)} = \frac{\text{Expected crashes after change } (C_{after})}{\text{Expected crashes before change } (C_{before})} \quad (6.5)$$

The base crash frequency for a road segment is obtained using the applicable base safety performance function. The expected crashes on that road segment can be obtained by multiplying the base crashes (or base crash frequency) on the road segment with the crash modification factor. It should be noted that the

TABLE 6.3
Base safety performance functions for rural and urban roads from 2009–2011 crash data.

Road Type	Crash Severity	Base Safety Performance Function
Rural Two-Lane	Fatal/Injury	$4.5896 \times 10^{-3} \times Length^{0.9299} \times AADT^{0.8165}$
	Property Damage	$7.8284 \times 10^{-3} \times Length^{0.8199} \times AADT^{0.9100}$
Rural Multi-Lane	Fatal/Injury	$1.7716 \times 10^{-3} \times Length^{0.8979} \times AADT^{0.7885}$
	Property Damage	$2.8929 \times 10^{-3} \times Length^{0.8309} \times AADT^{1.0520}$
Urban Two-Lane	Fatal/Injury	$5.9665 \times 10^{-3} \times Length^{0.8466} \times AADT^{0.9124}$
	Property Damage	$3.7203 \times 10^{-3} \times Length^{0.8199} \times AADT^{0.9100}$
Urban Multi-Lane	Fatal/Injury	$9.3904 \times 10^{-3} \times Length^{0.8754} \times AADT^{0.9378}$
	Property Damage	$5.1887 \times 10^{-3} \times Length^{0.8309} \times AADT^{1.0520}$

Note: The crashes predicted are the number of crashes every 3 years. Variable description is provided in Table 6.4.

TABLE 6.4
Variable mnemonics and descriptions used in the safety performance functions.

Variable Mnemonic	Variable Description
Length	Segment Length, in miles
AADT	Annual Average Daily Traffic (AADT), in vehicles/day
LW	Lane width, in feet
LW_missing	Lane width missing indicator (1-if lane width for the road segment is not available, 0-otherwise)
SW	Shoulder width, in feet
LSW	Left/Inside Shoulder width, in feet
ST_{Paved}	Paved shoulder (1-if shoulder is paved, 0-otherwise)
MW_{min20}	Median width minimum 20 feet (1-if median width is greater than or equal to 20 feet, 0-otherwise)
$BRDR_{min20}$	Border zone minimum 20 feet (1-if border zone is greater than or equal to 20 feet, 0-otherwise)
$BRDR_{min50}$	Border zone minimum 50 feet (1-if border zone is greater than or equal to 50 feet, 0-otherwise)
CTL	Continuous turning lane indicator (1-if continuous turning lane is present in the road segment, 0-otherwise)
CRB	Curb on both sides indicator (1-if curb is present on both sides, 0-otherwise)
$Unsig_{3leg}$	Number of un-signalized 3-legged intersections per mile
$Unsig_{4leg}$	Number of un-signalized 4-legged intersections per mile
Sig_{4leg}	Number of signalized 4-legged intersections per mile
$Arterial_{principal}$	Principal Arterial indicator (1-if functional class of road segment is Principal Arterial, 0-otherwise)
$Arterial_{minor}$	Minor Arterial indicator (1-if functional class of road segment is Minor Arterial, 0-otherwise)
$Collector_{mojor}$	Major Collector indicator (1-if functional class of road segment is Major Collector, 0-otherwise)

base crash function and the CMF shall be the same for both the sub-segments.

$$\text{Expected crashes} = [\text{Constant} \times \text{Length}^{\gamma} \times \text{AADT}^{\delta}] \times \text{CMF} \tag{6.6}$$

So, for the road segment with length l_k,

$$(C_{before})_{l_k} = [\text{Constant} \times l_k{}^{\gamma} \times \text{AADT}^{\delta}] \tag{6.7}$$

$$(C_{after})_{l_k} = [\text{Constant} \times l_k{}^{\gamma} \times \text{AADT}^{\delta}] \times \text{CMF}_{l_k} \tag{6.8}$$

Similarly, for the remaining road segment with length $(L - l_k)$,

$$(C_{before})_{L-l_k} = [\text{Constant} \times (L-l_k)^{\gamma} \times \text{AADT}^{\delta}] \tag{6.9}$$

$$(C_{after})_{L-l_k} = [\text{Constant} \times (L-l_k)^{\gamma} \times \text{AADT}^{\delta}] \times \text{CMF}_{L-l_k} \tag{6.10}$$

Since the geometry improvement is not applicable for $(L-l_k)$, the CMF for this segment is,

$$\text{CMF}_{L-l_k} = 1 \tag{6.11}$$

Where, the subscripts used in the above equations denote the length of the segment for which it is applicable. Using the above equations and Equation 5.2, we may define the CMF for the segment with partial improvement as:

$$\text{CMF}_L = \frac{(C_{after})_{l_k} + (C_{after})_{L-l_k}}{(C_{before})_{l_k} + (C_{before})_{L-l_k}} \tag{6.12}$$

$$\Rightarrow \text{CMF}_L = \frac{\left([\text{Constant} \times l_k{}^{\gamma} \times \text{AADT}^{\delta}] \times \text{CMF}_{l_k}\right) + [\text{Constant} \times (L-l_k)^{\gamma} \times \text{AADT}^{\delta}]}{[\text{Constant} \times l_k{}^{\gamma} \times \text{AADT}^{\delta}] + [\text{Constant} \times (L-l_k)^{\gamma} \times \text{AADT}^{\delta}]} \tag{6.13}$$

TABLE 6.5
Coefficients to calculate crash modification factors for geometry improvements on rural roads.

	Rural Two-Lane		Rural Multi-Lane	
Improvement Description	**b(FI)[1]**	**b(PD)[2]**	**b(FI)**	**b(PD)**
Widen traffic lane by Δx feet	**–0.0772**	**–0.0853**	**–0.2384**	–0.1944
Reduce average degree of curve by Δx degrees	+0.0293	+0.0196	—	—
Widen left/inside shoulder by Δx feet	—	–0.2886	–0.0697	**–0.0443**
Widen right shoulder by Δx feet	**–0.0279**	–0.0233	**–0.0412**	—
Widen median by Δx feet	—	—	–0.0071	–0.0048
Reduce average grade by Δx percent	+0.0196	+0.0205	—	—
Increase number of unsignalized 3-legged intersections by Δx per mile	**+0.0300**	**+0.0420**	**+0.1240**	**+0.1066**
Increase number of unsignalized 4 or more than 4-legged intersections by Δx per mile	**+0.0216**	**+0.0302**	**+0.0665**	**+0.0550**

[1]b(FI) – parameter b (or coefficient β) for fatal/injury crashes.
[2]b(PD) – parameter b (or coefficient β) for property-damage crashes.
Note: Coefficients in **boldface** are obtained from safety performance functions developed in the current study.
Source: Tarko et al. (2007).

TABLE 6.6
Coefficients to calculate crash modification factors for geometry improvements on urban roads.

Improvement Description	Urban Two-Lane		Urban Multi-Lane	
	b(FI)	b(PD)	b(FI)	b(PD)
Widen traffic lane by Δx feet	–0.1527	**–0.0678**	–0.1521	**–0.0205**
Widen left/inside shoulder by Δx feet	—	–0.1503	–0.2050	—
Widen right shoulder by Δx feet	+0.0754	**–0.0176**	—	**–0.0160**
Widen median by Δx feet	—	—	—	–0.0023
Increase number of through lanes by Δx; (Δx can take integer values only)	—	—	–1.0950	–0.9490
Increase number of unsignalized 3-legged intersections by Δx per mile	**+0.0198**	**+0.0233**	**+0.0478**	**+0.0473**
Increase number of unsignalized 4 or more than 4-legged intersections by Δx per mile	**+0.0196**	**+0.0276**	**+0.0420**	**+0.0552**
Increase number of signalized 4 or more than 4-legged intersections by Δx per mile	**—**	**+0.1007**	**+0.1288**	**+0.1662**

[1]b(FI) – parameter b (or coefficient β) for fatal/injury crashes.
[2]b(PD) – parameter b (or coefficient β) for property-damage crashes.
Note: Coefficients in **boldface** are obtained from safety performance functions developed in the current study.
Source: Tarko et al. (2007).

Simplifying,

$$\Rightarrow CMF_L = \frac{[l_k{}^{\gamma} \times CMF_{l_k}] + (L - l_k)^{\gamma}}{l_k{}^{\gamma} + (L - l_k)^{\gamma}} \quad (6.14)$$

The estimated coefficient corresponding to the segment length variable is almost equal to one. This allows us to assume that, $\tilde{a} \approx 1$. Simplifying the above equation further,

$$\Rightarrow CMF_L = \frac{[l_k \times CMF_{l_k}] + (L - l_k)}{l_k + (L - l_k)} \quad (6.15)$$

$$\Rightarrow CMF_L = 1 - \frac{l_k}{L}(1 - CMF_{l_k}) \quad (6.16)$$

If the geometry improvement is applicable to more than one sub-segment of the road segment, then the above equations still hold. From Equation 6.15,

$$\Rightarrow CMF_L = \frac{\sum_i [l_i \times CMF_{l_i}] + (L - \sum_i l_i)}{\sum_i l_i + (L - \sum_i l_i)} \quad (6.17)$$

$$\Rightarrow CMF_L = 1 - \frac{\sum_i l_i}{L}(1 - CMF_{l_i}) \quad (6.18)$$

Where the geometry improvement is applicable to all segments which are a subset of *i*. It should be noted that the CMF applicable to each of these sub-segments is the same.

The Equation 6.16 derived above is to calculate the CMF corresponding to any geometry improvement applicable to partial lengths of the road segment. In

TABLE 6.7
Parameters for selected geometry improvements on rural roads.

Improvement Description	Rural Two Lane		Rural Multi Lane	
	b(FI)[4]	b(PD)[5]	b(FI)	b(PD)
Change sideslope from 1V:3H to 1V:4H[1]	0.42	0.29	0.42	0.29
Change sideslope from 1V:4H to 1V:6H[1]	0.22	0.24	0.22	0.24
Increase distance to roadside obstacle from 1 m to 5 m[1]	0.22	0.22	0.22	0.22
Increase distance to roadside obstacle from 5 m to 9 m[1]	0.44	0.44	0.44	0.44
Install new guardrail along embankment[1]	0.47	0.44	0.47	0.44
Change barrier along embankment to less rigid type[1]	0.32	—	0.32	—
Install median guardrails on divided highways[1]	0.43	—	0.43	—
Install TWLTL (two-way left-turn lane) on two-lane road[2]	0.26	0.20	0.26	0.20
Install Continuous Turning Lane	—	—	—	**0.62**
Pave unpaved shoulder[3]	—	—	—	0.41
Construct Paved Shoulder	—	**0.05**	—	—
Increase border zone width to greater than 20 feet	**0.16**	—	—	—
Increase border zone width to greater than 50 feet	—	**–0.14**	**0.19**	—
Introduce partial access control[3]	—	—	0.21	0.11

[1]Elvik and Vaa (2004).
[2]Lyon et al. (2008).
[3]Tarko et al. (2007).
[4]b(FI) – parameter b (or Crash Reduction Factors) for fatal/injury crashes.
[5]b(PD) – parameter b (or Crash Reduction Factors) for property-damage crashes.
Note: Parameters in **boldface** are obtained from safety performance functions developed in the current study.

TABLE 6.8
Parameters for selected geometry improvements on urban roads.

	Urban Two Lane		Urban Multi Lane	
Improvement Description	**b(FI)[3]**	**b(PD)[4]**	**b(FI)**	**b(PD)**
Construct curb on both sides	**0.13**	**0.17**	—	—
Install TWLTL (two-way left-turn lane) on two-lane road[1]	0.20	0.20	0.20	0.20
Install Continuous Turning Lane	**–0.38**	—	—	—
Increase median width to greater than 20 feet	—	—	**0.11**	—
Pave unpaved shoulder[2]	—	0.29	0.15	0.29
Construct paved shoulder[2]	0.54	0.57	—	—
Construct earth shoulder[2]	0.23	0.25	—	—
Construct outside shoulder[2]	—	—	0.41	0.49
Increase border zone width to greater than 20 feet	—	—	—	**0.13**
Increase border zone width to greater than 50 feet	**0.36**	**0.51**	**0.20**	—
Introduce partial access control[2]	0.66	0.53	0.26	0.31

[1]Lyon et al. (2008).
[2]Tarko et al. (2007).
[3]b(FI) – parameter b (or Crash Reduction Factors) for fatal/injury crashes.
[4]b(PD) – parameter b (or Crash Reduction Factors) for property-damage crashes.
Note: Parameters in **boldface** are obtained from safety performance functions developed in the current study.

conjunction with Equation 5.8, which shows the principle of combining the CMFs of various geometry improvements to obtain the effect of multiple geometry improvements, one or more of these is applicable to the partial lengths of the road segment.

Using Equation 6.16, the CMFs obtained in Equations 6.1 and 6.2 can be modified as:

$$\mathrm{CMF(FI)_k} = 1 - \frac{\mathrm{l_k}}{\mathrm{L}}[1 - \exp(\mathrm{b(FI)_k} \times \Delta \mathrm{x_k})] \quad (6.19)$$

$$\mathrm{CMF(PD)_k} = 1 - \frac{\mathrm{l_k}}{\mathrm{L}}[1 - \exp(\mathrm{b(PD)_k} \times \Delta \mathrm{x_k})] \quad (6.20)$$

Similarly, the CMFs obtained in Equations 6.3 and 6.4 can be modified as:

$$\mathrm{CMF(FI)_k} = 1 - \frac{\mathrm{l_k}}{\mathrm{L}}[\mathrm{b(FI)_k}] \quad (6.21)$$

$$\mathrm{CMF(PD)_k} = 1 - \frac{\mathrm{l_k}}{\mathrm{L}}[\mathrm{b(PD)_k}] \quad (6.22)$$

7. SPEED COMPONENT

7.1 Base Speed

Base speed refers to the average speed corresponding to the current conditions of the road segment. This is usually calculated using the speed equations and the information available regarding the geometry elements of the road segment. In the absence of this information, the average value of the missing geometry elements may be used to estimate the base speed on the road segment. Various speed models used for calculating the base speed and deriving the speed adjustments are shown in Table 7.1 (see Table 7.2 for the description of the variables); the average values of the variables used in these speed equations are listed in Table 7.3. Different speed models are applicable for two-lane and multi-lane highways, with separate equations utilized for segments and curves for different types of roads.

Once the base speed on the road segment is known, the speed adjustments derived for various geometry elements can be used to determine the effect of a geometry change in the road segment. Several speed adjustments can be combined together and used in conjunction with the base speed to calculate the improved speed on the road segment. The next two sections describe the method of deriving and combining speed adjustments from various sources. Further, the application of the base speed and speed adjustments to evaluate mobility benefit shall be presented in Chapters 9 and 10.

7.2 Speed Adjustments

Speed Adjustments (SA) can be defined as the difference between the speed after change and the speed before change. The change refers to an improvement in the geometry or other attributes of the road segment. Speed Adjustments are derived from speed equations or models predicting the average speed from known geometry features and attributes of the road. The functional form of the speed equations is linear in nature, as shown below.

$$\mathrm{a} = \mathrm{b_0} + \sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{b_i x_i} \quad (7.1)$$

Where,

a is the predicted speed; and

b_i is the coefficient of the i^{th} variable or geometry element x_i.

TABLE 7.1
Equations for predicting mean speed on two-lane and multi-lane roads by facility type.

	Rural Multi-Lane Road
Segments	$55.491 - 2.759 \times PSL_{50} + 0.430 \times GSW + 0.047 \times USW$
Curves	$51.112 - 2.050 \times DC + 7.251 \times SE - 0.620 \times SE^2$
	Rural Multi-Lane Road
Segments & Curves	$55.679 - 4.764 \times PSL_{50} - 4.942 \times PSL_{45} - 6.509 \times PSL_{40} + 1.281 \times 10^{-3} \times SD - 0.320 \times INTD + 0.034 \times ECLR + 0.056 \times ICLR$
	Sub-Urban Multi-Lane Road
Segments & Curves	$54.027 - 4.764 \times PSL_{50} - 4.942 \times PSL_{45} - 6.509 \times PSL_{40} + 1.281 \times 10^{-3} \times SD - 0.320 \times INTD + 0.034 \times ECLR + 0.056 \times ICLR$

Note: See Table 7.2 for variable descriptions.
Source: Tarko et al. (2004).

From the above functional form and using the definition of the speed adjustment, we can derive the formula in the following manner.

$$\text{Speed Adjustment (SA)} = \text{Speed After Change}(S_{after}) - \text{Speed Before Change } (S_{before}) \quad (7.2)$$

Assuming that the k^{th} geometry element is changed and the speed equation has n variables in the equation. Corresponding to the geometry change Δx_k for the -k^{th} geometry element:

$$S_{before} = b_0 + b_1x_1 + \ldots + b_kx_k + \ldots + b_nx_n \quad (7.3)$$

$$S_{after} = b_0 + b_1x_1 + \ldots + b_k(x_k + \Delta x_k) + \ldots + b_nx_n \quad (7.4)$$

From the above two equations, speed adjustment for the k^{th} geometry element is,

$$SA_k = b_k\Delta x_k \quad (7.5)$$

When more than one geometry element is changed, the combined effect of various geometry improvements (the Combined Speed Adjustment (CSA)) applicable to the same road segment can be obtained. The following equations show us that the speed adjustments for various geometry elements should be combined in an additive manner.

$$CSA = \sum_{i=1}^{k} b_i\Delta x_i \quad (7.6)$$

$$\Rightarrow CSA = \sum_{i=1}^{k} SA_i \quad (7.7)$$

The speed parameters obtained from the speed equations (shown in Table 7.1) and other sources are listed in Table 7.4. These parameters can be used to derive the speed adjustments using Equation 7.5 shown above.

TABLE 7.2
Variable descriptions corresponding to the variables used in the speed equations.

Variable Mnemonics	Variable Description
PSL_{50}	Posted Speed Limit of 50 miles/hr (equal to '1' if speed limit is 50 miles/hr, equal to '0' if speed limit is 55 miles/hr)
PSL_{45}	Posted Speed Limit of 45 miles/hr (equal to '1' if speed limit is 45 miles/hr, '0' otherwise)
PSL_{40}	Posted Speed Limit of 40 miles/hr (equal to '1' if speed limit is 40 miles/hr, '0' otherwise)
GSW	Gravel Shoulder Width , in feet
USW	Untreated Shoulder Width, in feet
DC	Degree of Curvature, in degrees
SE	Maximum Super-elevation, in percent
SD	Sight Distance, in feet
ECLR	External Clear Zone Distance, in feet
ICLR	Median Width, in feet
INTD	Intersection Density, in 1/mile

7.3 Speed Adjustments from Highway Capacity Manual

Speed adjustments applicable to free-flow conditions are provided in the 2010 Highway Capacity Manual

TABLE 7.3
Average values of geometric elements for calculating average speed by facility type.

Variable	Rural and Sub-Urban Two Lane	Rural and Sub-Urban Four Lane
Gravel Shoulder Width, in feet	2.39	2.19
Untreated Shoulder Width, in feet	28.48	25.12
Sight Distance, in feet	910.14	1391.80
Lane Width, in feet	11.63	—
Maximum Super-elevation Rate, in percent	6.44	3.40
Degree of Curvature, in degrees	7.07	—
Intersection Density, in 1/mile	—	3.80
Driveway Density, in 1/mile	—	—
External Clear Zone Distance, in feet	—	24.52
Median Width, in feet	—	26.86

TABLE 7.4
Parameters corresponding to various geometry changes in the speed models.

Variable Description	Four-Lane Highways
Change the intersection density by Δx per mile;	−0.279
Change the driveway density by Δx per mile;	−0.023
Construct paved shoulder ($\Delta x = 1$)	+1.732
Widen outside clear zone (clear zone width measured to a vertical obstruction) by Δx feet	+0.020
Widen median (no median barrier) by Δx feet	+0.046
Increase lateral clearance to a median barrier by Δx feet	+0.046
Increase total lateral clearance by Δx feet	+0.225[1]
Construct ditch at less than 20 feet from the outside edge of the traveled way	−1.193
Construct a new median or a TWLT lane	+1.600
Change the posted speed limit by Δx miles/hr	+0.175
Increase lane width from 11 ft to 12 ft	+1.900[2]
Increase lane width from 10 ft to 12 ft	+6.600[3]
Variable Description	**Two-Lane Highways**
Reduce average grade by Δx percent	−0.131
Increase in residential driveways by Δx in a mile.	−0.100[4]
Change in density of intersections by Δx int/mile	−0.100[5]
Increase lane width by Δx feet	+0.728[6]
Increase paved shoulder width by Δx feet	+0.698[6]
Increase total gravel shoulder width by Δx feet	+0.394
Increase total untreated shoulder width[7] by Δx feet	+0.054
Increase the average degree of horizontal curvature by Δx degrees	+2.541
Change the posted speed limit by Δx miles/hr	+0.552[8]

[1]Assuming that the initial and the final total lateral clearance lie between 4 ft and 12 ft. This value is obtained from the linear equation estimated using least squares method to predict Reduction in FFS value from Total Lateral Clearance using the data provided in Exhibit 14-9, Chapter 14 of Highway Capacity Manual 2010. The function for calculating the speed adjustment for any combination of initial and final total lateral clearance is shown below:

$$\text{Speed Adjustment} = \begin{cases} 2.72 + [0.225\ (L_f - L_o)] - 0.675 \times L_o, & \text{if } L_o < 4\text{ft and } L_f > 4\text{f} \\ 0.900 \times (L_f - L_o), & \text{if } L_o < 4\text{ft and } L_f < 4\text{f} \\ 0.225 \times (L_f - L_o), & \text{if } L_o > 4\text{ft and } L_f > 4\text{f} \end{cases}$$

In the above equation, L_o = Initial Total Lateral Clearance (in ft) before improvement and L_f=Final Total Lateral Clearance (in ft) after expected improvement. Also, it is assumed that the total lateral clearance is always increased after improvement, i.e., $L_f > L_o$

Total Lateral Clearance = Right-side lateral clearance + left-side lateral clearance. Total lateral clearance can have maximum value of 12 ft and right and left clearance can have maximum value of 6 ft each.

[2]Represents the speed reduction for increase in lane width from a value of "≤11-12" ft to "12" ft, obtained from Exhibit 14-10, Chapter 14, Highway Capacity Manual 2010.

[3]Represents the speed reduction for increase in lane width from a value of $\leq 10 - 11$ ft to 12 ft, obtained from Exhibit 14-10, Chapter 14, Highway Capacity Manual 2010.

[4]Considering equal impact of driveways and intersections on speed as per speed reductions provided in Highway Capacity Manual 2010. For a change in residential driveway density from less than 10 per mile to more than 10 per mile, the speed reduction obtained for Indiana is -1.0031 which is approximated to: -1.003/10 = -0.100.

[5]The speed parameter for Indiana due to a change in intersections by Δx per mile is −0.056, which shows a lower impact of intersection than residential driveways. Thus, the value of -0.100 is used considering equal impact of driveways and intersections on speed as per speed reductions provided in Highway Capacity Manual 2010. It should be noted that the -0.056 value is obtained when the speed adjustment -0.422 per intersection is converted to adjustment for density: $-0.422 \times 2 \times 350/5280$.

[6]This value is obtained from the equation of the best fitting 2-dimensional plane estimated using least squares method to predict Reduction in FFS value for various combinations of Shoulder Width and Lane Width, using the data provided in Exhibit 14-10, Chapter 14 of Highway Capacity Manual 2010. The estimated equation is:

Reduction in FFS (mph) = 12.691 – 0.698 x Shoulder Width (ft) – 0.728 x Lane Width (ft)

[7]Untreated shoulder is measured beyond the gravel shoulder. The gravel shoulder width should be measured from the edge of the pavement whereas the untreated shoulder width should be measured from the edge of the gravel shoulder width.

[8]Adjustment of speed -2.759 corresponding to speed limit reduction from 55 to 50 miles/hr has been generalized for any speed limit change by Δx miles/hr as −2.759/-5 = +0.552.

Source: Tarko et al. (2004).

TABLE 7.5
Reduction in FFS for lane width.

Lane Width (ft)	Reduction in FFS (mi/h)
≥12	0.0
≥11–12	1.9
≥10–11	6.6

Source: Exhibit 14-10, Chapter 14, Highway Capacity Manual (TRB, 2010).

(HCM) for different types of roads (i.e., Multi-lane and Two-lane Highways). Keeping in mind the current scope of the study which applies to mostly rural and suburban regions, it is safe to assume that free-flow speeds closely resemble the average speeds in such regions due to the lack of prevalent congestion conditions. The use of adjustment factors (reduction in FFS) from the HCM to derive speed adjustments applicable to rural and suburban road segments shall be discussed in the following section.

Speed adjustment for various geometry changes can be obtained from the FFS Models in HCM 2010 by calculating the change in *Reduction in FFS*. HCM 2010 provides tables containing *Reduction in FFS* value for various geometry elements (Table 7.5). Adjustments for the following geometry elements can be calculated using FFS reductions from HCM 2010.

- **For Multi-Lane Highways:** Lane width, total lateral clearance, median type, and access-point density.
- **For Two-Lane Highways:** Lane width, shoulder width, and access-point density.

To calculate the speed adjustment (SA) from *Reduction in FFS* from the aforementioned HCM models, the following steps should be used:

1. Obtain the *Reduction in FFS* value corresponding to the existing/initial condition r_i for each geometry element.

TABLE 7.6
Reduction in FFS for total lateral clearance.*

Total Lateral Clearance (ft)	Four-Lane Highways Reduction in FFS (mi/h)	Six-Lane Highways Reduction in FFS (mi/h)
12	0.0	0.0
10	0.4	0.4
8	0.9	0.9
6	1.3	1.3
4	1.8	1.7
2	3.6	2.8
0	5.4	3.9

*Total Lateral Clearance = Right-side lateral clearance + Left-side lateral clearance. Total lateral clearance can have maximum value of 12 ft and right and left clearance can have maximum value of 6 ft each.

Source: Exhibit 14-9, Chapter 14, Highway Capacity Manual (TRB, 2010).

TABLE 7.7
Reduction in FFS for median type.

Median Type	Reduction in FFS (mi/h)
Undivided	1.6
TWLTL	0.0
Divided	0.0

TWLTL = Two-way left-turn lane.

Source: Exhibit 14-10, Chapter 14, Highway Capacity Manual (TRB, 2010).

2. Obtain the *Reduction in FFS* value corresponding to the improved/final condition r_f for each geometry element.
3. The speed adjustment corresponding to the improvement in the k^{th} geometry element is then calculated using the following equation:

$$SA_k = -(r_f - r_i) \quad (7.8)$$

4. The combined speed adjustment (CSA) can be further calculated by summing up the speed adjustments obtained from the above equation and other speed adjustment values obtained from Table 7.4.

7.3.1 Tables: Reduction in FFS Value for Multi-Lane Highways

The reduction in FFS values provided in HCM 2010 for multi-lane highways are shown in this section. The reduction in FFS values corresponding to Lane Width is shown in Table 7.5, Total Lateral Clearance is shown in Table 7.6, Median Type is shown in Table 7.7, and access point density is shown in Table 7.8.

The speed adjustments derived from these values have been shown in Table 7.4. In order to simplify the usage of these tables, linear regression models have been estimated corresponding to the reduction in FFS values for Total Lateral Clearance and Access Point Density. This allows us to use an approximated single parameter predicting the change in speed corresponding to a unit change in the geometry element.

TABLE 7.8
Reduction in FFS for access point density.*

Access Point Density (access points/mi)	Reduction in FFS (mi/h)
0	0.0
10	2.5
20	5.0
30	7.5
≥40	10.0

*Access Point Density is calculated by dividing the total number of access points (Driveways + Unsignalized Intersections) on right side of the highway segment in the direction of travel, divided by the segment length. Source: Exhibit 14-10, Chapter 14, Highway Capacity Manual (TRB, 2010).

TABLE 7.9
Reduction in FFS for lane width and shoulder width combination.

	Shoulder Width (ft)			
Lane Width (ft)	≥0<2	≥2<4	≥4<6	≥6
≥9<10	6.4	4.8	3.5	2.2
≥10<11	5.3	3.7	2.4	1.1
≥11<12	4.7	3.0	1.7	0.4
≥12	4.2	2.6	1.3	0.0

Source: Exhibit 15-7, Chapter 15, Highway Capacity Manual (TRB, 2010).

7.3.2 Tables: Reduction in FFS Value for Two-Lane Highways

The following section provides the reduction in FFS values applicable to two-lane highways. The effect of different lane width and shoulder width combinations is shown in Table 7.9. In order to simplify the usage of this table, a linear regression model in two variables was estimated from the values provided in this table. The coefficients estimated provided an approximation of the effect of lane width and shoulder width, which are shown in Table 7.4. However, the values provided in Table 7.9 can be used directly to calculate the speed adjustment for a change in lane and shoulder width combination. Similarly, the effect of access point density is shown in Table 7.10. Table 7.10 is simplified by estimating the single variable linear regression model and shown in Table 7.4. Again, the table can be used directly to obtain the speed adjustment using Equation 7.7. The use of these tables is demonstrated with the help of an example that follows.

Example: Speed Adjustments from HCM.

Calculate the speed adjustment applicable for a two-lane highway segment for the following geometry improvements: Shoulder width increased from 1.5 feet to 4.5 feet; Lane width increased from 10 feet to 11 feet; Access point density reduced from 15 to 10 per mile.

From Table 7.9, the reduction in FFS values for initial and final conditions are obtained as: r_i = 5.3 mi/hr and r_f = 1.7 mi/hr. The speed adjustment for the change in shoulder width and lane width combination is calculated as:

$$SA_1 = -(r_f - r_i) = -(1.7 - 5.3) = 3.6 \text{mi/hr}.$$

TABLE 7.10
Reduction in FFS for access point density.*

Access Point Density (access points/mi)	Reduction in FFS (mi/h)
0	0.0
10	2.5
20	5.0
30	7.5
40	10.0

*Access Point Density is calculated by dividing the total number of access points (Driveways + Unsignalized Intersections) on **both sides** of the roadway segment divided by the segment length.

Source: Exhibit 15-8, Chapter 15, Highway Capacity Manual (TRB, 2010).

From Table 7.10, the reduction in FFS corresponding to 15 access points per mile can be calculated by interpolating the reduction in FFS between 10 and 20 access points/mile. This gives the initial reduction value, r_i = 3.8 mi/hr, and the final reduction value, r_f = 2.5 mi/hr. Speed adjustment for change in access point density is given by:

$$SA_2 = -(r_f - r_i) = -(2.5 - 3.8) = 1.3 \text{mi/hr}.$$

7.4 Speed Adjustments for Partial Improvements

The speed adjustment derived in Equation 7.5 assumes that it is applicable for the entire road segment. If the road segment has a partial geometry improvement which is applicable only to a certain sub-segment, then the speed adjustment obtained would be different. It can be said intuitively that the effect of a partial geometry improvement shall be lower than the effect of a full geometry improvement (i.e., applicable to the entire road segment).

The speed adjustment for a partial geometry improvement which is applicable only to a certain length l_k of the road segment with length L is derived in the following manner.

Using the definition of SA from Equation 7.1:

$$\text{Speed}_{\text{after}} = SA + \text{Speed}_{\text{before}} \quad (7.9)$$

The base average speed on the road segment ($\text{Speed}_{\text{before}}$), traffic volume (AADT), and the geometry change (Δx_k) for the k^{th} geometry element remain the same for the entire road segment. The travel time (t) on the entire segment can be obtained as the sum of the travel times on the sub-segment with the geometry improvement and the sub-segment without the geometry improvement.

$$t = t_{l_k} + t_{L-l_k} \quad (7.10)$$

Similarly, the change in the travel time on the entire segment can be used to obtain the speed adjustment applicable for the entire road segment.

$$\Delta t = \Delta t_{l_k} + \Delta t_{L-l_k} \quad (7.11)$$

Since there is no change in the speed over the sub-segment without any geometry improvement:

$$\Delta t_{L-l_k} = 0 \quad (7.12)$$

The subscripts in the above equations represent the length of the segment for which it is applicable.

The change in travel time for the entire segment is equal to the change in the travel time for the sub-segment with geometry improvement. However, the speed adjustment for the entire segment should reflect the effect of the partial geometry improvement.

$$\Delta t = L \times AADT \times \left(\frac{1}{S_{before}} - \frac{1}{S_{before} + SA_L}\right) \quad (7.13)$$

$$\Delta t_{l_k} = l_k \times AADT \times \left(\frac{1}{S_{before}} - \frac{1}{S_{before} + SA_{l_k}}\right) \quad (7.14)$$

From the above two equations:

$$L \times AADT \times \left(\frac{1}{S_{before}} - \frac{1}{S_{before} + SA_L}\right) = l_k \times AADT \times \left(\frac{1}{S_{before}} - \frac{1}{S_{before} + SA_{l_k}}\right) \quad (7.15)$$

$$\Rightarrow L \times \left(\frac{1}{S_{before}} - \frac{1}{S_{before} + SA_L}\right) = l_k \times \left(\frac{1}{S_{before}} - \frac{1}{S_{before} + SA_{l_k}}\right) \quad (7.16)$$

$$\Rightarrow \frac{1}{S_{before}} \times (L - l_k) + \frac{1}{S_{before} + SA_{l_k}} \times l_k = \frac{1}{S_{before} + SA_L} \times L \quad (7.17)$$

Simplifying the above equation:

$$SA_L = \frac{l_k \times S_{before} \times SA_{l_k}}{[S_{before} \times L] - [SA_{l_k} \times (L - l_k)]} \quad (7.18)$$

$$\Rightarrow SA_L = \frac{\left(\frac{l_k}{L}\right) \times SA_{l_k}}{1 - \left[\frac{SA_{l_k}}{S_{before}} \times \frac{(L - l_k)}{L}\right]} \quad (7.19)$$

If we assume that the geometry improvement is applicable to a fairly larger portion of the road segment, then,

$$\left[\frac{SA_{l_k}}{S_{before}} \times \frac{(L - l_k)}{L}\right] \approx 0 \quad (7.20)$$

$$\Rightarrow SA_L = \left(\frac{l_k}{L}\right) \times SA_{l_k} \quad (7.21)$$

This result can be extended to a general case where the geometry improvement is applicable to several sub-segments of the segment in the following manner. Assume that *m* segments have the geometry improvement.

$$\Delta t = \sum_{i=1}^{m} \Delta t_{l_i} + \sum_{i=m+1}^{n} \Delta t_{L - l_i} \quad (7.22)$$

Since,

$$\sum_{i=m+1}^{n} \Delta t_{L - l_i} = 0 \quad (7.23)$$

$$\Rightarrow \Delta t = \sum_{i=1}^{m} \Delta t_{l_i} \quad (7.24)$$

$$\Rightarrow L \times \left(\frac{1}{S_{before}} - \frac{1}{S_{before} + SA_L}\right) = \sum_{i=1}^{m} l_i \times \left(\frac{1}{S_{before}} - \frac{1}{S_{before} + SA_{l_i}}\right) \quad (7.25)$$

Also, we know that the speed adjustment remains the same for all segments. Therefore,

$$SA_{l_i} = SA_l, \ \forall i \quad (7.26)$$

$$\Rightarrow L \times \left(\frac{1}{S_{before}} - \frac{1}{S_{before} + SA_L}\right) = \left(\frac{1}{S_{before}} - \frac{1}{S_{before} + SA_l}\right) \times \sum_{i=1}^{m} l_i \quad (7.27)$$

The above equation is reducible to Equation 7.15 using,

$$\sum_{i=1}^{m} l_i = l_k \quad (7.28)$$

Using the result obtained in Equation 7.4, the speed adjustment applicable to the entire segment is given as,

$$\Rightarrow SA_L = \left(\frac{l_k}{L}\right) \times b_k \times \Delta x_k \quad (7.29)$$

The speed adjustment derived in Equation 7.28 shows that the effect of a geometry improvement applies in the proportion of the length for which it is applicable. This is logical, since the absolute value of the speed adjustment estimated from the geometry change should be higher if it is applicable for a larger portion of the road segment.

8. STANDARDS FOR ROAD SCREENING

The desirable standards required for the road screening process are described in the current section. The overview of the road screening process was discussed in Section 4.2, and from Step b it can be seen that the minimum design standards corresponding to various geometry elements are one of the preliminary inputs required for the road screening process. The Indiana Design Manual (INDOT, 2013) provides the minimum and desirable standards for various geometry elements corresponding to different road types. The desirable standards are a more aggressive set of

TABLE 8.1
Design standards corresponding to relevant geometry elements for rural arterials.

Design Element		Rural Arterial—2 lanes			Rural Arterial—4 or More Lanes	
Design Year Traffic, AADT		**< 400**	**400 ≤ AADT < 2000**	**> 2000**	**Undivided**	**Divided**
Shoulder Width, in feet	Usable	6 ft	8 ft	11 ft	11 ft	Right: 11 ft Left: 4 ft
	Paved	4 ft	6 ft	10 ft	10 ft	Right: 10 ft Left: 4 ft
Median Width, in feet		N/A			0.0 ft	80 ft
Access Control		Partial Control/None			Partial Control/None	
Travel Lane Width, in feet		12 ft			12 ft	
Side Slope – Cut, (H:V)	Foreslope	6:1			6:1	
	Backslope	4:1 for 20 ft; 3:1 Max. to Top			4:1 for 20 ft; 3:1 Max. to Top	
Side Slope – Fill, (H:V)		6:1 to Clear Zone; 3:1 Max. to Toe			6:1 to Clear Zone; 3:1 Max. to Toe	
		Rural Arterial				
Design Speed, in miles/hr		**50 mph**	**55 mph**	**60 mph**	**70 mph**	
Maximum degree of curvature,[1] in degrees		7.65 deg	5.73 deg	4.44 deg	3.47 deg	
Average Grade,[2] in percent	Level	4%	4%	3%	3%	
	Rolling	5%	5%	4%	4%	

[1]The minimum radius values are converted and shown as maximum degree of curvature.
[2]Maximum grade is represented using average grade.
Source: Figure 53-2, Chapter 53, Indiana Design Manual (2013).

design standards as compared to the minimum requirements. This implies that a road segment which meets the desirable design standards shall exceed the minimum design standard requirements. The desirable standards corresponding to various road segments which are considered in the scope of this study are shown in Table 8.1. The Indiana Design Manual provides design criteria related to Design Controls, Cross-Sectional Elements, Bridges, and Alignment Elements. Separate sets of standards are provided for:

- Rural Arterial (2-lanes and 4 or more lanes)
- Rural Collector, State Route (2-lanes)
- Rural Collector, Local-Agency Route (2-lanes)
- Rural Local Roads (2-lanes)
- Urban Arterial (4 or more lanes)
- Urban Arterial (2-lanes)
- Urban Collector (By Type of Area: Suburban, Intermediate, and Built-Up)
- Urban Local Street (By Type of Area: Suburban, Intermediate, and Built-Up)

TABLE 8.2
Design standards corresponding to relevant geometry elements for rural collectors.

Design Element		Rural Collector, State Route—2 lanes			
Design Year Traffic, AADT		**< 400**	**400 ≤ AADT < 1500**	**1500 ≤ AADT < 2000**	**> 2000**
Travel Lane Width, in feet	Desirable	12 ft	12 ft	12 ft	12 ft
Shoulder Width, in feet	Usable	4 ft	6 ft	8 ft	10 ft
	Paved	2 ft	4 ft	6 ft	8 ft
Side Slope – Cut (H:V)	Foreslope	6:1			
	Backslope	4:1 for 20 ft; 3:1 Max. to Top			
Side Slope – Fill (H:V)		6:1 to Clear Zone			

Design Speed, in miles/hr		40 mph	45 mph	50 mph	55 mph	60 mph
Maximum degree of curvature,[1] in degrees		14.01 deg	9.72 deg	7.65 deg	5.73 deg	4.44 deg
Average Grade,[2] in percent	Level	7%	7%	6%	6%	5%
	Rolling	8%	8%	7%	7%	6%

[1]The minimum radius values are converted and shown as average degree of curvature.
[2]Maximum grade is represented using average grade.
Source: Figure 53-3, Chapter 53, Indiana Design Manual (INDOT, 2013).

TABLE 8.3
Design Standards corresponding to relevant geometry elements for urban arterials.

Design Element		Design Value (By Type of Area): Suburban	
		Urban Arterial, 2 Lanes	Urban Arterial, 4 or More Lanes
Access Control			Partial Control/None
Travel Lane Width, in feet	Curbed	12 ft	12 ft
	Uncurbed		
Paved Shoulder Width (Curbed), in feet	Right	12 ft	10 ft
	Left		4 ft
Curb Offset, in feet		2 ft	2 ft
Paved Shoulder Width (Uncurbed), in feet	Right	10 ft	10 ft
	Left		4 ft
Median Width (Depressed),[1] in feet		N/A	38 ft
Median Width, in feet	Raised Island	N/A	18 ft
	Flush/Corrugated		16 ft

Design Speed, in miles/hr		Urban Arterial				
		30 mph	35 mph	45 mph	50 mph	55 mph
Maximum Degree of Curvature,[2] in degrees	For e_{max}=4%	22.17 deg	13.67 deg	9.56 deg	7.65 deg	5.73 deg
	For e_{max}=6%	24.05 deg	14.73 deg	10.43 deg	7.65 deg	5.73 deg
Average Grade,[3] in percent	Level	8%	7%	6.5%	6%	5.5%
	Rolling	9%	8%	7.5%	7%	6.5%

[1]The depressed median width considered for urban arterial with 4 or more lanes is assumed to be the average of 26.5 ft and 50 ft.
[2]The minimum radius values are converted and shown as maximum degree of curvature.
[3]Maximum grade is represented using average grade.
Source: Figure 53-6 and 53-7, Chapter 53, Indiana Design Manual (INDOT, 2013).

For the rural roads, the design criteria for Design Controls, Cross-Sectional Elements, and Bridges depend on the design year traffic (AADT), whereas the design criteria for the Alignment Elements depend on the design speed. For urban roads, the design criteria for Design Controls, Cross-Sectional Elements, and Bridges depend on the type of area or design value. Since the current study uses safety and speed models which were

TABLE 8.4
Design Standards corresponding to relevant geometry elements for urban collectors.

Design Element		Design Value (By Type of Area): Suburban
		Urban Collector
Access Control		None
Travel Lane Width, in feet	Curbed Uncurbed	12 ft
Paved Shoulder Width (Curbed), in feet	Right Left	8 ft
Curb Offset, in feet		1 ft
Paved Shoulder Width (Uncurbed), in feet	Right Left	10 ft
Median Width, in feet	Raised Island	18 ft
	Flush/Corrugated	16 ft

Design Speed, in miles/hr		Urban Arterial			
		30 mph	35 mph	45 mph	50 mph
Maximum Degree of Curvature[1], in degrees	For e_{max}=4%	21.34 deg	13.35 deg	9.40 deg	7.54 deg
	For e_{max}=6%	23.07 deg	14.36 deg	10.25 deg	7.54 deg
Average Grade[2], in percent	Level	9%	9%	8%	7%
	Rolling	11%	10%	9%	8%

[1]The minimum radius values are converted and shown as maximum degree of curvature.
[2]Maximum grade is represented using average grade.
Source: Figure 53-8, Chapter 53, Indiana Design Manual (INDOT, 2013).

developed for rural and suburban road segments in Indiana, the urban design criteria corresponding to the suburban type of area is considered.

Several geometry elements present in these design standards are applicable for the road screening process, such as Access Control, Travel Lane Width, Shoulder Width, Median Width, Side-Slope, Minimum Radius, Maximum Grade, and Clear-Zone Width. The desirable standards corresponding to these geometry elements have been shown in Tables 8.1 to 8.4. Since the scope of the current study includes state administered roads, rural and urban local streets are excluded from the study. The information related to the design standards can be used only if the data corresponding to these geometry elements is available in the road inventory and there exists known crash modification factors and speed adjustments which can be used to quantify the deficiencies in these elements.

9. ROAD SCREENING

The road screening process is the first step for project identification in the asset management process. The steps involved in the road screening process were briefly discussed in Section 4.2 of Chapter 4. The road screening process can be used to identify the least adequate segments in the road network, which can be used for a more detailed project evaluation process to determine the most beneficial projects. The current section will discuss in detail the road screening process using various equations and tables that were discussed in previous chapters. Appropriate references to these tables and equations shall be made wherever required.

9.1 Scope of Road Screening

The scope of the road screening process should be identified based on the functional class of the road segments. If specific functional classes of roads are desired to be included in the road screening process, the road segments should be filtered using this criterion. In the absence of any specific functional class, all road segments in the desired road network shall be chosen. For the current study, only state administered roads are considered for Indiana. All interstates and local roads, both in the rural and urban system, are removed from the screening process.

9.2 Decision Criteria

The decision criteria required for the road screening primarily includes the minimum or desirable geometric design standards. These standards obtained from the Indiana Design Manual have been discussed in Chapter 8. Table 9.1 in this chapter show the desirable design standards for various geometry elements for different facilities. The user may also choose a customized set of standards, if required, for the screening process. The screening process depends largely on the standards provided as an input to calculate deficiencies of various geometry elements. As such, the output of the road screening process shall vary if the standards are changed.

TABLE 9.1
Average unit cost (in 2010 USD) of crashes per facility type.

	Crash Severity	
Facility Type	**Injury/Fatal Crashes**	**Property Damage Crashes**
Rural Two-Lane Roads	451,234	5,101
Rural Multi-Lane Roads	448,021	6,198
Urban Two-Lane Roads	368,754	7,063
Urban Multi-Lane Roads	287,207	7,210

9.3 Safety Benefit without Considering Increase in Lanes

After determining the scope and the desired geometric standards for the road screening process, the evaluation of the benefits can be performed. The two major types of benefits obtainable by performing geometry improvements to a road segment are the (1) Safety Benefit and (2) Mobility Benefit. The current section describes the process of evaluating safety benefits from possible geometry improvements for the process of road screening (considering the number of lanes in the road segment is not increased). It should be noted that only the evaluation of potential benefits is possible in the screening process. The evaluation of actual benefits is possible during project evaluation, when the estimated geometry improvements are known. Section 9.4 shows the steps for evaluating the safety benefits when an increase in the number of lanes is considered for the road segment. This is followed by the calculation of mobility benefits in Section 9.5.

The safety benefit for screening refers to the equivalent monetary benefits from crashes saved by improving a road segment to the desired standards. The safety benefits give us a measure of the existing geometric deficiencies corresponding to the road segment. Thus, higher safety benefits have higher deficiencies in the existing geometry of the road as compared to the desirable geometric design standards. The process of calculating these benefits can be shown in several sequential steps as follows.

STEP 9.3A Determine the Crash Modification Factors (CMFs) for Geometric Deficiencies

The crash modification factors for various geometry improvements can be used to calculate the crashes saved on the road segment due to these improvements. For the road screening process, the geometry improvements refer to improving the geometry of the road to meet the desirable standards. The geometry deficiencies in various elements should be calculated based on the desirable design standard chosen for the screening process.

The existing deficiency in a geometry element (Δx) is calculated as the difference between the existing condition and the desirable standard condition. Higher deficiency in the geometry element implies higher safety benefit from the geometry improvement. This is only true if the geometry improvement has a known safety benefit, (i.e., has a CMF less than 1). However, if the existing condition of a geometry element meets or exceeds the desirable standard, it is assumed that there exists no deficiency in that particular geometry element (i.e., $\Delta x = 0$). It is also assumed that all geometry improvements can be performed for all elements which have a non-zero geometric deficiency. It should be noted that the geometric deficiency can never be negative (i.e., $\Delta x \geq 0$), assuming a positive geometry change Δx decreases the expected number of crashes.

To calculate the CMF corresponding to a geometry deficiency, Equations 6.1 and 6.2 should be used, along with the values of the coefficients shown in Table 6.5. These equations are shown below:

$$CMF(FI)_k = \exp(b(FI)_k \times \Delta x_k) \tag{9.1}$$

$$CMF(PD)_k = \exp(b(PD)_k \times \Delta x_k) \tag{9.2}$$

Where,

$CMF(FI)_k$ is the fatal/injury crash modification factor corresponding to the deficiency in the geometry element k;

$b(FI)_k$ is the coefficient of fatal/injury crashes for geometry change k selected from Table 6.5;

$CMF(PD)_k$ is the property-damage crash modification factor corresponding to the deficiency in the geometry element k;

$b(PD)_k$ is the coefficient of property-damage crashes for geometry change k selected from Table 6.5;

Δx_k denotes the deficiency in geometry expressed in units specified in Table 6.5, corresponding to the applicable geometry change; and

L is the length of the road segment in miles.

STEP 9.3B Calculate the Combined Crash Modification Factor (CCMF) for each Road Segment

The CMF corresponding to all geometry deficiencies in a road segment can be calculated using the method described in the previous step. When there are deficiencies in several geometry elements, we obtain different CMFs corresponding to every deficient geometry element and for both crash severities. These CMFs can be combined to calculate a combined CMF (or CCMF) for the segment corresponding to each of the crash severities. To calculate the CCMF, Equation 5.9 can be used as shown below:

$$CCMF(FI) = CMF(FI)_1 \times CMF(FI)_2 \times CMF(FI)_3 \times \ldots \times CMF(FI)_n \tag{9.3}$$

$$CCMF(PD) = CMF(PD)_1 \times CMF(PD)_2 \times CMF(PD)_3 \times \ldots \times CMF(PD)_n \tag{9.4}$$

Where,

$CCMF(FI)$ is the combined fatal/injury crash modification factor;

$CCMF(FI)_k$ is the fatal/injury crash modification factor for the improvement corresponding to the k^{th} geometry deficiency;

$CCMF(PD)$ is the combined property-damage crash modification factor; and

$CCMF(PD)_k$ is the property-damage crash modification factor for the improvement corresponding to the k^{th} geometry deficiency.

STEP 9.3D Calculate the Crashes Saved on Each Road Segment

Using the CCMF obtained in Step 9.3B and the Base Crash Frequency (BCF) calculated with the safety performance functions found in Table 6.1, or using the base safety performance functions found in Table 6.3, calculate the number of crashes saved annually by improving the geometry of the road segment to the desired standard using the following equations:

$$\Delta C(FI)_i = BCF(FI)_i \times \left[1 - CCMF(FI)_i\right] \tag{9.5}$$

$$\Delta C(PD)_i = BCF(PD)_i \times \left[1 - CCMF(PD)_i\right] \tag{9.6}$$

Where,

$\Delta C(FI)_i$ is the number of fatal-injury crashes saved annually on the i^{th} segment by improving the geometry on this segment to the desirable standards;

$BCF(FI)_i$ is the base fatal-injury crash frequency calculated for the i^{th} segment;

$CCMF(FI)_i$ is the combined fatal-injury crash modification factor for the i^{th} segment;

$\Delta C(PD)_i$ is the number of property-damage crashes saved annually on the i^{th} segment;

$CCMF(PD)_i$ is the combined property-damage crash modification factor for the i^{th} segment by improving the geometry on this segment to the desirable standards; and

$BCF(PD)_i$ is the base property-damage crash frequency calculated for the i^{th} segment.

STEP 9.3D Calculate the Annual Safety Benefit for each Road Segment

The safety benefit for the i^{th} segment can be calculated by summing the safety benefit for all crash severities:

$$BS_i = [\Delta C(FI)_i \times CC(FI)] + [\Delta C(PD)_i \times CC(PD)] \quad (9.7)$$

Where,

BS_i is the annual safety benefit obtained by improving the geometry on the i^{th} segment to the desirable standards,

$\Delta C(FI)_i$ is the fatal/injury crashes saved annually for the i^{th} segment calculated in Step 9.3C,

CC(FI) is the unit crash cost of fatal/injury crashes,

$\Delta C(PD)_i$ is the property damage crashes saved annually for i^{th} segment calculated in Step 9.3C,

CC(PD) is the unit crash cost of property damage crashes taken from Table 9.1.

9.4 Safety Benefit Considering Increase in Lanes

The following steps are used to determine the safety benefit for a road segment in the screening process when an increase in the number of lanes is considered as a possible road improvement.

STEP 9.4A Calculate the Expected Crashes for Existing Conditions

The expected number of crashes (C_1) for the road segment (two-lane rural/urban road segment) with the existing deficient road geometry should be calculated using the safety performance functions for the two-lane roads provided in Table 6.1. The expected number of crashes for each crash severity can be calculated using these equations. The safety performance functions require information regarding the geometry elements and various other attributes of the road segments. If any of these geometry elements is not known for the road segment, then the average value of the geometry element can be used for the road type. The average values of various geometry features used in these equations are shown in Table 5.1 for rural and urban two-lane roads respectively.

STEP 9.4B Calculate the Expected Crashes after Geometry Improvements

The expected number of crashes (C_2) for the road segment (multi-lane rural/urban) with improved geometry elements, including an increase in the number of lanes, should be calculated using the safety performance functions for multi-lane roads in Table 6.1. The average values of the geometry features provided in Table 5.2 (corresponding to rural and urban multi-lane roads) can be used in the safety performance functions if needed.

STEP 9.4C Calculate Crashes Saved on the Segment

The crashes saved on the segment due to the increase in the number of lanes and the resulting new geometry of the road segment can be obtained using the following equations:

$$\Delta C(FI)_i = C_1(FI)_i - C_2(FI)_i \quad (9.8)$$

$$\Delta C(PD)_i = C_1(PD)_i - C_2(PD)_i \quad (9.9)$$

Where,

$\Delta C(FI)_i$ is the number of fatal-injury crashes saved annually on the i^{th} segment;

$C_1(FI)_i$ is the fatal-injury crashes predicted for existing conditions on the i^{th} segment of the road using equations for two-lane roads shown in Table 6.1;

$C_2(FI)_i$ is the fatal-injury crashes predicted for improved conditions on the i^{th} segment of the road using equations for multi-lane roads shown in Table 6.1;

$\Delta C(PD)_i$ is the number of property-damage crashes saved annually on the i^{th} segment,

$C_1(PD)_i$ is the property-damage crashes predicted for existing conditions on the i^{th} segment of the road using equations for two-lane roads shown in Table 6.1; and

$C_2(PD)_i$ is the property-damage crashes predicted for improved conditions on the i^{th} segment of the road using equations for multi-lane roads shown in Table 6.1.

STEP 9.4D Calculate the Annual Safety Benefit for Each Segment

The annual safety benefit for each segment can be obtained using the calculated number of crashes saved for each crash severity from Equations 9.8 and 9.9. Use Equation 9.7 and crash cost values from Table 9.1 to obtain the annual safety benefit for the segment.

9.5 Mobility Benefit without Considering an Increase in Lanes

The mobility benefit is the monetary equivalent of the travel time savings from an increase in average speed due to the geometry improvements on a road segment. The speed equations and the speed adjustments relevant to the current study have been discussed in Chapter 7. The speed equations predict the average speed based on the geometry features and other attributes of the road segments, whereas the speed adjustments show the effect of a geometry change on the average speed in the road segment.

The current section describes the steps for calculating the travel time savings on a road segment due to geometry improvements. These steps are applicable for road segments for which the number of lanes is not increased. Section 9.6 describes the steps for calculating the travel time savings if the number of lanes is increased.

STEP 9.5A Determine the Speed Adjustments (SAs) for Geometric Deficiencies

The speed adjustments for various geometry improvements can be used to calculate the increased average speed on the road segment. The speed adjustment depends on the speed parameter shown in Table 7.4 and the deficiency in the geometry element (Δx). We assume that the geometry improvements can be carried out corresponding to the geometry deficiencies that exist in the road segment. The deficiencies are calculated with respect to the chosen geometric design standards.

The following equation has been derived in Section 7.2 and should be used to calculate the speed adjustment:

$$SA_k = b_k \times \Delta x_k \quad (9.10)$$

Where,

SA_k is the speed adjustment corresponding to the deficiency in the k^{th} geometry element;

b_k is the speed parameter for the geometry improvement k selected from Table 7.4; and

Δx_k is the deficiency in the k^{th} geometry element.

STEP 9.5B Calculate the Combined Speed Adjustment (CSA) for each Road Segment

Speed adjustments obtained for different geometry deficiencies for a road segment should be combined to obtain the combined speed adjustment. The equation for calculating the combined speed adjustment has been derived and discussed in Section 7.2 and is shown below:

$$CSA = SA_1 + SA_2 + SA_3 + \ldots + SA_n \quad (9.11)$$

Where,

CSA is the combined speed adjustment due to the geometry improvements corresponding to various deficiencies existing in the road segment; and

SA_k is the speed adjustment corresponding to the deficiency in the k^{th} geometry element, considering n geometry elements exist with non-zero deficiencies.

STEP 9.5C Calculate the Base Average Speed (BAS) on Each Segment

The base average speed on a road segment can be obtained using the speed equations shown in Table 7.1. Different equations are applicable for straight segments and curves for two-lane and multi-lane highways. These equations may be used, along with the average values of various geometry elements shown in Table 7.3, wherever the actual information for the road segment is not available.

To simplify the calculations for obtaining base average speed, the average speed on straight and curved segments can be assumed to be equal to the posted or legal speed limit (SL) with some adjustments. It is assumed that an adjustment of 5 miles/hr gives a good estimate of the average speed. This is shown in the following equation:

$$BAS = SL + 5\text{miles/hr} \quad (9.12)$$

STEP 9.5D Calculate the Time Saved on Each Segment

The geometry improvements result in speed adjustments which increase the average speed on the segment. The travel time saved due to the increase in the average speed can be calculated using the following equation:

$$T_i = \left(\frac{L_i}{BAS_i} - \frac{L_i}{BAS_i + CSA_i}\right) \times AADT_i \times 365 \quad (9.13)$$

Where,

ΔT_i is the travel time saved on the i^{th} segment;

L_i is the length of the i^{th} segment;

CSA_i is the combined speed adjustment for the i^{th} segment;

BAS_i is the base average speed for the i^{th} segment before any geometry improvement; and

$AADT_i$ is the traffic volume in vehicles/day on the i^{th} segment.

STEP 9.5E Calculate the Annual Mobility Benefit for Each Segment

The annual mobility benefit is the monetary equivalent of the travel time savings calculated in the previous step. The travel time value (TV) gives us themonetary value of a unit travel time saved, which is equal to \$20/hr. This value is the average cost of one hour when travelling in a car or a light truck based on the results shown in Sinha and Labi (2007). The annual mobility benefit for a segment can be calculated using the following equation:

$$BM_i = \Delta T_i \times TV \quad (9.14)$$

Where,

BM_i is the mobility benefit for the i^{th} segment;

ΔT_i is the total times saved on segment i; and

TV is the time value when traveling ($/hour).

9.6 Mobility Benefit Considering an Increase in Lanes

The mobility benefit for road segments for which the number of lanes is increased as a geometry improvement can be calculated using the speed equations shown in Table 7.1. The method for calculating the mobility benefit for an increase in the number of lanes varies from the method when the increase in number of lanes is not considered because there is no single speed adjustment which can account for this type of improvement.

STEP 9.6A Calculate the Base Average Speed for Existing Conditions

The base average speed for the existing conditions (BAS_1) on the two-lane rural/urban road segment with deficient geometry elements should be calculated using the relevant speed equations from Table 7.1. The average values of these geometry features for the speed equations should be used if the current information regarding any of these inputs is missing. The average values are shown in Table 7.3.

STEP 9.6B Calculate the Base Average Speed for Improved Conditions

The base average speed for the improved conditions (BAS_2) corresponding to the multi-lane rural/urban road segment with improved geometry elements should be calculated using the relevant speed equations from Table 7.1. As mentioned before, the average values of these geometry features should be used form Table 7.3 if needed.

STEP 9.6C Calculate the Time Saved on Each Segment

The travel time savings can be calculated in a similar manner as shown in the previous section. The following equation should be used to calculate the travel time saved on each segment:

$$T_i = \left(\frac{L_i}{(BAS_1)_i} - \frac{L_i}{(BAS_2)_i} \right) \times AADT_i \times 365 \qquad (9.15)$$

Where,

ΔT_i is the total times saved on segment i;

L_i is the length of the i^{th} segment;

$(BAS_1)_i$ is the base average speed on the i^{th} segment for the existing conditions (i.e., two-lane road before the increase in the number of lanes);

$(BAS_2)_i$ is the base average speed on the i^{th} segment for the improved conditions (i.e., multi-lane road); and

$AADT_i$ is the traffic volume in vehicles/day on the i^{th} segment.

STEP 9.6D Calculate the Annual Mobility Benefit for each Segment

The annual mobility benefit due to the travel time saved as a result of the increase in the number of lanes of the road segment can be calculated in a similar manner to that shown in STEP 9.5E. The following equation is also applicable here:

$$BM_i = \Delta T_i \times TV \qquad (9.16)$$

Where,

BM_i is the mobility benefit for the i^{th} segment;

ΔT_i is the total times saved on segment i; and

TV is the time value when traveling ($/hour).

9.7 Total Annual Benefit for Each Segment

The total annual benefit (B) for each segment due to geometry improvements performed on deficient geometry elements can be calculated by summing up the safety and the mobility benefits on that segment.

$$B_i = (BS_i + BM_i),\ \forall i \qquad (9.17)$$

Where,

B_i is the annual benefit due to geometry improvements on segment i;

BS_i is the annual safety benefit for segment i; and

BM_i is the mobility benefit for segment i.

The total monetary benefit expressed in the above equation should be converted to a normalized benefit. This can be calculated by dividing the total benefit on each segment by the segment length. Thus, the following equation gives the normalized benefit (NB) on each segment.

$$NB_i = \left(\frac{B_i}{L_i} \right),\ \forall i \qquad (9.18)$$

Where,

NB_i is the normalized annual benefit on segment i;

B_i is the total annual benefit on segment i; and

L_i is the length of segment i.

9.8 Screening Roads Based on Normalized Benefit

The normalized benefit for each road segment is obtained in Equation 9.18. This benefit reflects the total safety and mobility benefit that can be obtained by performing relevant geometry improvements corresponding to the existing deficient geometry elements. The normalized benefit is used for screening roads because the annual benefit calculated in Equation 9.17 shall depend largely on the length of the road segment. However, for longer road segments, the cost of geometry improvement escalates, which makes the benefits on segments with varying lengths incomparable. The normalized benefit thus, takes into account the length of the road segment and gives us the total annual benefit per unit length of the road segment due to geometry improvements. The normalized benefit can be used to sort the road segments to identify the least adequate road segment in the network.

10. PROJECT EVALUATION

The project evaluation process is used to identify and prioritize possible future projects on the basis of the evaluated benefits from the geometry improvements and the annualized capital cost in performing these improvements. The term "project" is used here to identify a set of geometry changes which can be performed on the road segments under consideration. The project evaluation process is similar to the previously discussed road screening process in many ways, but involves a more detailed analysis in terms of the geometry improvements and the resulting benefits. The project evaluation process differs mostly from road screening in the fact that it takes into account the annualized cost of the project.

A certain number of road segments identified by the road screening process as the least adequate segments may be used to develop projects for implementation using the project evaluation process. This process of filtering segments using road screening and using them for project evaluation was shown schematically earlier. However, it is not at all necessary to use segments selected through the screening process in the project evaluation method. The project evaluation method can be applied to any desired road segment(s) using the geometry improvements defined in the scope of the project.

The steps in the project evaluation process shall be discussed in this section. Several of these steps are very similar to those in the road screening process, with additional inputs and modified equations. The required steps are discussed briefly, with proper references to equations and tables shown in previous chapters.

10.1 Dividing the Road Section into Smaller Segments

The road section under consideration for a project should be divided into smaller segments based on the similarity in the geometry and traffic volume. Typically each segment begins and ends at an intersection (with any number of intersections within the segment). The segments need not be divided into smaller segments if partial improvements in geometry are expected within the segment. The methodology for project evaluation takes into account geometry improvements applicable only to a part of the segment. If the road segments selected from the road screening process are used for project evaluation, this step may be skipped.

10.2 Safety Benefit without Considering Increase in Lanes

Once the segments have been selected and divided properly, the next step is to evaluate the benefits from estimated geometry improvements. The safety benefit for segments without an increase in the number of lanes should be calculated using the steps described in this section. Section 10.3 describes the steps for calculating the safety benefit when the number of lanes is increased for the road segment.

STEP 10.2A Determine the Crash Modification Factors (CMFs) for Geometric Improvements

To obtain the safety benefit, the first step is to calculate the crash modification factors for all geometry improvements. The estimated geometry change (Δx) can be used, with known parameters corresponding to various geometry changes shown in Table 6.5 to calculate the CMFs using the following equations:

$$CMF(FI)_k = 1 - \frac{l_k}{L}[1 - \exp(b(FI)_k \times \Delta x_k)] \quad (10.1)$$

$$CMF(PD)_k = 1 - \frac{l_k}{L}[1 - \exp(b(PD)_k \times \Delta x_k)] \quad (10.2)$$

Where,

$CMF(FI)_k$ is the fatal/injury crash modification factor for the k^{th} geometry improvement;

$b(FI)_k$ is the coefficient of fatal/injury crashes for geometry change k selected from Table 6.5 and Table 6.6;

$CMF(PD)_k$ is the property-damage crash modification factor for the k^{th} geometry improvement;

$b(PD)_k$ is the coefficient of property-damage crashes for geometry change k selected from Table 6.5;

Δx_k denotes the estimated geometry change expressed in units specified in Table 6.5, corresponding to the k^{th} geometry change;

l_k is the length for which the geometry change k is applicable ($l_k \leq L$); and

L is the length of the road segment in miles.

It can be seen from Equations 10.1 and 10.2 that the partial geometry improvements are taken into account using the parameter l_k, which is the length of the improvement. Equations 10.1 and 10.2 have been derived in Section 6.3.

STEP 10.2B Calculate the Combined Crash Modification Factor (CCMF) for Each Road Segment

The CMFs corresponding to various geometry changes can be combined using the following equations:

$$CCMF(FI) = CMF(FI)_1 \times CMF(FI)_2 \times CMF(FI)_3 \times \ldots \times CMF(FI)_n \quad (10.3)$$

$$CCMF(PD) = CMF(PD)_1 \times CMF(PD)_2 \times CMF(PD)_3 \times \ldots \times CMF(PD)_n \quad (10.4)$$

Where,

CCMF(FI) is the combined fatal/injury crash modification factor;

$CCMF(FI)_k$ is the combined fatal/injury crash modification factor for the estimated geometry improvements;

CCMF(PD) is the combined property-damage crash modification factor; and

$CCMF(PD)_k$ is the combined property-damage crash modification factor for the estimated geometry improvements.

STEP 10.2C Calculate the Crashes Saved on Each Road Segment

The next step is to calculate the crashes saved on each road segment due to the estimated geometry improvements in the road segment.

$$\Delta C(FI)_i = BCF(FI)_i \times \left[1 - CCMF(FI)_i\right] \quad (10.5)$$

$$\Delta C(PD)_i = BCF(PD)_i \times \left[1 - CCMF(PD)_i\right] \quad (10.6)$$

Where,

$\Delta C(FI)_i$ is the number of fatal-injury crashes saved annually on the i^{th} segment due to the geometry improvements;

$BCF(FI)_i$ is the base fatal-injury crash frequency calculated for the i^{th} segment;

$CCMF(FI)_i$ is the combined fatal-injury crash modification factor for the i^{th} segment;

$\Delta C(PD)_i$ is the number of property-damage crashes saved annually on the i^{th} segment;

$CCMF(PD)_i$ is the combined property-damage crash modification factor for the i^{th} segment due to the geometry improvements; and

$BCF(PD)_i$ is the base property-damage crash frequency calculated for the i^{th} segment.

STEP 10.2D Calculate the Annual Safety Benefit for Each Road Segment

The safety benefit for the i^{th} segment can be calculated by summing the safety benefit for all crash severities:

$$BS_i = \left[\Delta C(FI)_i \times CC(FI)\right] + \left[\Delta C(PD)_i \times CC(PD)\right] \quad (10.7)$$

Where,

BS_i is the annual safety benefit for the estimated geometry improvements on the i^{th} segment,

$\Delta C(FI)_i$ is the fatal/injury crashes saved annually for i^{th} segment calculated in Step 10.2C,

CC(FI) is the unit crash cost of fatal/injury crashes taken from Table 9.1;

$\Delta C(PD)_i$ is the property damage crashes saved annually for i^{th} segment calculated in Step 10.2C,

CC(PD) is the unit crash cost of property damage crashes taken from Table 9.1.

10.3 Safety Benefit Considering an Increase in Lanes

The following steps are used to determine the safety benefit for a road segment in the project evaluation process when an increase in the number of lanes is considered as a possible road improvement. The steps are very similar to the road screening process (Section 9.4) and are described very briefly in this section.

STEP 10.3A Calculate the Expected Crashes for Existing Conditions

The expected number of crashes (C_1) for the road segment (two-lane rural/urban road segment) with the existing geometry should be calculated using the SPFs for the two-lane roads provided in Table 6.2. The average values of various geometry features should be used form Table 5.1 if required.

STEP 10.3B Calculate the Expected Crashes after Geometry Improvements

The expected number of crashes (C_2) for the road segment (multi-lane rural/urban) with improved geometry elements, including an increase in the number of lanes, should be calculated using the SPFs for multi-lane roads shown in Table 6.1. Use average values if needed.

STEP 10.3C Calculate Crashes Saved on the Segment

The crashes saved on the segment can be calculated using:

$$\Delta C(FI)_i = C_1(FI)_i - C_2(FI)_i \quad (10.8)$$

$$\Delta C(PD)_i = C_1(PD)_i - C_2(PD)_i \quad (10.9)$$

Where,

$\Delta C(FI)_i$ is the number of fatal-injury crashes saved annually on the i^{th} segment;

$C_1(FI)_i$ is the fatal-injury crashes predicted for existing conditions on the i^{th} segment;

$C_2(FI)_i$ is the fatal-injury crashes predicted for improved conditions on the i^{th} segment;

$\Delta C(PD)_i$ is the number of property-damage crashes saved annually on the i^{th} segment,

$C_1(PD)_i$ is the property-damage crashes predicted for existing conditions on the i^{th} segment; and

$C_2(PD)_i$ is the property-damage crashes predicted for improved conditions on the i^{th} segment.

STEP 10.3D Calculate the Annual Safety Benefit for Each Segment

The annual safety benefit for each segment can be obtained using the calculated number of crashes saved for each crash severity from Equations 10.8 and 10.9. Use equation 10.7 and crash cost values from Table 9.1 to obtain the annual safety benefit for each segment.

10.4 Mobility Benefit without Considering an Increase in Lanes

The mobility benefit calculations for project evaluation are also similar to the road screening process except for the fact that project evaluation takes into account partial geometry improvement.

STEP 10.4A Determine the Speed Adjustments (SAs) for Geometric Deficiencies

The speed adjustment for estimated geometry improvements should be calculated using the following equation:

$$SA_L = \left(\frac{l_k}{L}\right) \times b_k \Delta x_k \quad (10.10)$$

Where,

SA_k is the speed adjustment corresponding to the k^{th} geometry change;

b_k is the speed parameter for the geometry change k selected from Table 7.4; and

Δx_k is the estimated change in the k^{th} geometry element;

l_k is the length for which the geometry change k is applicable ($l_k \leq L$); and

L is the length of the road segment in miles.

The difference in Equation 10.10 for project evaluation and Equation 9.10 for road screening occurs because the partial geometry changes are taken into account in project evaluation. It should be noted that Equation 10.10 has been derived in Section 7.4 assuming that the geometry improvement is applicable for a large portion of the road segment.

STEP 10.4B Calculate the Combined Speed Adjustment (CSA) for Each Road Segment

Speed adjustments obtained for different geometry deficiencies for a road segment should be combined using the following equation:

$$CSA = SA_1 + SA_2 + SA_3 + \ldots + SA_n \quad (10.11)$$

Where,

CSA is the combined speed adjustment due to the estimated geometry improvements; and

SA_k is the speed adjustment corresponding to the k^{th} geometry change.

STEP 10.4C Calculate the Base Average Speed (BAS) on Each Segment

The base average speed on a road segment can be obtained using the speed equations shown in Table 7.1. For simplicity, the average speed on straight and curved segments is assumed to be equal to the posted or legal speed limit (SL) with some adjustments, shown by the following equation:

$$BAS = SL + 5\text{miles/hr} \quad (10.12)$$

STEP 10.4D Calculate the Time Saved on Each Segment

The travel time saved due to the increase in the average speed can be calculated using the following equation:

$$T_i = \left(\frac{L_i}{BAS_i} - \frac{L_i}{BAS_i + CSA_i}\right) \times AADT_i \times 365 \quad (10.13)$$

Where,

ΔT_i is the travel time saved on the i^{th} segment;

L_i is the length of the i^{th} segment;

CSA_i is the combined speed adjustment for the i^{th} segment;

BAS_i is the base average speed for the i^{th} segment before any geometry improvement; and

$AADT_i$ is the traffic volume in vehicles/day on the i^{th} segment.

STEP 10.4E Calculate the Annual Mobility Benefit for Each Segment

Similar to the road screening process, the annual mobility benefit for a segment can be calculated using the following equation:

$$BM_i = \Delta T_i \times TV \quad (10.14)$$

Where,

BM_i is the mobility benefit for the i^{th} segment;

ΔT_i is the total times saved on segment *i*; and

TV is the time value when traveling ($/hour).

10.5 Mobility Benefit Considering an Increase in Lanes

The mobility benefit for road segments for which the number of lanes is increased as a geometry improvement can be calculated using the speed equations shown in Table 7.1. The steps are very similar to the ones described in Section 9.6 and are discussed briefly here.

STEP 10.5A Calculate the Base Average Speed for Existing Conditions

The base average speed for the existing conditions (*BAS_1*) on the two-lane rural/urban road segment before any geometry improvements should be calculated using the relevant speed equations from Table 7.1. The average values for various geometry elements shown in Table 7.3 should be used if needed.

STEP 10.5B Calculate the Base Average Speed for Improved Conditions

The base average speed for the improved conditions (*BAS_2*) corresponding to multi-lane rural/urban road segments with improved geometry elements should be calculated using the relevant speed equations from Table 7.1. Use average values from Table 7.3 if needed.

STEP 10.5C Calculate the Time Saved on Each Segment

The travel time saved on each segment due to the estimated geometry improvement should be calculated using the following equation:

$$T_i = \left(\frac{L_i}{(BAS_1)_i} - \frac{L_i}{(BAS_2)_i}\right) \times AADT_i \times 365 \quad (10.15)$$

Where,

ΔT_i is the total times saved on segment *i*;

L_i is the length of the i^{th} segment;

$(BAS_1)_i$ is the base average speed on the i^{th} segment for the existing conditions (i.e., two-lane road before an increase in the number of lanes);

$(BAS_2)_i$ is the base average speed on the i^{th} segment for the improved conditions (i.e., multi-lane road); and

$AADT_i$ is the traffic volume in vehicles/day on the i^{th} segment.

STEP 10.5D Calculate the Annual Mobility Benefit for Each Segment

The annual mobility benefit on each road segment can be calculated using the following equation:

$$BM_i = \Delta T_i \times TV \quad (10.16)$$

Where,

BM_i is the mobility benefit for the i^{th} segment;

ΔT_i is the total times saved on segment *i*; and

TV is the time value when traveling ($/hour).

10.6 Total Annual Benefit for Each Project

The total annual benefit for a project comprises of the summation of the total benefits for all segments lying in the scope of the project. Unlike the road screening process, a project may contain several road segments, and the total annual benefit for the project is calculated using the following equation:

$$B = \sum_{\forall i} (BS_i + BM_i) \quad (10.17)$$

Where,

B is the total annual benefit for the project due to geometry improvements;

BS_i is the annual safety benefit for segment *i*; and

BM_i is the mobility benefit for segment *i*.

10.7 Benefit-Cost Ratio for the Project

Once the total benefit for a project is calculated using the steps mentioned above, the Benefit-Cost Ratio (B/C Ratio) for the project needs to be calculated. The project capital cost is annualized and used to calculate the project B/C ratio as shown below:

$$C = PCC \times I \tag{10.18}$$

Where,

C is the annualized project capital cost in dollars;

PCC is the project capital cost; and

I is the interest rate; typically, $I = 0.04$.

The annualized project capital cost can be used to calculate the B/C Ratio using the following equation:

$$B/C = \frac{B}{PCC \times I} \tag{10.19}$$

10.8 Geometry B/C Score and Geometry Raw Score

The Geometry Raw Score is obtained by rescaling the B/C Ratio for the project to the 0-6 scale. In order to do this, a Ref B/C Score is needed, which is an expected or desired maximum value that the B/C Ratio can take for any project. In other words, it is a value selected by the INDOT asset management group that corresponds to the B/C ratio sufficiently high to fully satisfy decision-makers. Two alternatives are possible to calculate the Geometry Raw Score.

Alternative 1

The following re-scaling assigns points to any positive geometry benefit, even if the B/C ratio is less than 1. It makes sense if the cost C includes costs of project components other than the geometry improvements considered in the benefit estimation.

Geometry B/C Score

$$= \begin{cases} 0, & \text{if } B/C \leq 0, \\ 6 \times \frac{B/C}{RefB/C}, & \text{if } B/C \text{ is between 0 and Ref } B/C, \\ 6, & \text{if } B/C \text{ is} \geq \text{ Ref } B/C. \end{cases} \tag{10.20}$$

Alternative 2

The second alternative is that only geometry improvements with B/C ratio higher than 1 should have assigned points. Then, the following formula should be used (this time C should reflect only the part of the cost allocated to the geometry improvements considered in the benefit estimation):

Geometry B/C Score

$$= \begin{cases} 0, & \text{if } B/C \leq 1, \\ 6 \times \frac{B/C-1}{RefB/C}, & \text{if } B/C \text{ is between 1 and } RefB/C, \\ 6, & \text{if } B/\ C\text{is} \geq \text{Ref } B/C. \end{cases} \tag{10.21}$$

Finally, the Geometry Raw Score can be calculated by adding up to 4 points to the Geometry B/C Score. The Geometry Raw Score is on the 0-10 scale, which includes 0-6 points from Cross-Section and Alignment and Safety. The additional 0-4 points should be added based on the evaluation of the project with respect to Drainage and compliance with ADA.

$$Geometry\ Raw\ Score = Geometry\ B/C\ Score + [Drainage + ADA] \tag{10.22}$$

The Geometry Raw Score calculated using the steps described above is used as an input in Equation 2.1. The Geometry Raw Score evaluates the safety and mobility effects of various geometry improvements and integrates this into the road scoring process.

11. CONCLUSIONS AND FUTURE RESEARCH

11.1 Conclusions

The presented study developed a method of evaluating geometry adequacy for a project scoring application in the current INDOT asset management process. The proposed method is an improvement of the existing point-based method. It has been developed in two versions. The road screening version is a new development that allows INDOT to select candidate roads for improvement projects. The project evaluation version is an improved existing method. The road screening process narrows down or identifies road segments most suitable for a detailed project evaluation process. Various projects may be formed and evaluated on these road segments, which are identified as least adequate because of their existing geometry deficiencies. The project evaluation method, however, need not be preceded by the road screening process and can be used separately to evaluate future projects.

The proposed methodology is based on the evaluation of safety and mobility benefits due to expected geometry improvements. Several data sources have been used in the current study to obtain relevant safety equations, crash modification factors, speed equations, and speed adjustment factors that can be used for this evaluation process. To ensure that the method is relevant and up-to-date, new safety performance functions were developed from the crash records in Indiana for the period 2009–2011. These equations not only provide up-to-date information regarding crash modification factors for various geometry elements, but also include additional information such as intersection density classified into several categories, which was not available from previous research.

Safety performance functions were developed for rural two-lane, rural multi-lane, urban two-lane, and urban multi-lane roads corresponding to each crash severity (fatal/injury and property damage). Several parameters were identified from these models which affect the expected number of crashes for a road segment. For rural roads, segment length, traffic volume, lane width, shoulder width, border zone, number of unsignalized 3-legged intersections, and number of unsignalized 4-legged intersections were found significant in the models. For urban roads, curb indicator, continuous turning lane indicator, and number of signalized 4-legged intersections were the additional variables which were found to affect the expected number of crashes on a segment.

11.2 Implementation of the Methodology

The aim of the current research was to develop a point-based project scoring method which can be easily implemented and used by the roadway asset team of INDOT. The methodologies described in the study were integrated into an Excel-spreadsheet based tool that provides the estimated benefits from various improvements applicable to various road segments. The user needs to input only the applicable improvements and the estimated geometry changes corresponding to each improvement. The output obtained includes the safety and mobility benefits for these improvements, which can be further used to prioritize the projects.

The Excel-spreadsheet based tool was developed as one of the final outcomes of the JTRP research project "SPR-3640: *Performance Assessment Measure that Indicates Geometry Sufficiency of State Highways*."

11.3 Future Research

The safety performance functions and speed equations which have been used extensively in the current study are the backbone of the proposed methodology. The development of updated models using better statistical techniques shall provide a better estimation of the effect of various improvements on the expected number of crashes and the average speed in a road segment. For example, using a simultaneous equations approach for the safety model (to account for a common error term for crashes of different severities occurring on the same road segment) can result in better statistical models. Similarly, using a negative binomial model with random effects to account for spatial factors can result in better prediction of crashes.

The safety and speed models are used to derive CMFs and SAs that are also very critical to the current methodology. Several geometry improvements could not be accounted for in the current study because of the lack of knowledge of crash modification factors and speed adjustments corresponding to these changes. For example, separate evaluation methodologies have been adopted in the proposed road screening and project evaluation method for road segments where an increase in the number of lanes is considered as a geometry improvement. This is because there is a lack of knowledge of the effect of converting two-lane roads to multi-lane roads. In other words, there exists no single crash modification factor and speed adjustment which can take into account the effect of this geometry change. Had there been such a factor, both these methodologies could have been simplified to a large extent. Further, the effect of several factors which are classified under the categories "Drainage" and "Compliance with ADA" need to be accounted for using the current methodology in the future. The effects of various factors which fall in these categories (See Section 1.4) are currently not known, and hence could not be taken into account in the study.

Future research generating from the current study should focus heavily on obtaining better safety and speed models that can provide accurate factors for prediction of crashes and average speeds. There needs to be more research to develop better crash modification factors and speed adjustments, not only for a variety of geometry improvements, but also specific to various types of roads, crash severities, and state or geographic location, among other factors. The availability of such information can help the asset management method reflect the effect of changes more accurately, resulting in a better ranking of projects based on estimated improvements.

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APPENDIX: USER MANUAL FOR PROJECT EVALUATION AND ROAD SCREENING TOOL

INTRODUCTION

The Project Evaluation and Road Screening (PEARS) tool can assist with identifying roads with limited geometry adequacy and selecting the most cost-effective projects for implementation. Consequently, PEARS has two components:

1. Road Screening
2. Project Evaluation

The Road Screening component compares the geometry of road segments in a large road network with relevant design standards and calculates the benefits of bringing the geometry in line with these standards. The screening results list the benefit per mile for all segments of the screened road network, which can be useful for identifying the most promising candidates for road improvement projects.

The Project Evaluation component predicts the benefit to be generated by projects developed for the selected road segments based on the screening results. The evaluation results include the benefit-cost and the net benefit estimated based on the anticipated geometry improvements for these road segments.

This manual describes the steps necessary to install and use the Excel spreadsheet-based PEARS application. The reader should refer to the research report that explains the concepts on which the tool was developed.

OVERVIEW AND PRELIMINARY SETUP

The user should have access to Microsoft Excel 2007 or 2010 versions in order to run this application. Three files are provided to the user as shown in Table A.1.

After opening the Excel *Asset_Mngmt_Proj_Eval.xlsm* file, the user should enable Macros if "**Security Warning** Macros have been disabled" appears, as shown in Figure A.1. Clicking on the *Options* and then *Enable this content* buttons enables the macros.

TABLE A.1
PEARS files.

File	Description
Asset_Mngmt_Proj_Eval.xlsm	This file contains the program and the user interface.
Proj_Eval_Template.xlsx	This file facilitates the calculations. It is a read-only file and it contains formulae but not data.
AM_SegDB.csv	This file contains a segments database used for screening a road network (Indiana state roads in the provided set).

The Excel spreadsheet after PEARS is launched allows entering *Road Screening* or *Project Evaluation*. It also gives an option to exit the tool (Figure A.2). The Excel workbook initially contains only the *AM Tool* spreadsheet.

If the *Proj_Eval_Template.xlsx* file is not found, the program will ask the user to locate this file before entering the *Road Screening* or *Project Evaluation* modules.

ROAD SCREENING

Clicking on the *Road Screening* button displays the Excel road screening input worksheet (Figure A.3) and a road screening execution box (Figure A.4). These two windows can be moved by the user to convenient positions on the computer monitor.

Clicking on the *Load* button of the *Screening* execution box (Figure A.4) displays a *Load Files* window where the user can type the location of the file with the database for road screening or browse the computer to find this file (Figure A.5). The user also has an option of opening a file that includes a past screening input and results by entering this file in the lower entry field (Figure A.5). If both of the entry fields are completed, then the database file information in the upper entry field is ignored.

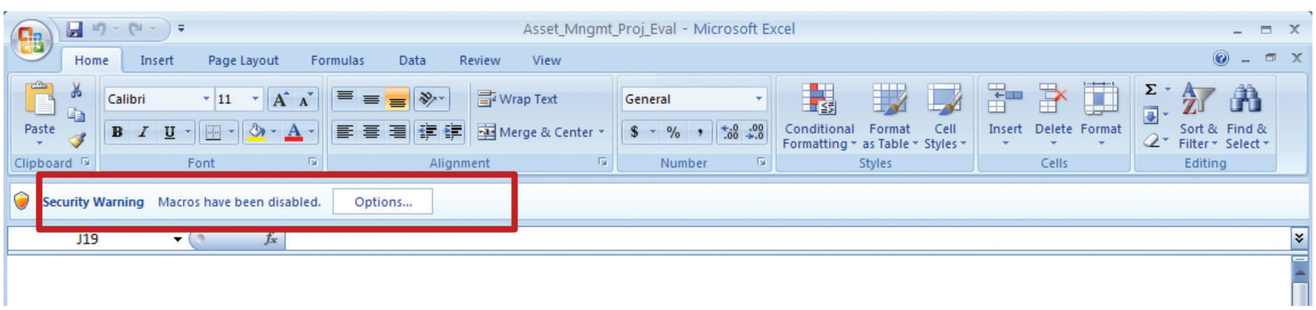


Figure A.1 Warning about disabled macros.

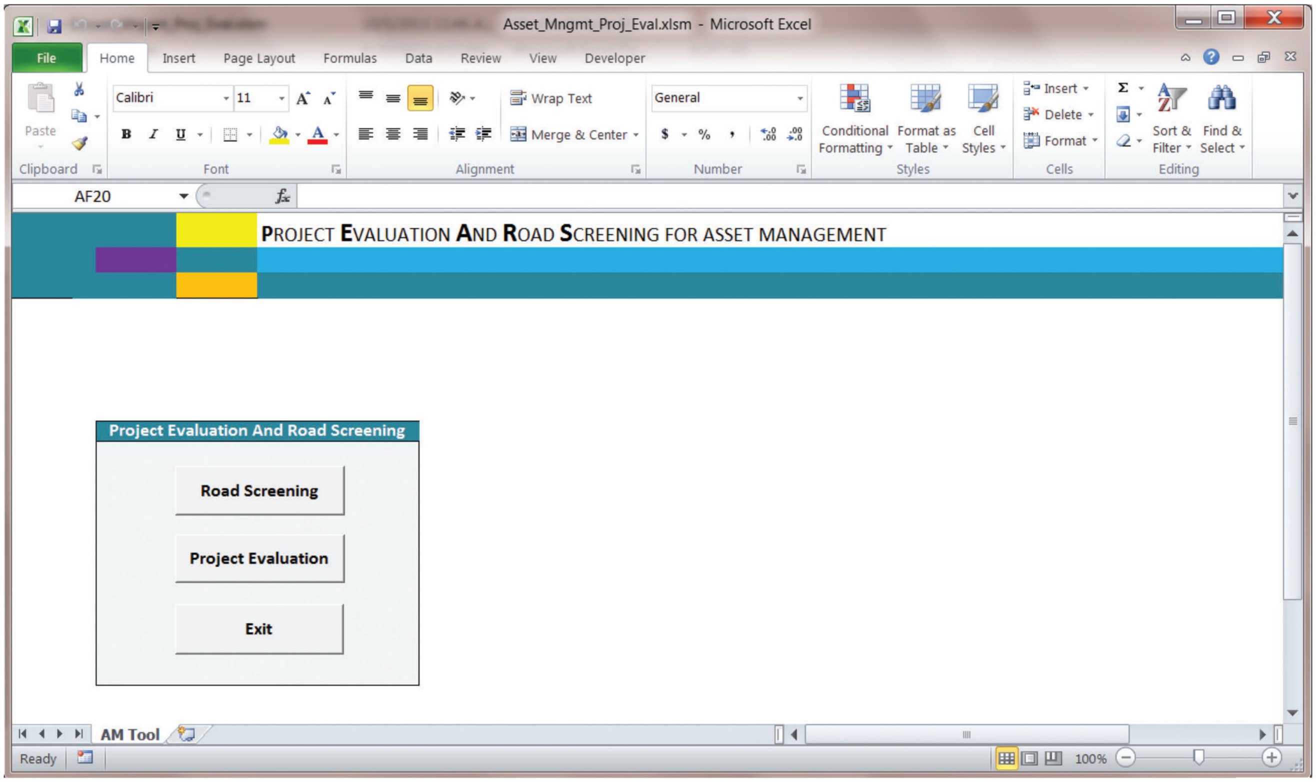
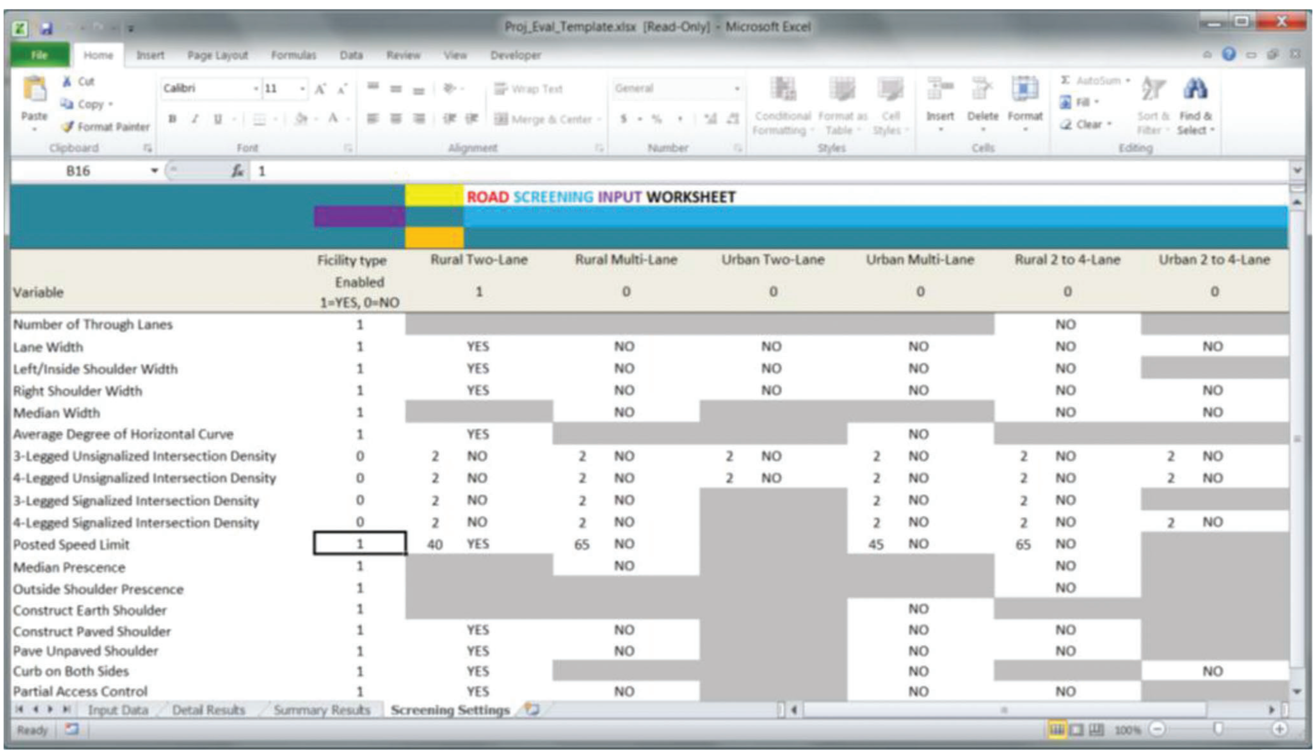


Figure A.2 First window of PEARS.



Variable	Ficility type Enabled 1=YES, 0=NO	Rural Two-Lane 1	Rural Multi-Lane 0	Urban Two-Lane 0	Urban Multi-Lane 0	Rural 2 to 4-Lane 0	Urban 2 to 4-Lane 0
Number of Through Lanes	1					NO	
Lane Width	1	YES	NO	NO	NO	NO	NO
Left/Inside Shoulder Width	1	YES	NO	NO	NO	NO	
Right Shoulder Width	1	YES	NO	NO	NO	NO	NO
Median Width	1		NO			NO	NO
Average Degree of Horizontal Curve	1	YES			NO		
3-Legged Unsignalized Intersection Density	0	2 NO	2 NO	2 NO	2 NO	2 NO	2 NO
4-Legged Unsignalized Intersection Density	0	2 NO	2 NO	2 NO	2 NO	2 NO	2 NO
3-Legged Signalized Intersection Density	0	2 NO	2 NO		2 NO	2 NO	
4-Legged Signalized Intersection Density	0	2 NO	2 NO		2 NO	2 NO	2 NO
Posted Speed Limit	1	40 YES	65 NO		45 NO	65 NO	
Median Prescence	1		NO			NO	
Outside Shoulder Prescence	1					NO	
Construct Earth Shoulder	1				NO		
Construct Paved Shoulder	1	YES	NO		NO	NO	
Pave Unpaved Shoulder	1	YES	NO		NO	NO	
Curb on Both Sides	1	YES			NO		NO
Partial Access Control	1	YES	NO		NO	NO	

Figure A.3 Screening settings worksheet.

Figure A.4 Road screening execution box.

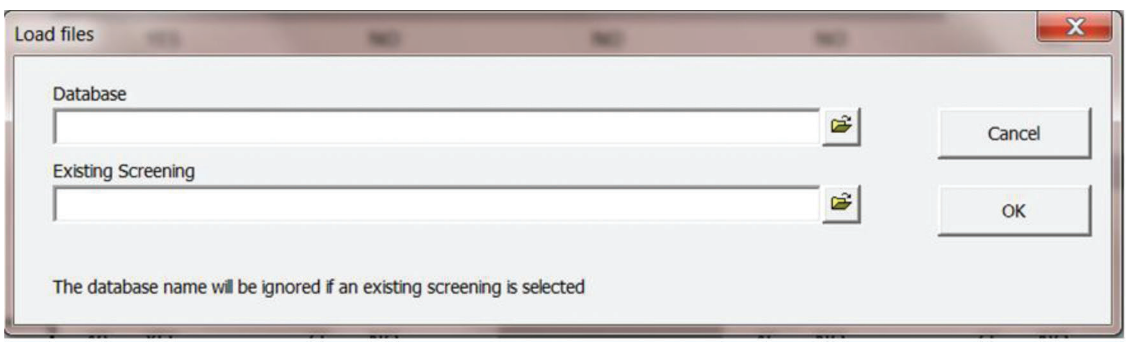


Figure A.5 Load files execution window.

After the database for new screening (or a file from a previous screening session) is loaded, the user has an opportunity to modify the settings in the road screening input worksheet (Figure A.3). There are two major cases of potential road improvements:

1. Upgrading the geometry of roads without adding new lanes (rural two-lane, rural multi-lane, urban two-lane, and urban multi-lane), and
2. Upgrading two-lane roads to four-lane roads (rural roads and urban roads).

The resulting six road improvement cases correspond to six screening cases. The user then includes the case in the screening by entering the number 1 in the top row of the *Screening Settings* worksheet (Figure A.3). The two-lane roads have two possible scenarios (adding lanes and not adding lanes). The user can compare the estimated benefits for the two alternative cases and select the more efficient one or limit the screening to only one case.

Due to the memory limit in versions of Excel earlier than 2010, it is recommended to run each screening case individually and then merge the lists and sort the combined list in a separate Excel file.

The *Screen Roads* button in the *Screening* execution box (Figure A.4) should be activated by now; clicking on this button launches the screening process. The screening may take several minutes. The progress is displayed at the bottom of the Excel screening input worksheet. The loading of the data is completed when a box appears on the screen containing information about the number of segments added (Figure A.6). The user should click OK to let the tool start the calculations and sort the segments. The progress is displayed in the Excel worksheet.

The screening results are stored in the *Summary Results* and *Detail Results* spreadsheets (Figure A.7). They are sorted by the benefit per mile. These results and the input settings can be saved by clicking on the *Save* or *Save As* buttons in the *Screening* execution box (Figure A.4). This action opens another entry window to allow the user to name the file and select the destination folder for saving the file (Figure A.8).

To end the screening session, the user should click the End button in the *Screening* execution box. The currently open windows and boxes are closed and the initial window is displayed (Figure A.2). This may happen after some delay, during which PEARS clears the memory and resets the workbooks to make them ready for the next calculation session.

In case the user forgets to save the current working file, the program will ask if he wants to save the results (Figure A.9).

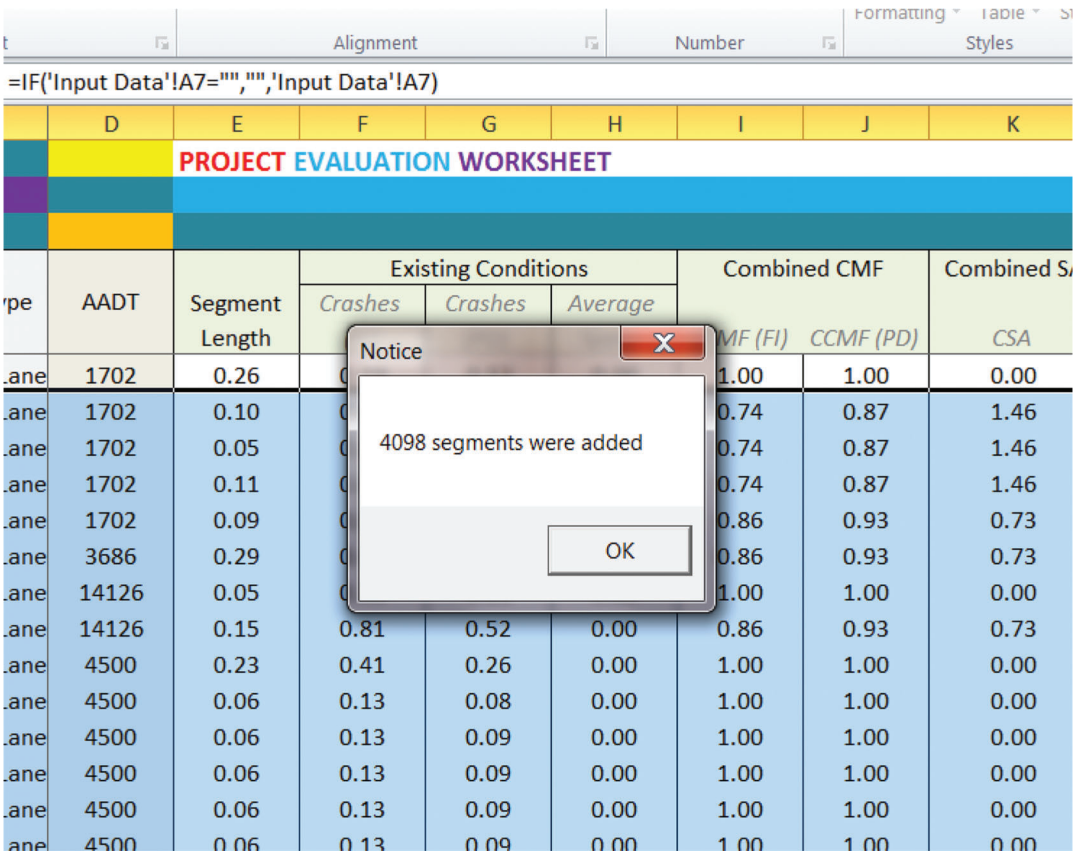
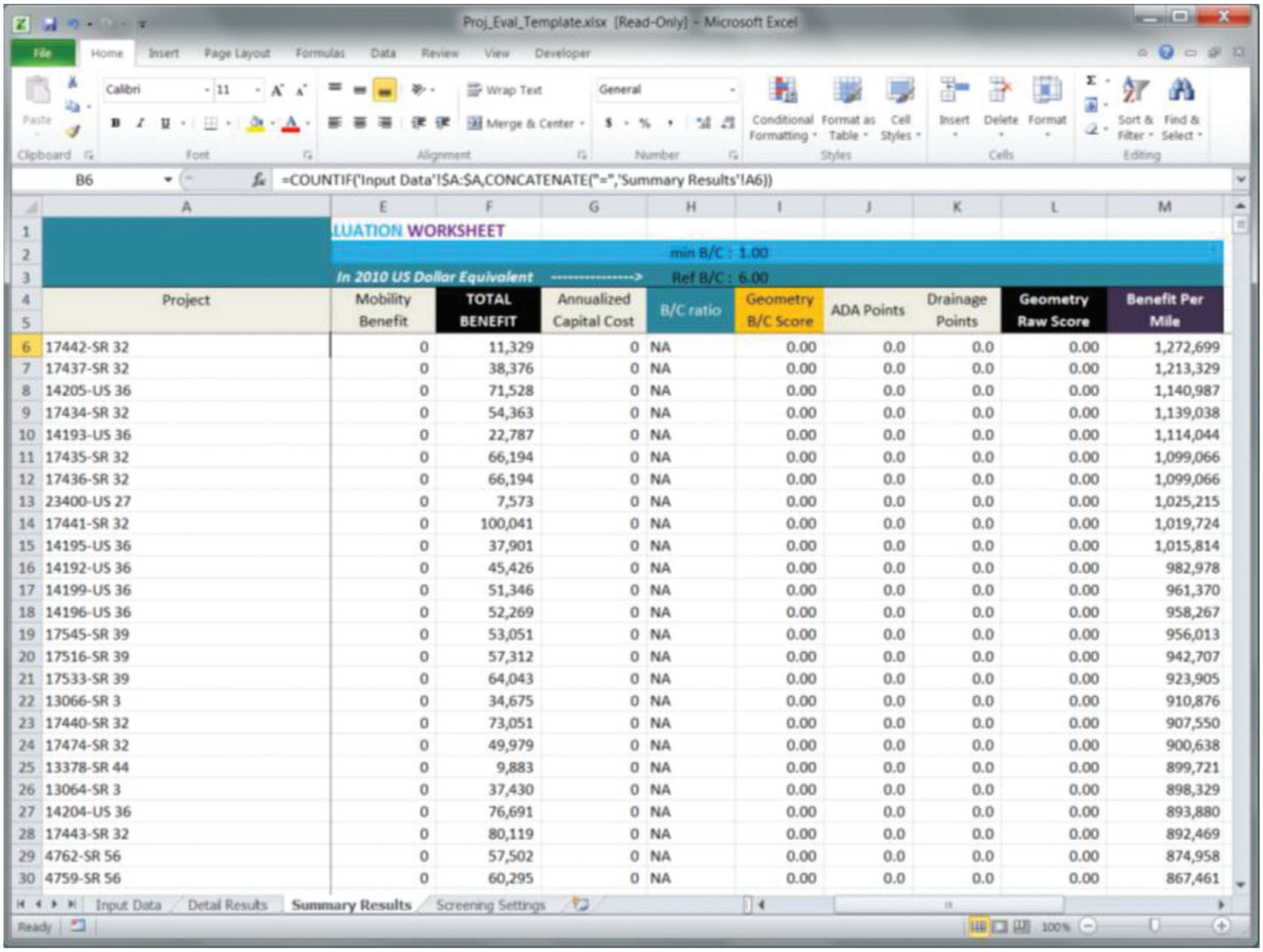


Figure A.6 Messages about the completion of the screening process.



	A	E	F	G	H	I	J	K	L	M
1		LUATION WORKSHEET								
2					min B/C : 1.00					
3		In 2010 US Dollar Equivalent		----------------->	Ref B/C : 6.00					
4–5	Project	Mobility Benefit	TOTAL BENEFIT	Annualized Capital Cost	B/C ratio	Geometry B/C Score	ADA Points	Drainage Points	Geometry Raw Score	Benefit Per Mile
6	17442-SR 32	0	11,329	0	NA	0.00	0.0	0.0	0.00	1,272,699
7	17437-SR 32	0	38,376	0	NA	0.00	0.0	0.0	0.00	1,213,329
8	14205-US 36	0	71,528	0	NA	0.00	0.0	0.0	0.00	1,140,987
9	17434-SR 32	0	54,363	0	NA	0.00	0.0	0.0	0.00	1,139,038
10	14193-US 36	0	22,787	0	NA	0.00	0.0	0.0	0.00	1,114,044
11	17435-SR 32	0	66,194	0	NA	0.00	0.0	0.0	0.00	1,099,066
12	17436-SR 32	0	66,194	0	NA	0.00	0.0	0.0	0.00	1,099,066
13	23400-US 27	0	7,573	0	NA	0.00	0.0	0.0	0.00	1,025,215
14	17441-SR 32	0	100,041	0	NA	0.00	0.0	0.0	0.00	1,019,724
15	14195-US 36	0	37,901	0	NA	0.00	0.0	0.0	0.00	1,015,814
16	14192-US 36	0	45,426	0	NA	0.00	0.0	0.0	0.00	982,978
17	14199-US 36	0	51,346	0	NA	0.00	0.0	0.0	0.00	961,370
18	14196-US 36	0	52,269	0	NA	0.00	0.0	0.0	0.00	958,267
19	17545-SR 39	0	53,051	0	NA	0.00	0.0	0.0	0.00	956,013
20	17516-SR 39	0	57,312	0	NA	0.00	0.0	0.0	0.00	942,707
21	17533-SR 39	0	64,043	0	NA	0.00	0.0	0.0	0.00	923,905
22	13066-SR 3	0	34,675	0	NA	0.00	0.0	0.0	0.00	910,876
23	17440-SR 32	0	73,051	0	NA	0.00	0.0	0.0	0.00	907,550
24	17474-SR 32	0	49,979	0	NA	0.00	0.0	0.0	0.00	900,638
25	13378-SR 44	0	9,883	0	NA	0.00	0.0	0.0	0.00	899,721
26	13064-SR 3	0	37,430	0	NA	0.00	0.0	0.0	0.00	898,329
27	14204-US 36	0	76,691	0	NA	0.00	0.0	0.0	0.00	893,880
28	17443-SR 32	0	80,119	0	NA	0.00	0.0	0.0	0.00	892,469
29	4762-SR 56	0	57,502	0	NA	0.00	0.0	0.0	0.00	874,958
30	4759-SR 56	0	60,295	0	NA	0.00	0.0	0.0	0.00	867,461

Figure A.7 Example screening results (summary).

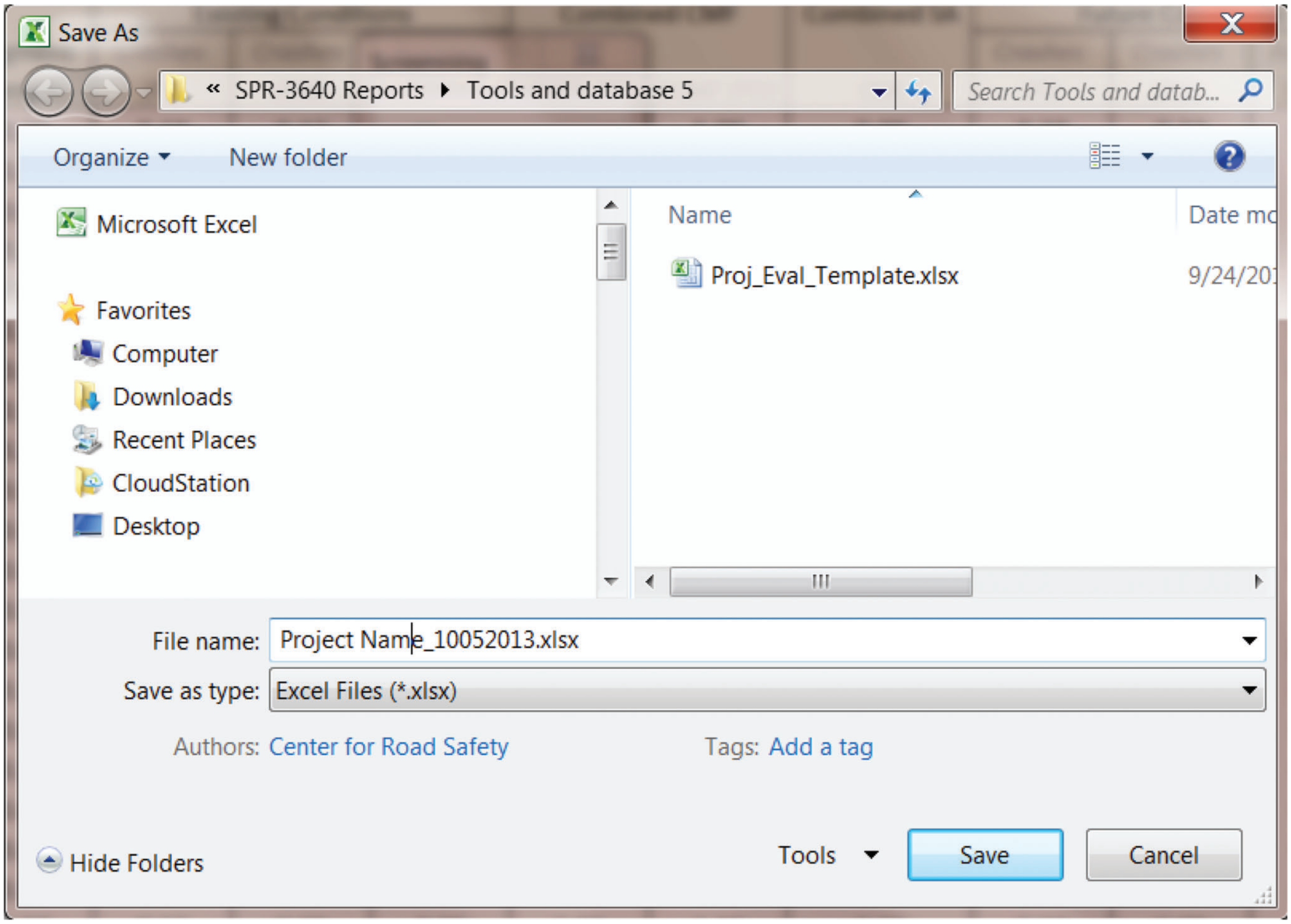


Figure A.8 Saving the results of road network screening.

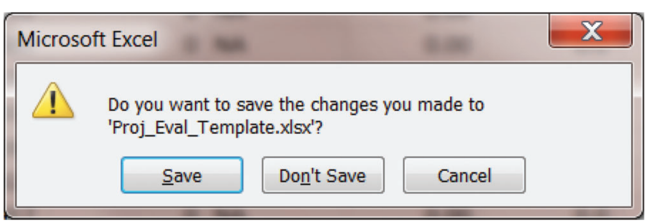


Figure A.9 Saving reminder box.

PROJECT EVALUATION

Clicking on the *Road Screening* button in the initial PEARS window (Figure A.2) displays the Excel project evaluation input worksheet and the project *Evaluation* execution box (Figure A.10). These two windows can be moved by the user to convenient positions on the computer screen.

The project *Evaluation* execution box allows changing the general evaluation settings including the ref B/C, min B/C (0 or 1), and the sorting criterion (B/C or benefit per mile) (Figure A.11). The reader should refer to the report that explains these settings and their use in the evaluation calculations.

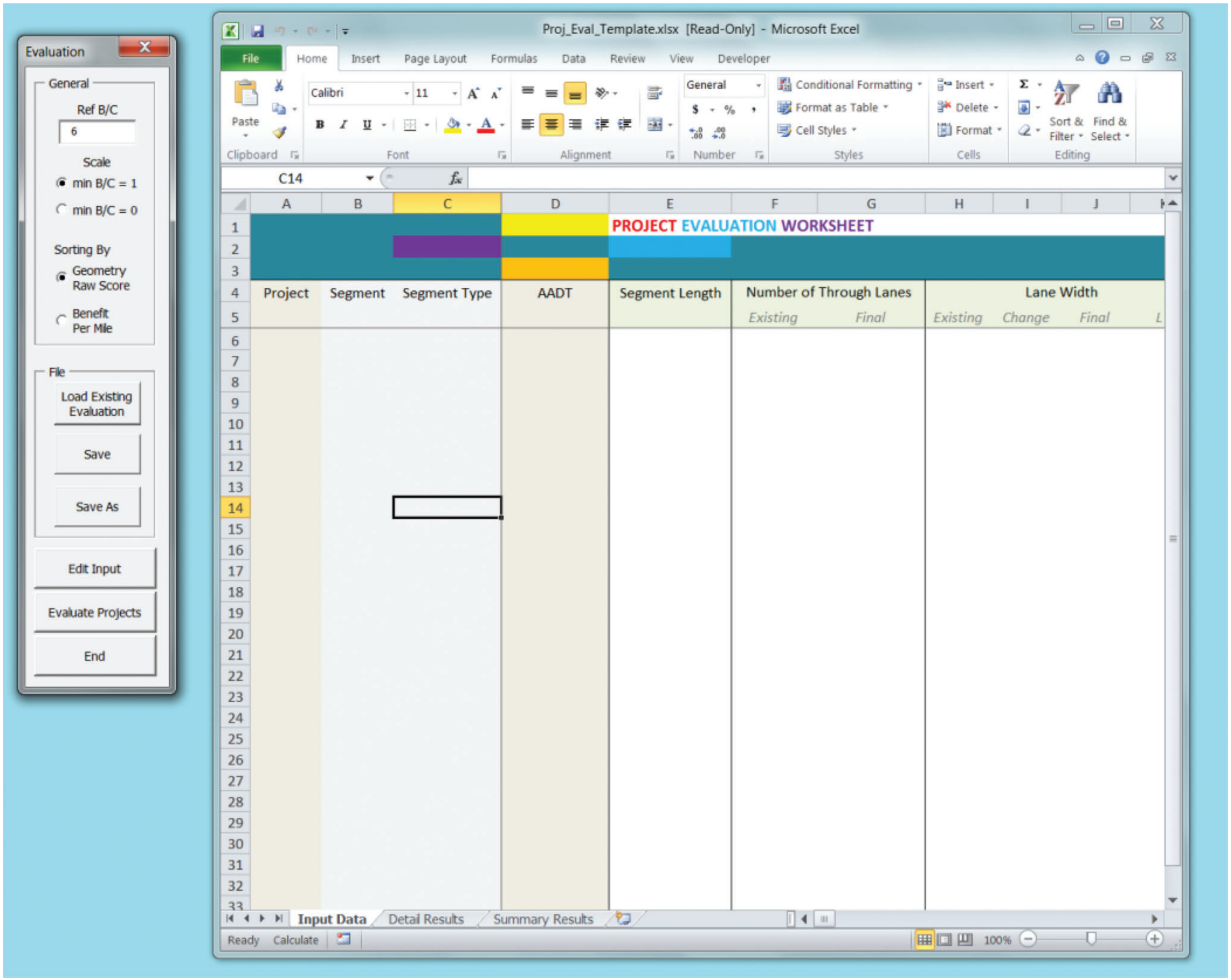


Figure A.10 Projects evaluation execution box and input data spreadsheet.

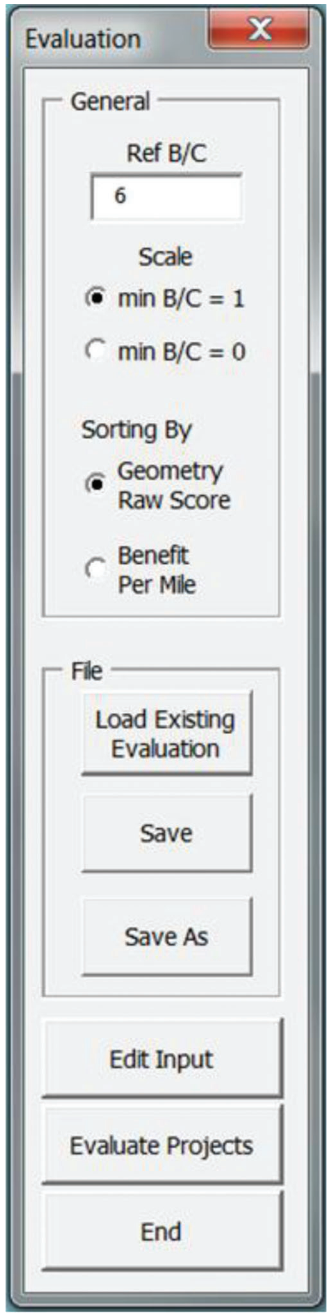


Figure A.11 Projects evaluation execution box.

The user has two options: load an existing project evaluation file to continue analysis or to start a new evaluation session by clicking on the *Evaluate Projects* button in the *Evaluation* execution box (Figure A.11). This action will open a blank *Input Module* for entering projects and their segments (Figure A.12).

The *Input Module* allows entering multiple projects with single or multiple road segments. The displayed top portion of the *Input Module* facilitates entering input information, including the project name for identification on the list, the annualized capital cost of the project, and the additional points earned by the project for meeting the ADA regulations and for drainage. Once the project is added, its name appears on the pull-down list of existing projects (Figure A.13). It can be conveniently selected from that list for further data adding or editing. The project can also be deleted by clicking on the *Delete* button.

Adding a project activates the bottom part of the Input Module for entering segments of the project. Even adding a project with its name only opens the bottom part and adds an empty project line in the Excel spreadsheet of projects (Figure A.14).

Similarly, adding a segment with its name only adds a line of segment data in the PEARS spreadsheet (Figure A.14) and activates the bottom part of the Input Module for entering segments of the project (Figure A.15).

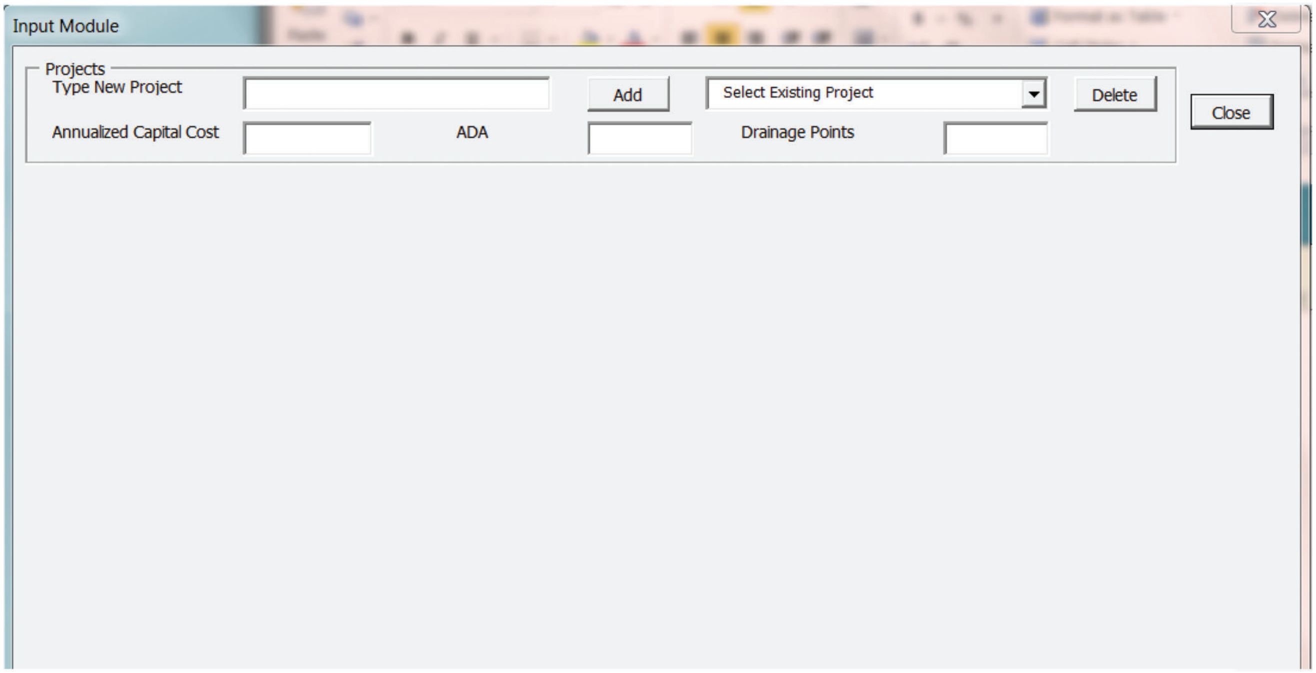


Figure A.12 Input module for entering projects input data.

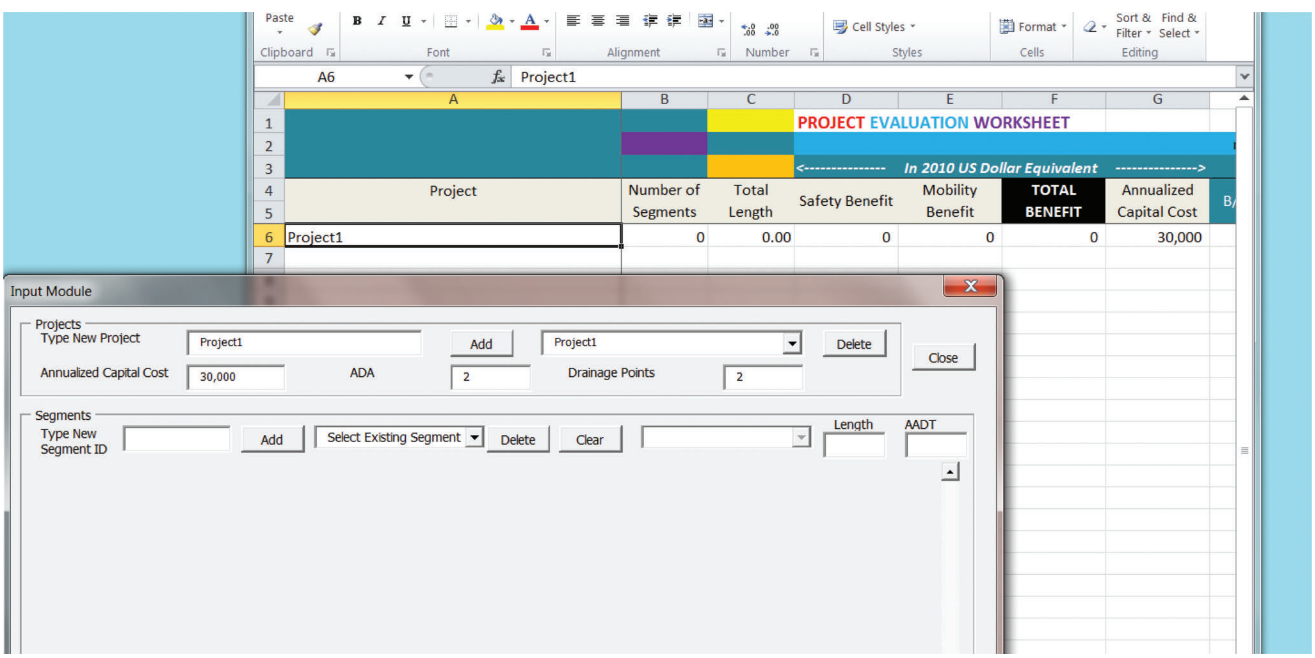


Figure A.13 New project added in PEARS (only project's name specified at this time).

The user enters the existing and future geometry dimensions or existing geometry and the change in the road's dimensions. The distance along which the improvement is applied is required in the last column unless the improvement applies to the entire segment.

Adding another segment within the same project replicates the input data from the previous segment to reduce the effort needed to enter data. The user will only modify the improvements that do not apply to the current segment. If the next segment has improvements quite different from the improvements for the previous segment, then the user can clear the inputs by clicking on the *Clear* button in the *Input Module* to start entering new data.

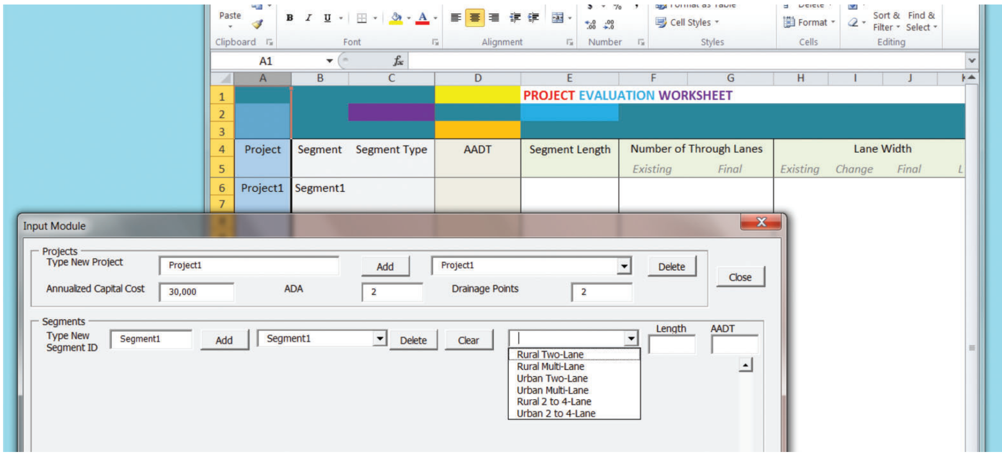


Figure A.14 New segment added in PEARS (only segment's name specified thus far).

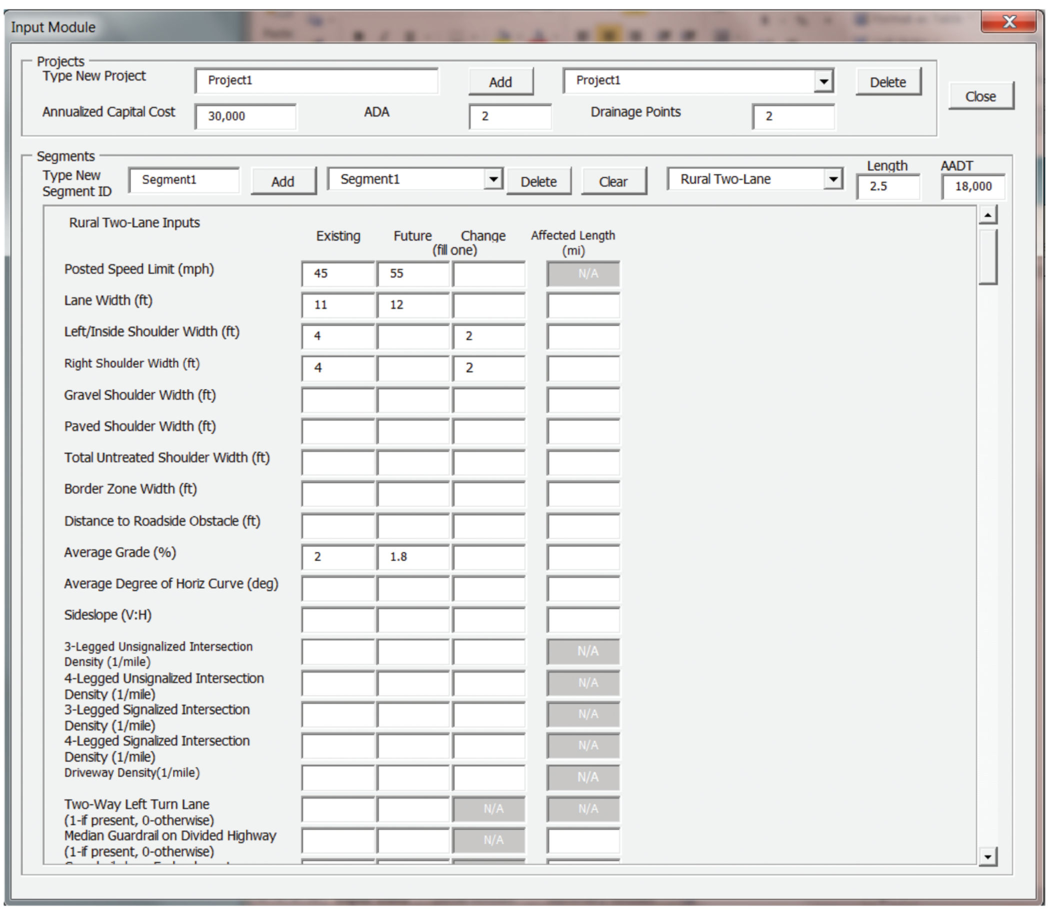


Figure A.15 Fully activated Input Module for entering project and segment data for evaluation.

After all the projects and segments are entered, the user should save the inputs using the *Save* or *Save As* buttons in the *Evaluation* execution box (Figure A.11). A new window appears (Figure A.16) that allows naming the new file and finding the destination folder through browsing the computer.

An existing input file from a previous project evaluation can be loaded using the *Load* button in the *Evaluation* execution box and then viewed with the *Input Module*. Any project and segment data can be modified as needed by selecting the existing project and segment from the pull-down lists in the *Input Module* window. Figure A.17 and Figure A.18 present two examples of input data for segments with corresponding content in the *Input Module*.

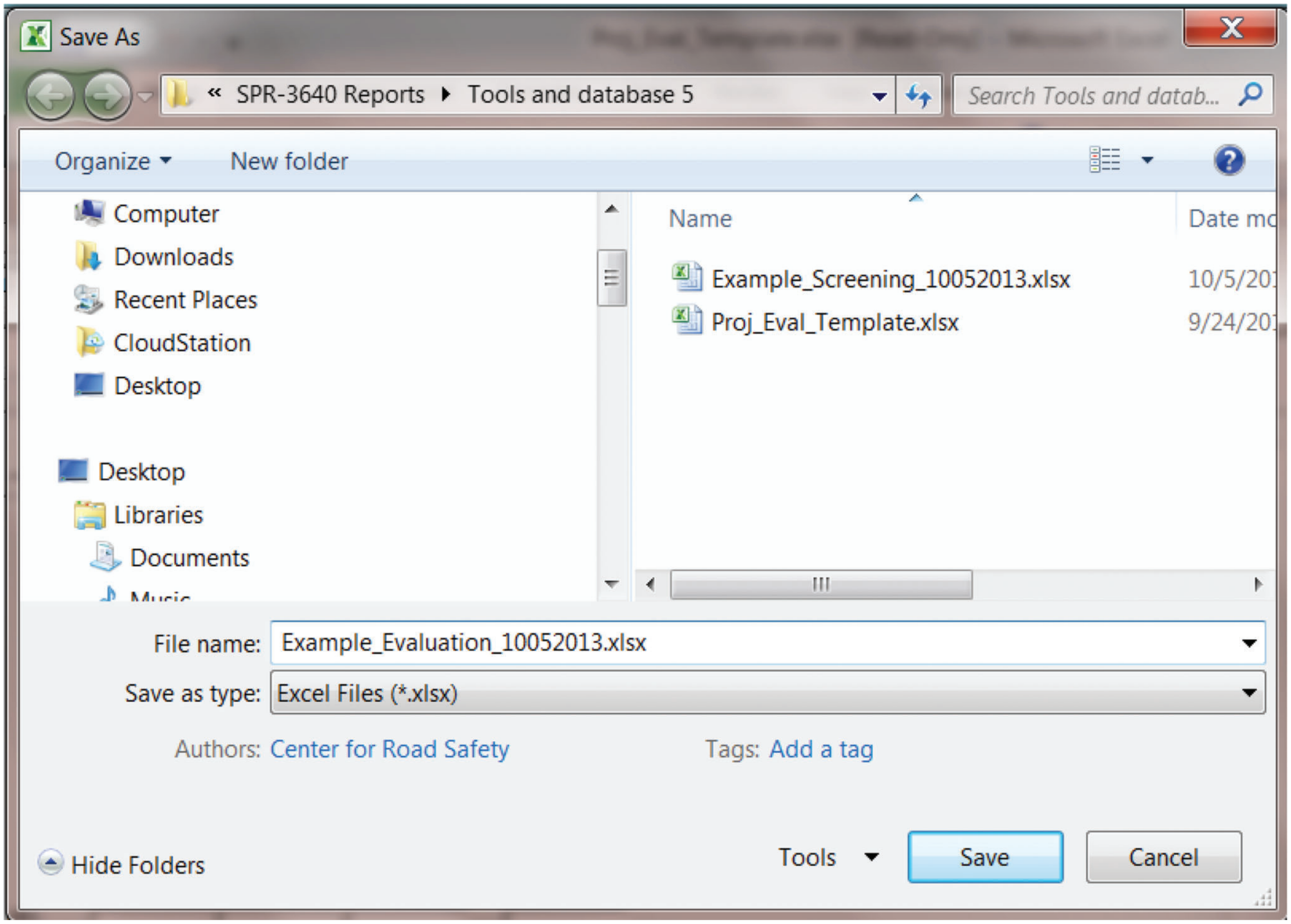


Figure A.16 Saving the project's evaluation file.

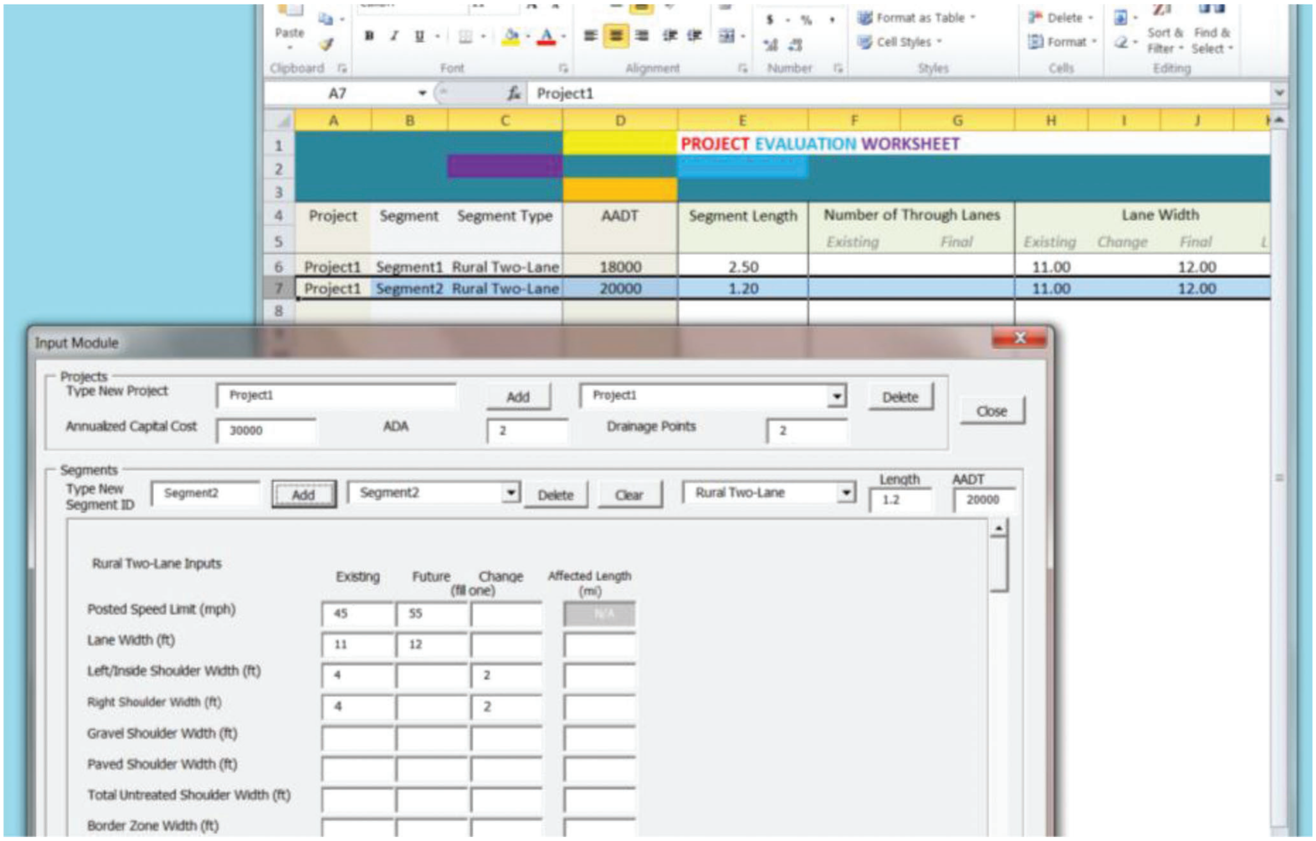


Figure A.17 First example input data on the project list and in the Input Module.

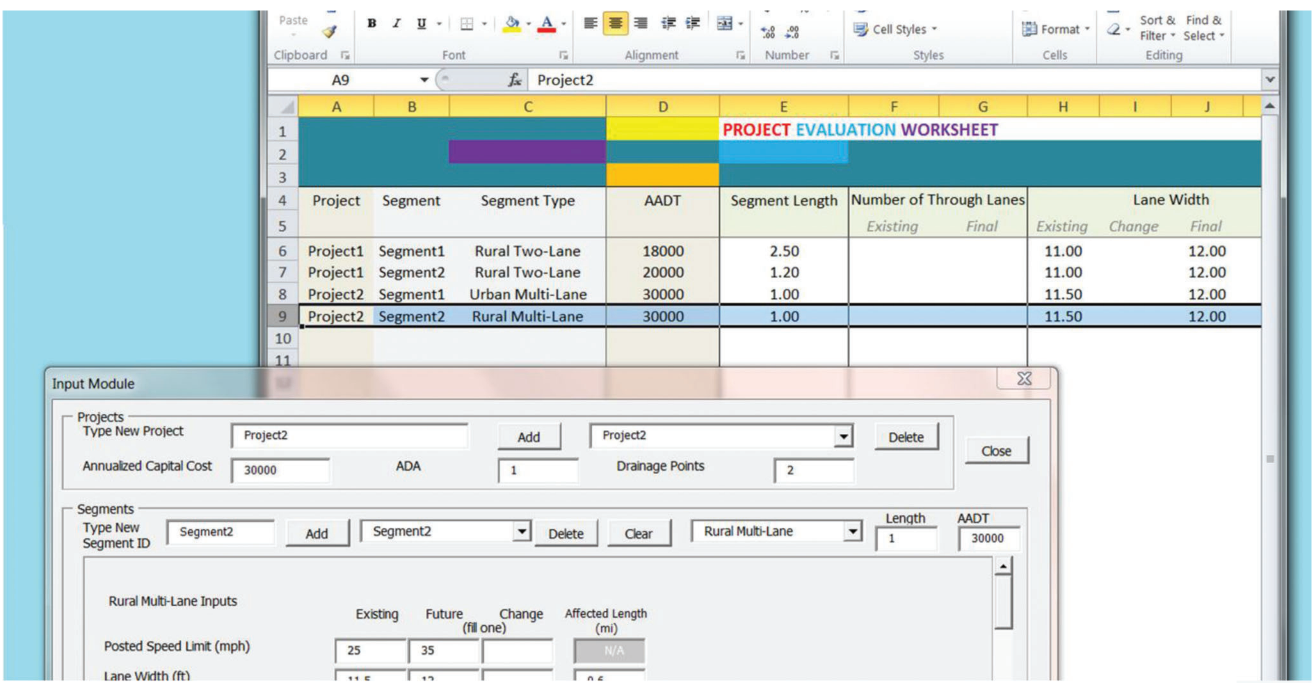


Figure A.18 Second example input data on the project list and in the Input Module.

The project's evaluation is executed by clicking on the *Evaluate Projects* button in the *Evaluation* execution box (Figure A.11). The evaluation results can be viewed in two formats: summary (*Summary Results* tab) and detail (*Detail Results* tab)—see Figure A.19 and Figure A.20. Clicking on the *End* button in the Evaluation execution box ends the analysis, cleans the memory space, and closes the results spreadsheets. The PEARS tool returns to the initial window (Figure A.2).

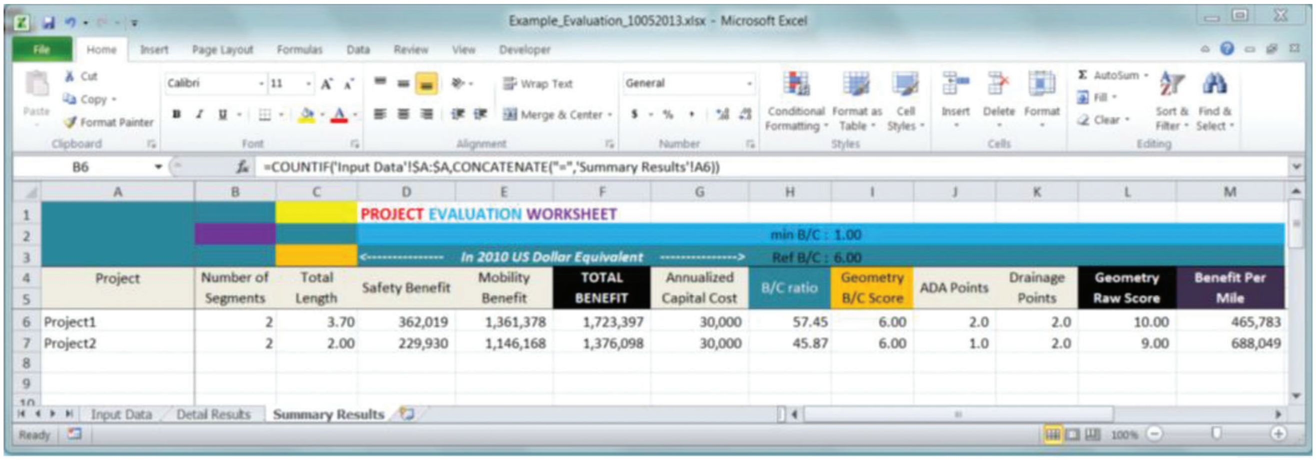


Figure A.19 Summary results of the example project evaluation session.

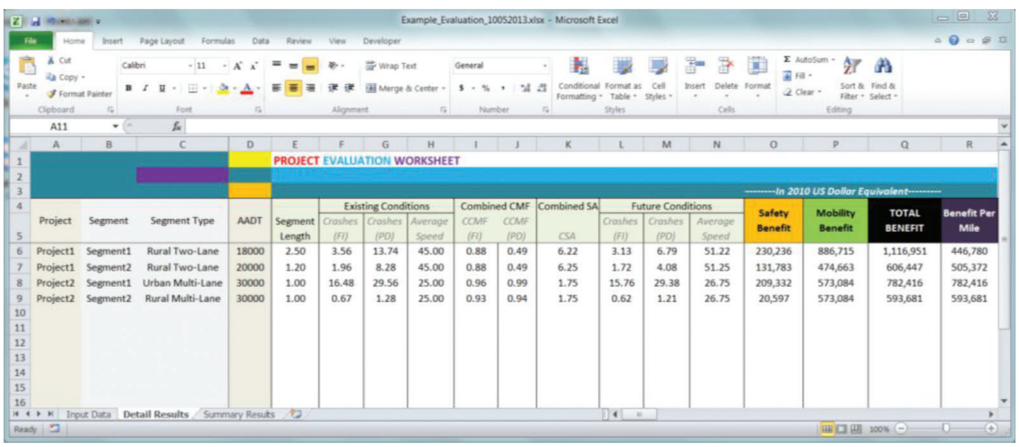


Figure A.20 Detailed results of the example project evaluation session.

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,500 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at: http://docs.lib.purdue.edu/jtrp

Further information about JTRP and its current research program is available at: http://www.purdue.edu/jtrp

About This Report

An open access version of this publication is available online. This can be most easily located using the Digital Object Identifier (doi) listed below. Pre-2011 publications that include color illustrations are available online in color but are printed only in grayscale.

The recommended citation for this publication is:

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