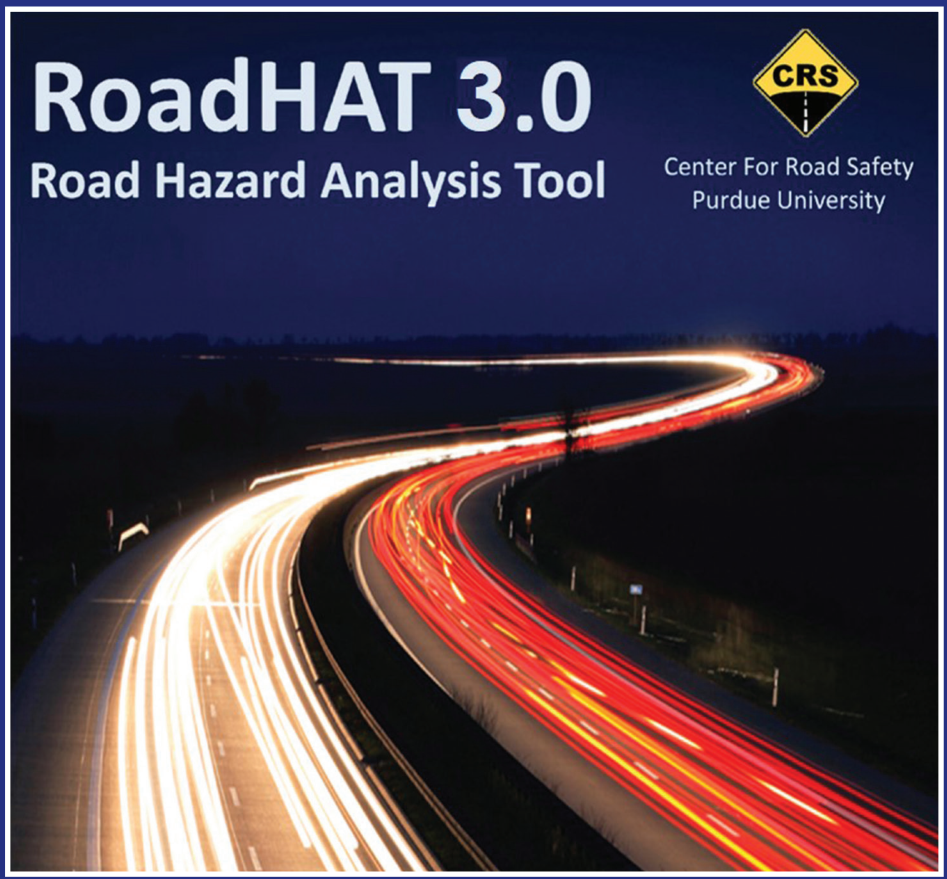
JOINT TRANSPORTATION RESEARCH PROGRAM
INDIANA DEPARTMENT OF TRANSPORTATION AND PURDUE UNIVERSITY

Updating RoadHAT: Collision Diagram Builder and HSM Elements



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SPR-3726 • Report Number: FHWA/IN/JTRP-2016/11 • DOI: 10.5703/1288284316334

RECOMMENDED CITATION

Tarko, A. P., Romero, M., Thomaz, J., Ramos, J., Sultana, A., Pineda, R., & Chen, E. (2016). *Updating RoadHAT: Collision diagram builder and HSM elements* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2016/11). West Lafayette, IN: Purdue University. http://dx.doi.org/10.5703/1288284316334

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JOINT TRANSPORTATION RESEARCH PROGRAM

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Print ISBN: 978-1-62260-407-4
ePUB ISBN: 978-1-62260-408-1

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/IN/JTRP-2016/11		

4. Title and Subtitle	5. Report Date
Updating RoadHAT: Collision Diagram Builder and HSM Elements	January 2016
	6. Performing Organization Code
7. Author(s) Andrew P. Tarko, Mario Romero, Jose Thomaz, Jorge Ramos, Afia Sultana, Raul Pineda, Erdong Chen	8. Performing Organization Report No. FHWA/IN/JTRP-2016/11
9. Performing Organization Name and Address Joint Transportation Research Program Purdue University 550 Stadium Mall Drive West Lafayette, IN 47907-2051	10. Work Unit No.
	11. Contract or Grant No. SPR-3726
12. Sponsoring Agency Name and Address Indiana Department of Transportation State Office Building 100 North Senate Avenue Indianapolis, IN 46204	13. Type of Report and Period Covered Final Report
	14. Sponsoring Agency Code

15. Supplementary Notes

Prepared in cooperation with the Indiana Department of Transportation and Federal Highway Administration.

16. Abstract

In order to minimize the losses resulting from traffic crashes, Indiana developed its road safety management methods before the Highway Safety Manual and the SafetyAnalyst became available. The considerable cost of replacing the Indiana current practice with the safety management based on the Highway Capacity Manual prompted the Indiana DOT to continue using its own safety management tools. This study includes two related but distinct components: (1) comparison of the HSM-based and Indiana methods of safety management, and (2) development of a Collision Diagram Builder (CDB) to improve current Indiana safety management tools.

This study concluded that the HSM SPFs would need to be calibrated to the Indiana conditions before they could be used. Calibrating the SPFs for, so-called, base conditions would lead to an insufficient number of roads and, consequently, to estimates that were not trustworthy. This problem is amplified by the large number of road categories and crash types in HSM (110 categories and 468 crash severity proportions). Furthermore, a re-calibration process must be repeated over time to keep the SPFs updated to the changes in safety.

An advanced statistical simulation of a safety management system aimed to maximize the total safety benefit was performed. The results indicate that two best performing criteria: the HSM EPDO-based criterion and the Indiana total cost of crashes criterion are equivalent and they produce the same results. It is important that the HSM provides guidance as to which screening criteria support which screening objectives because some of the HSM criteria were found inadequate for maximizing the overall safety benefit. It also was concluded that although the cost of crashes and the Index of Crash Cost and Frequency used separately proved to be good screening criteria in Indiana, the combined use of these two measures did not deliver any considerable improvement.

Two differences were found between the HSM and Indiana procedures for evaluating the benefits and costs of safety projects: the infinite period of analysis and the road capacity constraint on traffic growth. Consequently, Indiana results depend on the capacity constraints while the HSM results depend on the length of the analysis period. The differences between the two methods were quite limited and they could be fully reconciled if the capacity constraints was relaxed in the Indiana method and a long analysis period assumed in the HSM method.

A second major component of the study was to improve the current Indiana safety management tool, RoadHAT2, by developing a computer application facilitating preparation of a so-called collision diagram. These diagrams are an important element of safety audits. They are not used frequently due to a considerable time required to build collision diagrams. The developed application reduces this time from one or two days to an hour or less. The application also provides additional tools for analyzing and visualization of crash patterns. A developed CDB User Manual introduces the user to the tool and provides examples to help the user get familiar with the application.

17. Key Words	18. Distribution Statement
road safety management, road network screening, economic evaluation, collision diagram builder	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	52	

Form DOT F 1700.7 (8-69)

EXECUTIVE SUMMARY

UPDATING ROADHAT: COLLISION DIAGRAM BUILDER AND HSM ELEMENTS

Introduction

This study includes two separate but related components:

1. Comparison of the HSM-based and Indiana methods of safety management; and
2. Development of a Collision Diagram Builder (CDB) to improve current Indiana safety management tools.

Indiana developed and started implementing its road safety management methods before the Highway Safety Manual (HSM) and SafetyAnalyst became available. The considerable cost of replacing the Indiana current practice with safety management based on the HSM prompted the Indiana Department of Transportation (INDOT) to continue using its own safety management tools. This study compared the HSM-based and Indiana safety management methods in order to identify similarities and differences. The primary motivation of this study was to point out possible improvements of the Indiana and HSM-based approaches to safety management. This study had three objectives:

1. Evaluate the HSM safety performance functions (SPFs) with Indiana data;
2. Determine the best network screening strategy available in the HSM and compare it to the Indiana strategy; and
3. Compare the HSM and Indiana procedures for economic evaluation of safety improvement projects.

To address the three research objectives, the HSM was studied with a particular focus on the chapters describing the criteria for identification of high-crash locations, SPFs, and life-cycle estimation of the benefits and costs of safety measures. The HSM and Indiana SPFs were compared and their performance evaluated using Indiana data. The HSM models also were checked as to whether they would perform better in Indiana by calibrating them with Indiana data.

A second major component of the study was to improve the current Indiana safety management tool, RoadHAT2, by developing a computer application facilitating preparation of a so-called collision diagram. These diagrams are an important component of safety audits. However, they are not used frequently due to the considerable time required to build collision diagrams.

Findings

This study concluded that the HSM SPFs would need to be calibrated to the Indiana conditions before they could be used. Calibrating the SPFs for so-called base conditions would lead to an insufficient number of roads and, consequently, to estimates that could not be trusted. This problem is amplified by the large number of road categories and crash types in HSM (110 categories and 468 crash severity proportions). Furthermore, the re-calibration process is not a one-time effort. It must be repeated over time to keep the SPFs updated to the changes in safety.

An advanced statistical simulation of a safety management system aimed to maximize the total safety benefit was performed. The results indicate that the two best-performing criteria—the HSM EPDO-based criterion and the Indiana total cost of crashes criterion—are equivalent and they produce the same results. Some of the criteria proposed by HSM are inadequate for maximizing the overall safety benefit. It is important that the HSM provides guidance as to which screening criteria support which screening objectives.

Although the total number of crashes was shown to be an effective criterion of identifying locations with high potential for safety savings, its usefulness strongly depends on a stable correlation between severe and less severe crashes. It was also concluded that although the cost of crashes and the Index of Crash Cost and Frequency used separately proved to be good screening criteria in Indiana, the combined use of these two measures did not deliver any considerable improvement.

Two major differences were found between the HSM and Indiana procedures for evaluating the benefits and costs of safety projects: the infinite period of analysis and the road capacity constraint on traffic growth. The Indiana results depend on the capacity constraints, while the HSM results depend on the length of the analysis period. The differences between the two methods are typically limited. The results from both methods can be fully reconciled by relaxing the road capacity constraint in the Indiana method and by using a long analysis period in the HSM method.

The developed Collison Diagram Builder reduces the time needed to prepare a collision diagram from one to two days to an hour or less. The application provides additional tools for analyzing and visualizing crash patterns.

Implementation

The findings of this study help improve the Indiana network screening method. The screening tool, SNIP2, has already been modified to implement the EB estimation of the crash cost. There is no need to modify another Indiana tool, RoadHAT2. Both tools already use Safety Performance Functions and crash unit costs developed and updated to the Indiana conditions on a regular basis. These tools are flexible, incorporating the recommended changes through modifying the application settings and without modifying the computer code.

A beta version of the Collision Diagram Builder was developed and delivered to INDOT for testing and evaluation. A CDB User Manual was developed to help implement and use the tool. A workshop was delivered by the research team to introduce the CDB tool to INDOT users.

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INTRODUCTION

In order to minimize the losses resulting from traffic crashes, state DOTs and a growing number of local transportation agencies are developing and maintaining their own safety management systems, many of them utilizing the FHWA-sponsored Highway Safety Manual (HSM) and SafetyAnalyst to develop their safety management programs. Indiana developed its road safety management methods gradually over the last 18 years—several years before the Highway Safety Manual (AASHTO, 2010) and SafetyAnalyst (Harwood, Torbic, Richard, & Meyer, 2010) became available—Indiana developed and incorporated two primary tools in its procedures: the Safety Needs Identification Program (SNIP) and the Roadway Hazard Analysis Tool (RoadHAT). SNIP applies a set of Indiana safety performance functions (SPFs) and specific network screening strategies to identify roads with safety needs; and RoadHAT facilitates safety analysis at selected roads by confirming the safety needs, providing check-lists for site investigation, and supporting economic evaluation of safety projects. Their entire safety analysis process is described in their Guidelines to Safety Management through Road Improvements (INDOT, 2013).

AASTHO published the first nationwide guidelines for safety management in its HSM in 2010. Indiana was among the states participating in the pilot study meant to provide feedback to the HSM implementation tool developers. The considerable cost of replacing the Indiana current practice with the safety management based on the Highway Capacity Manual prompted the Indiana DOT to continue using its own safety management tools. This study includes two related but distinct components:

1. Comparison of the HSM-based and Indiana methods of safety management, and
2. Development of a Collision Diagram Builder (CDB) to improve current Indiana safety management tools.

The first study component was aimed to compare the HSM-based and Indiana safety management methods in order to identify similarities and differences. The primary interest in this study was to point out possible improvements of the Indiana and HSM methods. There are three objectives of this study:

1. Evaluate the HSM SPFs with Indiana data.
2. Determine the best network screening strategy available in the HSM and compare it to the Indiana strategy.
3. Compare the HSM and Indiana procedures for economic evaluation of safety improvement projects.

The HSM was studied with a particular focus on the chapters describing the criteria for identification of high-crash locations, SPFs, and life-cycle estimation of the benefits and costs of safety measures. The HSM and Indiana SPFs were compared and their performance evaluated using Indiana data. The HSM models also were checked as to whether they would perform better in Indiana by calibrating them with Indiana data.

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A second major component of the study was to improve the current Indiana safety management tool: RoadHAT2, by developing a computer application facilitating preparation of a so-called collision diagram. These diagrams are an important element of safety audits. They are not used frequently due to a considerable time required to build collision diagrams. The developed application reduces this time from one or two days to an hour or less. The application also provides additional tools for analyzing and visualization of crash patterns. A developed CDB User Manual introduces the user to the tool and provides examples to help the user get familiar with the application.

The remainder of this report is organized in two parts: Part I—Highway Safety Manual vs. Indiana Safety Management, and Part II—Collison Diagram Builder User's Manual.

First chapter of Part I synthesizes the crash frequency modeling approaches of Indiana and the HSM using rural two-lane two-way segments and signalized intersections. The modeling approaches were evaluated based on certain assumptions, limitations, and goodness of fit. The detailed procedure and results of the roadway network screening are presented in the second chapter. The next chapter examines a case study conducted in this study to demonstrate the cost-benefit analysis of a safety improvement project. Finally, the last chapter of Part I summarizes the results of these comparisons.

Part II presents the information required to successfully installed the CDB tool, uploading input files and an intersection diagram, preparation of the image for automatic and manual positioning of crash icons on the diagram, checking and correcting the crash data, and finally creating, setting, and saving collision diagrams and tables.

PART I. HIGHWAY SAFETY MANUAL VS. INDIANA SAFETY MANAGEMENT

SAFETY PERFORMANCE FUNCTIONS

SPFs are the statistical relationships between crash frequency and road and traffic characteristics. SPFs are used to identify roads with excessive numbers of crashes and to estimate the safety benefits through cost-benefit analyses. The HSM provides a large number of SPFs developed by various authors for various regions and states and also offers proposed BSPFs estimated for a sample of roads that meet certain base geometry conditions (Vogt, 1999; Vogt & Bared, 1998a,b). A calibration factor must be applied to adjust the BSPF (Base SPF) to the state or other local conditions. Several states such as Utah, Louisiana, Kansas and Oregon etc. conducted research on the calibration of HSM SPF for rural two-lane two-way road. These research works showed that jurisdiction-specific models have different relationships between crashes and roadway characteristics from those presented in the HSM and without calibration factor, HSM SPFs predicts less crashes (Brimley, Saito, Grant & Schultz, 2012; Howard & Schrock, 2012; Sun, Magri, Shirazi, & Gillella, 2011; Xie, Gladhill, Dixon, & Monsere, 2011). In addition, crash modification factors (CMFs) must be applied to account for specific road geometry and traffic control factors (AASHTO, 2010).

This section of the report compares the HSM BSPFs with the corresponding SPFs developed with Indiana data. Three versions of the HSM SPFs were considered: (1) original (not calibrated) HSM SPFs, (2) HSM SPFs calibrated with the method of maximum likelihood (ML), (3) HSM SPFs calibrated with the HSM-recommended method of moments. The first comparison was conducted to confirm the importance of the model calibration.

The HSM SPFs were developed using historical crash data from selected states with the assumption that the obtained models would be applicable to any state after calibration. The following sections compare the performance of the following three SPFs:

1. HSM SPF without calibration to demonstrate the importance of calibration.
2. HSM SPF calibrated with the HSM-recommended method of moments (MM).
3. Indiana SPF without intersection density.
4. Indiana SPF with intersection density to demonstrate the improvement.

Evaluated Safety Performance Functions

The above four different SPF cases were compared as follows.

HSM SPFs and Their Calibration

The HSM BSPFs for total crashes and for rural two-lane two-way road segments and signalized intersections are shown below:

$$\text{Segment}: a_i = C_r \cdot Q_i \cdot L \cdot 365 \cdot 10^{-6} \cdot e^{-0.312} \tag{I.1}$$

$$\text{Intersection}: a_i = C_r \cdot Q_{mjr}^{0.60} \cdot Q_{mnr}^{0.20} \cdot e^{-5.13} \tag{I.2}$$

where:
C_r is the calibration factor;
a_i= estimated frequency of crash at segment/intersection i;
Q_i= annual-average traffic volume on the state road (veh/day) at segment i;
L= segment length (miles);
$Q_{mjr,i}$= annual-average traffic volume on the major approach of the state road (veh/day) intersection i;
$Q_{mjr,i}$= annual-average traffic volume on the minor approach of the state road (veh/day) intersection i.

The SPFs in Eq. I.1 and Eq. I.2 predict the expected number of crashes, while the crashes at various levels of severity are calculated as proportions of the total number estimated for the population. The C_r calibration factor is calculated as the total number of crashes reported by police divided by the total number of crashes predicted with the SPR to be calibrated:

$$C_r = \frac{\sum_{allsites} ObservedCrashes}{\sum_{allsites} PredictedCrashes} \tag{I.3}$$

The predicted number of crashes for each road segment on rural two-lane two-way roads were predicted with the SPF and calibrated to Indiana conditions using Eq. I.3. The calibration factor for rural two-lane segment crash data was C_r = 3.76. The calibration factor obtained for intersections using the same method was C_r = 1.49. Although the SPFs were developed for the base conditions, the calibrated SPFs represent the Indiana average condition.

Indiana Safety Performance Functions

The INDOT-administered road segments are the stretches of road between adjacent major intersections while all the minor intersections are included as part of the segments. A collector and arterial road crossing a state-administered road forms a major intersection; and a local road crossing a state-administered road is a minor intersection. The SPFs for segments and intersections were estimated using the maximum likelihood method without restricting the segment length and AADT parameters. The estimated models are shown in Eq. I.4 and Eq. I.5.

$$\text{Segment}: a_i = Q_i^{0.6997} \cdot L^{0.8007} \cdot \leq e^{-4.4299} \quad (I.4)$$

$$\text{Intersection}: a_i = Q_{mjr,i}^{0.5175} \cdot Q_{mnr,i}^{0.4954} \cdot e^{-6.5250} \quad (I.5)$$

where:

a_i = estimated frequency of crash at segment/ intersection i;

Q_i = annual-average traffic volume on the state road (veh/day) at segment i;

L=segment length (miles);

$Q_{mjr,i}$ = annual-average traffic volume on the major approach of the state road (veh/day) intersection i;

$Q_{mjr,i}$ = annual-average traffic volume on the minor approach of the state road (veh/day) intersection i.

The over-dispersion parameters were estimated at 0.93 and 0.64, respectively.

To improve the performance of the Indiana SPFs, the improved segment SPFs included the minor intersections density (intersections/mile), while the intersection SPFs included a T-intersection indicator and the road class FC34. These two variables were considered as additional exposure variables (see Eq. I.6 and Eq. I.7).

$$\text{Segment}: a_i = Q_i^{0.6707} \cdot L^{0.9679} \cdot e^{-4.2938 + 0.0771 \cdot \text{IntD}} \quad (I.6)$$

$$\text{Intersection}: a_i = Q_{mjr}^{0.5013} \cdot Q_{mnr}^{0.4363} \cdot e^{-6.0323 - 0.1805 \cdot T_i + 0.2728 \cdot FC34} \quad (I.7)$$

where:

a_i = estimated frequency of crash at segment/ intersection i;

Q_i = annual-average traffic volume on the state road (veh/day) at segment i;

L = segment length (miles);

$Q_{mjr,i}$ = annual-average traffic volume on the major approach of the state road (veh/day) intersection i;

$Q_{mjr,i}$ = annual-average traffic volume on the minor approach of the state road (veh/day) intersection i;

T_i = 1 if the intersection has three legs; 0, otherwise;

IntD = intersection density (Number of minor intersection/segment length);

FC34 = Road Functional class 3 and 4.

The estimated over-dispersion parameters were 0.88, and 0.63, respectively.

Comparison of the Safety Performance Functions

Segments

The Indiana rural two-lane two-way segments included 10,200 state road segments. The average segment length was 0.71 mile with a standard deviation of 0.23 mile and a maximum length of 1.0 mile. The mean segment AADT was 3,856 veh/day with a standard deviation of 3,135 veh/day. The average numbers of crashes on these rural two-lane segments was 2.71 crashes with a standard deviation of 4.38 crashes during three years (2011–2013). Although the maximum number of crashes was 99, zero crashes were observed on 31% of the segments.

TABLE I.1
Performance of SPFs for all crashes on rural two-lane road segments.

MOE	HSM SPF without Calibration	HSM SPF Calibrated with MM	Indiana SPF without Intersection Density	Indiana SPF with Intersection Density
SE	4.55	3.92	3.90	3.82
ρ2	-0.095	0.18	0.19	0.23

The comparison between the performance of the Indiana and HSM SPFs in estimating the number of crashes during the studied period is discussed in this section. Two MOEs were used: the standard error (SE), and the coefficient of determination (ρ^2). These MOEs are shown in Table I.1.

The smaller the SE and the higher the ρ^2 (varies from -1 to 1) are, the better is the performance of the SPF. The two MOEs indicated that among the compared four SPFs, the Indiana SPF that included intersection density provided the best estimation of the number of crashes. Even the Indiana SPFs without intersection density performed better than the calibrated HSM SPFs.

The extremely poor performance of the original HSM SPF (negative and nearly zero ρ^2) indicated that calibration was necessary.

Intersections

Among nearly 2,000 signalized intersections on Indiana state roads, 275 signalized intersections are located in rural areas and only 94 intersections are on rural two-lane roads. This situation illustrates the disadvantage of assuming too many categories of roads: it leads to small samples. Only 94 intersections could be used in our study. The average AADT on major approaches was 11,094 veh/day with a standard deviation of 6,556 veh/day. The average AADT on minor approaches was 10,114 veh/day with a standard deviation of 4,656 veh/day. The average numbers of crashes was 16.20 with a standard deviation of 15.67 crashes. The maximum number of crashes that occurred on these intersections was 80 with all the intersections experiencing crashes during the three-year period (2011–2013). The MOEs used to measure the performance of the studied SPFs in estimating the number of crashes during the studied period were the same as the MOEs used for the road segments: SE, and ρ^2. The results are shown in Table I.2.

The two MOEs indicated that, among the compared four SPFs, the Indiana SPFs for intersections outperformed the HSM SPFs. Again, the extremely poor performance

TABLE I.2
Performance of SPFs for all crashes at rural state signalized intersections.

MOE	HSM without Calibration	HSM Calibrated with MM	Indiana SPFs without Additional Variables	Indiana SPFs with Additional Exposure Variables
SE	16.23	14.85	14.52	14.54
ρ2	-0.096	0.082	0.120	0.122

of the original HSM SPF (negative and nearly zero ρ^2) indicated that calibration was necessary.

Discussion

In all the evaluated cases, the Indiana SPFs exhibited better performance than the HSM SPFs. Although the SE values for the calibrated HSM SPFs were only slightly worse than those for the Indiana SPFs, the coefficients of determination indicated a considerably higher difference. The particularly poor performance of the original HSM SPFs was not a surprise as they were developed for different states than Indiana. Additional sources of these discrepancies included:

1. The HSM SPFs were estimated for the base geometry conditions so the relationship between the exposure and crashes applies to these conditions, while Indiana uses all the available data and the obtained SPFs are therefore an average of all the geometry conditions.
2. The HSM restricts the crash frequency to being a linear function of the segment length and to the AADT in some cases; Indiana allows a non-linear power function.
3. The HSM calibration is restricted to a single "slope" parameter and is based on the method of moments; Indiana uses the ML method without restricting the parameter values.

In addition, the HSM uses the injury proportions to split the SPF-predicted injuries into different levels of severity; Indiana practice, on the other hand, estimates the crash frequencies at different injury levels using separate SPFs. This difference was not evaluated here.

There are three concerns regarding the BSPFs:

1. The BSPFs were estimated with data collected for roads that meet the base conditions. The number of such roads is much lower than roads in any conditions. This poses a serious challenge for estimating SPFs confidently.
2. It is possible that unknown conditions associated with the base conditions roads and not included in the SPFs are different from the unknown conditions associated with roads in the non-base conditions. Thus, the transferability (applicability) of the BSPFs to the non-base conditions may be questionable.
3. Applying the CMFs developed with data that represent other regions is another source of concern.

The first two concerns may be mitigated by using the average SPFs that are representative of the entire population of roads in a region. If the equation for any specific conditions, including the base conditions, is needed, then the model estimated for the average conditions can be adjusted to other conditions if the effect of these conditions on safety is known. Furthermore, expansion of the equation with CMFs can be avoided by fitting the SPFs expanded with variables supported with the available data.

Another concern is raised by the large number of SPFs proposed in the HSM. A total of 110 SPFs are shown in the HSM (see Appendix B) with 468 proportions for different types of collisions needing to be calibrated to Indiana before they can be used. Adding the requirement of the base conditions on the roads with data for calibration creates two problems: (1) the large effort needed for identifying such roads and then processing the data and calibrating the equations, and (2) most likely, small numbers of roads in narrow categories that meet the base conditions will result in poor calibration (noisy results).

In contrast, Indiana has SPFs for 19 different types of roads and three levels of crash severity and provides 57 SPFs without requiring crash proportions for various severities. These SPFs are calibrated for all roads and not just for those with the base conditions. If needed, these average-conditions SPFs can be easily reformatted to the base conditions.

ROAD NETWORK SCREENING

Introduction

Numerous performance measures and three screening methods for screening road networks have been proposed in HSM (AASHTO, 2010). To be specific, HSM presents 13 performance measures and leaves the decision of which criteria to use to transportation engineers and safety professionals. The performance measure and screening strategy used in Indiana was developed at the Purdue University Center for Road Safety (CRS). These methodologies use somewhat different concepts that have led to different performance measures.

The existing literature does not provide sufficient guidance for selecting appropriate performance measures. Although Kwona et al. (2013) used excess expected average crash frequency with Empirical Bayes (EB) adjustment as a performance measures to evaluate three screening methods Sliding Moving Window, Peak Searching and Continuous Risk Profile. The primary cause of this void is the lack of an appealing and commonly agreeable ground for comparing the alternatives. The main purpose of this study therefore is to make a fair comparison of the selected performance measures. The approach presented here is to establish link between the screening strategy with the ultimate performance of the safety management process using statistical simulation based on actual data supplemented with knowledge of safety properties.

The roads and safety are represented by the risk exposure and safety deficiencies and their effect on the crash frequency and severity. The modeled safety management includes alternative network screening strategies, safety audits, and performance-based selection of countermeasures. The simulated decision-making in safety management is based on random crash counts, crash means estimated with a SPF, and an imperfect safety audit. On the other hand, the evaluation of the simulated management outcome is based on full and correct information including the true crash means. There are three simulated components:

1. Road network represented by unsignalized intersections and its safety.
2. Safety management, including a network screening strategy, safety audits of identified roads, and a method of selecting roads and safety countermeasures for implementation.
3. Performance estimation of the safety management based on cost-effectiveness.

Road Network and Its Safety

The studied roads included 21,284 unsignalized intersections on state and local roads in Indiana: 12,308 intersections in rural areas and 8,976 intersections in urban areas. Table I.3 presents the basic statistics of the studied intersections.

Safety at intersection i is measured with the frequency of crashes a_{is} at three levels of severity s=1, 2, and 3:

1. Fatal or incapacitating injury crashes (a_{i1}).
2. Non-incapacitating or possible injury crashes (a_{i2}).
3. Property-damage crashes (a_{i3}).

Each severity level has a corresponding average crash cost (L_1, L_2, L_3), which was estimated for this study by CRS (see Table I.4). The studied intersections were characterized by two variables that are important exposure factors of safety: state road AADT and the number of intersection legs. In addition, 30 safety deficiencies were also taken into account to estimate the expected number of crashes (deterministic mean).

TABLE I.3
Descriptive statistics of the studied intersections.

Variables	Mean	Standard Deviation	Minimum	Maximum
Urban	0.42	0.49	0	1
Major ADT	8253.46	7620.23	60	66360
Number of Legs	3.38	0.5	2	6

Safety Deficiencies

The presence of road safety deficiencies d at intersection i are represented by binary variables D_{id} which take a value of 1 if deficiency d is present at intersection i and value 0 otherwise. Elimination of deficiency D_{id} changes the initial frequency a_{is} of crashes of severity s at intersection i to the new value $a_{is}F_{ds}$. Factor F_{ds} becomes the CMF for countermeasure d and crash severity s. The annualized cost of countermeasure d is C_d. Deficiency d is expected to be present at a certain proportion of intersections U_d. More than one deficiency can be present at an intersection. The values of F_{ds}, C_d, and U_d for d=1…30 and s=1, 2, 3 were generated using the following rules.

1. The initial value, called the Base CMF (BF_d) for countermeasure d, was drawn between Min=0.3 and Max = 0.9 from a symmetric Beta distribution, which was accomplished by transforming the Beta-distributed variable X (parameters: á = 4 and â = 4) into Y such that $Y = Min + X\cdot(Max - Min)$. Then, the CMF ($F_{ds}$) for countermeasure d and for each severity s was drawn from another Beta distribution between $Min = BF_d - H$ and $Max = BF + H$, where H was the lower value of BF_d and (1-BF_d), using the same method set for generating BF_d.
2. The annualized capital costs C_d were drawn from a uniform distribution between $2,000 and $500,000.
3. The proportion U_d of intersections with deficiency d was drawn from a uniform distribution between 0.1 and 0.3.

The summary of generated values of the deficiency variables are presented in Table I.5. These values represent the corresponding deficiencies characteristics for one set of deficiencies on the entire road network.

The generated 30 deficiencies were randomly assigned to the studied intersections using the proportion U_d as the probability that deficiency d is present at an intersection. This assignment resulted in matrix D_{id} 21,284 × 30 in size. Table I.5 summarizes the distribution of the deficiencies at the studied intersections. The table includes the percentiles (1, 5, 25, 50, 75, 5, 1), mean, and standard deviation of the following statistics: number of deficiencies and total CM $F_{is} = \prod_{d=1}^{30} {F_{ds}}^{D_{id}}$ for each intersection i for each severity s.

TABLE I.4
Average crash cost at studied intersections.

Element Type	Total Cost of Crashes ($1000)			Average Crash Cost ($1000)		
	KA	BC	PD	KA	BC	PD
Unsignalized Rural State-Local	414558	194542	138029	424.32	31.08	5.81
Unsignalized Urban State-Local	215574	199235	178759	299.83	30.11	6.8

TABLE I.5
Distribution of deficiencies at the studied intersections.

Parameter	Sum Def	Fi1	Fi2	Fi3
Mean	6.86	0.04	0.03	0.04
Standard Deviation	2.28	0.07	0.06	0.07
Minimum	0	2.72E-05	2.60E-06	2.42E-05
Maximum	16	1	1	1
Percentile 0.01	2	0.0004	0.0001	0.0003
Percentile 0.05	3	0.0012	0.0004	0.0012
Percentile 0.15	5	0.0033	0.0012	0.0032
Percentile 0.25	5	0.0059	0.0024	0.0057
Percentile 0.50	7	0.0164	0.0080	0.0160
Percentile 0.75	8	0.0428	0.0252	0.0421
Percentile 0.85	9	0.0703	0.0451	0.0684
Percentile 0.95	11	0.1496	0.1119	0.1504
Percentile 0.99	13	0.3295	0.2728	0.3248

True Safety Performance Functions

A True Safety Performance Function (TSPF) links intersection i exposure and the presence of safety deficiencies with the frequency of crashes a_{is} of severity s:

$$a_{is} = g \cdot e^{\gamma_s + \alpha_{Qs} \ln(Q_i) + \alpha_{Ts} T_i + \sum_d \hat{a}_{ds} D_{id}} \qquad \text{(I.8)}$$

where:

a_{is}= true frequency of crash of severity s at intersection i;

g= Gamma-distributed variable with mean equals 1 and a small variance (0.05 used);

γ_s= model coefficient;

α_{Qs}= coefficient associated with the traffic volume;

Q_i= annual-average traffic volume on the state road (veh/day);

α_{Ts}= coefficient associated with the three-leg intersection indicator;

T_i= 1 if the intersection has three legs, 0 otherwise;

$\hat{a}_{ds}$= In(F_{ds}), $\hat{a}_{ds}$ is a calculated model parameter.

F_{ds}= CMF for countermeasure (deficiency) d and severity s.

D_{id}= 1 if safety deficiency d is present at intersection i, 0 otherwise.

TSPFs at three crash severity levels were assumed for rural and urban intersections. To make the assumptions realistic, the values of the SPFs were estimated for the studied intersections. Then, the CMFs F_{ds} were generated and $\hat{a}_{ds}$= In(F_{ds}) was calculated. The TSPFs were then expanded with $\hat{a}_{ds}D_{id}$ terms and coefficients γ_s that were assumed at such values so that the total number of crashes calculated with the TSPFs approximately matched the total number of crashes actually reported at the studied intersections. Appendix C presents the TSPFs. The true means were equal to the deterministic counts after adding the gamma variable noise and were used later to estimate the true net benefit after applying a screening strategy.

Crash Counts

Crash counts are the most important input to a safety management system. They were generated in this study for three severity levels. The followings steps were used for each intersection and each crash severity level:

1. The value g in Eq. I.8 was drawn from the Gamma distribution with the mean equals 1 and the variance equals 0.05.
2. The intersection characteristics and the g value obtained in step 1 were used in Eq. I.8 to calculate the true mean crash count for three years.
3. The crash count then was drawn from the Poisson distribution with the mean equal to the true mean obtained in step 2.

The true means were the key element in the evaluation and comparison of alternative screening strategies.

Safety Management

A safety management based on road improvements employs the following steps in order to identify roads and projects for implementation:

1. Screen roads to identify the most promising candidates for improvement.
2. Audit the top roads to identify their safety deficiencies and adequate countermeasures.
3. Select the most cost-effective safety countermeasures and projects for implementation.

A modern safety management utilizes SPFs in the first and third steps. The resulting statistical models are estimated with road, traffic, and crash data. The BSPF links the expected number of crashes with the exposure variables (here traffic and number of intersection legs). A, so-called Full SPF (FSPF) include as many other road variables as permitted by the available data and the statistical significance of these variables.

In this study, the FSPFs included all the deficiencies found to be significant based on the statistical analysis of the crash counts and knowledge of where the deficiencies were present. This allowed checking the effectiveness of the safety management system where its imperfections are introduced only by the random crash counts and the weaknesses of the safety audit. The following several sections introduce the safety management components simulated in this study.

Safety Management Database

The Indiana state-local intersection data supplemented with additional simulated values were used as

TABLE I.6
Basic statistics of the generated crash counts.

Parameter	Npd	Nbc	Nka
Mean	3.24	0.82	0.20
Standard Deviation	7.44	2.28	0.63
Range	307	54	16
Minimum	0	0	0
Maximum	336	78	17
Sum	72172	10865	2916

the safety management database, which included the following:

- Intersection ID.
- Area type (rural, urban).
- AADT on major (state) road, Q in veh/day.
- Binary indicator of a three-leg intersection, T.
- Thirty binary road variables (D_1, $D_2 \ldots D_{30}$) indicating which of the selected 30 road deficiencies are present at intersections.
- Three-year crash counts at three levels of severity (KA, BC, and O), N_1, N_2, N_3 in crashes/three years.

Table I.6 summarizes the descriptive statistics of the generated crashes.

Safety Performance Functions

Six BSPFs were estimated for rural and urban intersections for the three crash severity levels using the traditional Negative Binomial regression technique:

$$a_{is} = e^{\gamma_s + \alpha_{Qs}\ln(Q_i) + \alpha_{Ts}T_i} \quad \text{(I.9)}$$

where:

a_{is}= estimated frequency of crash of severity s at intersection i;

g= Gamma-distributed variable with mean equals 1 and small variance (0.05 used);

γ_s= estimated parameter;

α_{Qs}= estimated traffic volume coefficient;

Q_i= annual-average traffic volume on the state road (veh/day);

a_{Ts}= estimated parameter for the three-leg intersection;

T_i= 1 if the intersection has three legs, 0 otherwise.

The estimated parameters and statistical performance are presented in Appendix C.

Six FSPFs were estimated for rural and urban intersections for the three crash severity levels using the traditional Negative Binomial regression technique. The selected deficiencies are the ones with higher significance:

$$a_{is} = g \cdot e^{\gamma_s + \alpha_{Qs}\ln(Q_i) + \alpha_{Ts}T_i + \hat{a}_{1s}D_{i1} + \ldots + \hat{a}_{30s}D_{i30}} \quad \text{(I.10)}$$

where:

a_{is}= estimated frequency of crash of severity s at intersection i;

g= Gamma distributed variable with mean equal 1 and small variance (0.05 used);

γ_s= estimated parameter;

α_{Qs}= estimated traffic volume parameter;

Q_i= annual-average traffic volume on the state road (veh/day);

α_{Ts}= estimated parameter for the three-leg intersection;

T_i= 1 if the intersection has three legs, 0 otherwise;

$\hat{a}_{ds}$= estimated parameters for deficiencies: 1 through 30;

D_{id}= 1 if safety deficiency d (d=1, 2…30) is present at intersection i, 0 otherwise.

The estimated parameters and statistical performance are presented in Appendix C.

Network Screening

Evaluation of alternative network screening performance measures was one of the primary objectives of this study. A few performance measures were selected from the HSM and supplemented with additional ones were applied to the studied intersections. Some of the strategies used the basic and others used the full versions of the estimated SPFs. All the evaluated measures included in the sorting criteria for ranking the intersections. Several criteria were included:

1. *Potential for Improvement* is the statistical evidence that there is a systematic source of crashes other than high exposure; thus, the safety can be improved by eliminating the source of the risk. Three measures were evaluated: Level of Safety Service (*LOSS*), Index of Crash Cost (I_{cc}), and Index of Crash Frequency (I_{cf}).
2. *Crash Frequency* is the expected number of crashes reported at the intersections during the analyzed three years. This value was estimated in five different ways: (1) total number of reported crashes (N_{obs}), (2) number of crashes predicted with the BSPF (N_B), (3) number of crashes predicted with the BSPF updated with the crash counts using the EB method ($N_{B\text{-}EB}$), (4) number of crashes predicted with the FSPF (N_F), and (5) number of crashes predicted with the FSPF updated with the crash counts using the EB method ($N_{F\text{-}EB}$). This criterion reflects the overall safety problem at a road without consideration for the severity of crashes.
3. *Total Crash Cost* is the expected total cost of all crashes during the analyzed three years. This criterion was obtained by multiplying the crash frequency at each level of severity by the average costs, which were then summed up for the total costs. This value was estimated in three different ways corresponding to the three methods of estimating the crash frequency described in the crash frequency case (C_{obs}, $C_{B\text{-}EB}$, $C_{F\text{-}EB}$). This criterion reflects the overall safety problem at a road as determined by the frequency and severity of crashes.
4. *EPDO Frequency* was obtained by dividing the total crash cost (C_{obs}, $C_{B\text{-}EB}$, $C_{F\text{-}EB}$) by the average cost of a PDO crash which yielded three corresponding EPDO frequencies: $EPDO_{obs}$, $EPDO_{B\text{-}EB}$, and $EPDO_{F\text{-}EB}$. This criterion yields results that are identical to the results obtained

TABLE I.7
Screening criteria.[1]

Symbol	Sorting Criterion	Group	Figure
I_{cf}	Index of Crash Frequency	Potential for improvement	Figure I.1
I_{cc}	Index of Crash Cost	Potential for improvement	Figure I.1
$N_{Delta\text{-}B}$	Potential number of crashes to save (N_{obs}-N_B)	Potential for improvement	Figure I.1
$N_{Delta\text{-}F}$[2]	Potential number of crashes to save (N_{obs}-N_F)	Potential for improvement	Figure I.1
C_{obs}	Total cost of crashes based on counts	Frequency and severity	Figure I.2
$C_{B\text{-}EB}$	Total cost of crashes based on BSPF EB	Frequency and severity	Figure I.2
$C_{F\text{-}EB}$	Total cost of crashes based on FSPF EB	Frequency and severity	Figure I.2
N_{obs}[1]	Crash count reported (observed)	Frequency	Figure I.3
N_B	BSPF-based estimate of crash count	Frequency	Figure I.3
$N_{B\text{-}EB}$	BSPF-based EB estimate of crash count	Frequency	Figure I.3
N_F	FSPF-based estimate of crash count	Frequency	Figure I.3
$N_{F\text{-}EB}$	FSPF-based EB estimate of crash count	Frequency	Figure I.3
RSI	Relative Severity Index	Severity	Figure I.4
LOSS	Level of Service of Safety	Other	Figure I.4

[1]All measures apply to the period of analysis.
[2]This measure is tested only when the BSPF properly reflects the exposure as a reference level.

with the *Total Crash Cost* criterion if the average cost of a PDO crash is the same at all screened roads. Otherwise, slight differences were present in the results.

5. *Relative Severity Index (RSI)* is the ratio of the average crash cost on a road and in the entire population of roads. This criterion reflects the severity of crashes but does not account for their frequency.

A detailed presentation of these measures can be found in Appendix D. The evaluated screening strategies, which are combinations of the sorting and selection criteria, are summarized in Table I.7.

Application of a screening strategy resulted in a list of intersections ranked by the performance measures. These alternative lists served as inputs to the next steps as described in the following two sections.

Safety Audits

The auditing results for the top-ranked intersections were generated with the following assumptions regarding auditing imperfections:

- A safety audit might not reveal all the deficiencies present at an intersection; therefore, the probability of discovering the existing deficiency (true positive) was assumed as 0.80 while the probability of missing the existing deficiency (false negative) was assumed as 0.20. These results were generated randomly using the assumed probabilities.
- A safety audit may incorrectly point out an absent deficiency as existing (false positive). The likelihood of this error was assumed as quite low at 0.02. Thus, the true negative result was probable at 0.98. These results were generated randomly using the assumed probabilities.
- The results of the safety audits formed a $21{,}284 \times 30$ audit results matrix A with elements that indicated the outcome of the safety audit A_{id} with A_{id} equals1 if deficiency d was claimed present at intersection i, and A_{id} equals 0 otherwise. These results may be true or false.

Selecting Countermeasures for Implementation

After identifying the deficiencies at each intersection (both true and false positives), the safety management determines the corresponding countermeasures with associated CMFs F_d and annualized costs C_d. The selection of countermeasures for implementation among those identified was based on their economic feasibility and effectiveness estimated based on the information available to the safety analysts, which included crash counts, SPFs, results of safety audits, and relevant CMFs and cost components. The selection of the countermeasures at the top-ranked intersections ended when the available budget was exhausted. The process is described below.

1. Starting with the top intersection not yet processed, the expected number of crashes at each level of severity was estimated by combining the SPF (Full or Basic) estimate with the crash count.
2. The potential benefit-cost ratios associated with each audit-identified countermeasure not selected yet for implementation were estimated:

$$B_{id} = \sum_{s=1}^{3} (1 - F_{ds}) \cdot \hat{N}_{is} \cdot C_s \qquad (I.11)$$

where:

B_{id} = predicted safety benefit to be generated at intersection i if countermeasure d were implemented;

F_{ds} = CMF for countermeasure d and crash severity s;

$\hat{N}_{is}$ =EB-estimate of crashes of severity s at intersection i adjusted for the countermeasures already selected for this intersection (still may be the original EB-estimate obtained in step 1 if no countermeasure was selected yet for the current intersection);

C_s = average cost of a crash of severity s.

1. An available countermeasure was found that had the highest ratio B_{id}/C_d. This countermeasure was selected if its ratio was higher than 1 and the remaining budget was sufficient. The expected number of crashes then was updated as: $F_{ds}\hat{N}_{is}$ for all severity levels s.
2. Steps 2 and 3 were repeated until the remaining budget was insufficient or there were no more countermeasures to select from that would generate a B_{id}/C_d higher than 1.
3. Steps 1-4 were repeated if the budget remained sufficient.

The selected implementation countermeasures were represented by a $21{,}284 \times 30$ selected-for-implementation countermeasures matrix S with elements S_{id} equals 1 if a countermeasure was selected for implementation and 0 otherwise.

Estimated Performance

The cost-effectiveness of the safety management predicted by a safety analyst was calculated with the following set of equations:

$$B = \sum_{i=1}^{21{,}284} \sum_{s=1}^{3} \hat{N}_{is} C_s \left(1 - \prod_{d=1}^{30} F_{ds}{}^{S_{id}} \right)$$

$$C = \sum_{i=1}^{21{,}284} \sum_{d=1}^{30} S_{id} C_d \qquad \text{(I.12)}$$

where:

B = predicted total safety benefit to be generated at all the intersections with safety improvements during the next three years;

$\hat{N}_{is}$ = EB-estimate of crash frequency of severity s at intersection i without safety countermeasures implemented;

C_s = average cost of a crash of severity s;

F_{ds} = CMF for countermeasure d and crash severity s;

S_{id} = 1 if countermeasure d is selected for implementation at intersection i, 0 otherwise;

C = total cost of all countermeasures implemented.

Performance Analysis

The actual cost-effectiveness of the safety management with the studied alternative network screening strategies can be calculated with the following set of equations:

$$B = \sum_{i=1}^{21{,}284} \sum_{s=1}^{3} a_{is} C_s \left(1 - \prod_{d=1}^{30} F_{ds}{}^{D_{id} S_{id}} \right)$$

$$C = \sum_{i=1}^{21{,}284} \sum_{d=1}^{30} S_{id} C_d \qquad \text{(I.13)}$$

where:

B = total safety benefit generated at all the intersections with safety improvements during three years;

a_{is}= true mean crash frequency of severity s at intersection i without safety countermeasures implemented;

C_s = average cost of a crash of severity s;

F_{ds} = CMF for countermeasure d and crash severity s;

D_{id} = 1 if deficiency d is present at intersection i, 0 otherwise;

S_{id} = 1 if countermeasure d is selected for implementation at intersection i, 0 otherwise;

C = total cost of all countermeasures implemented.

Results

The road network and the safety management were simulated by applying the models and assumptions described in the previous sections of this report. The following steps were followed:

1. Each of the 30 road deficiencies were generated by:

    a. The probability of occurrence.
    b. Three CMFs corresponding to three levels of severity.
    c. The cost of eliminating the deficiency.

2. For each road intersection, the following elements were generated:

    d. Present deficiencies.
    e. The expected number of crashes at each level of severity in the three-year period.

3. For each intersection, the following values were generated:

    f. Crash counts at each level of severity in the three-year period.
    g. Present deficiencies correctly identified and absent deficiencies incorrectly claimed to be present.
    h. Deficiencies (correct and false) with the estimated B/C>1 selected for elimination.

4. For each evaluated screening criterion (see Table I.7):

    i. All the intersections were sorted by the screening criterion.
    j. The benefits and costs for each intersection were calculated cumulative from the top to the current intersection.

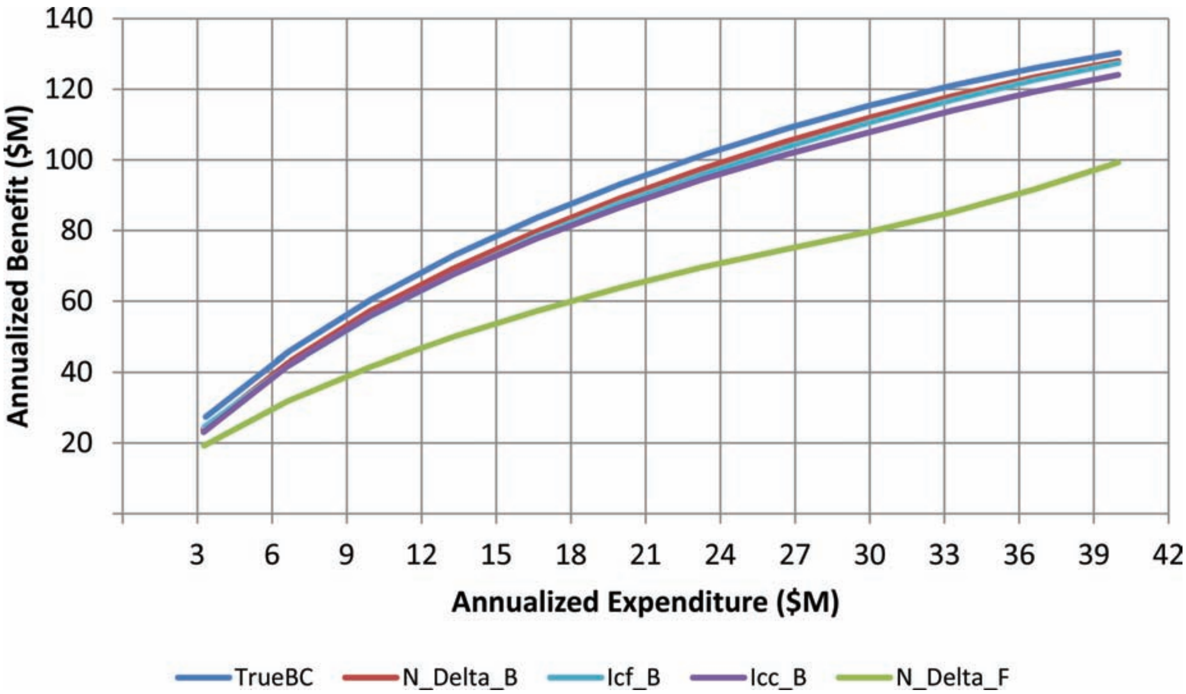

Figure I.1 Economic effectiveness of screening criteria—potential for safety improvement.

k. The intersection at each budget level on the sorted list for which the cumulative cost was still below or at the budget and the next higher intersection were identified. The cumulative benefits and costs corresponding to the budget level were saved.

Steps 3 and 4 were repeated 50 times and the benefits and costs were averaged for each screening criterion and each budget level. The obtained benefits and costs are graphically presented and discussed below.

The investigated screening criteria were divided into four groups as shown in Table I.7 and Figures 3.1 through 3.4:

1. Potential for improvement
2. Frequency and severity
3. Frequency
4. Other: LOSS and RSI

The best performance of the network screening and the highest cost-effectiveness of the management system can be accomplished if the true deficiencies and the true benefits from their elimination are known. This case corresponds to sorting the road locations by the true B/C ratio. The studied criteria were compared to this ideal case called *TrueBC*.

Figure I.1 presents the total true safety benefit (cost of crashes saved) if the intersections were sorted by one of the four criteria that represented the evidence of the source of crash risk not related to exposure. Indeed, the Index of Crash Frequency, the Index of Crash Cost, and the $N_{Delta\text{-}B}$ related the crashes and their costs to the values expected when only the exposure variables were accounted for. The $N_{Delta\text{-}F}$ value does not have this meaning as it relates the crash counts to the counts expected based not only on the exposure but also on the road deficiencies. As expected, the performance of the safety management based on this screening criterion was much lower than when the other three screening criteria were used.

Surprisingly, the $N_{Delta\text{-}B}$ slightly outperformed the other two measures, I_{cf} and I_{cc}, which are statistically more advanced and the I_{cc} includes crash severity, which is the strong factor of crash costs and thus the safety benefits. Although the I_{cc} performed slightly worse than the other two, most likely due to certain approximations in the calculations, it was preferred. The performance of I_{cf} and $N_{Delta\text{-}B}$ may be lower if the screening roads experience much more diversified crash costs than the ones assumed in the simulation. The three screening criteria compared well with the True BC criterion.

Figure I.2 presents the performance of the three criteria that represented the total cost of crashes. These criteria do not focus on the potential sources of the excessive risk, thus they may favor roads with high exposure. As expected, the cost estimation with the use of the FSPF slightly increased the screening performance. This difference was particularly small when the selection of roads for improvement focused on the top locations.

Figure I.3 compares the criteria that represent the crash frequency without regard for the severity of the crashes. It is rather surprising that the EB method did not make much difference; the sole crash counts used for sorting the roads performed as well as the two EB estimates. The explanation may be in the useful information about safety deficiencies included in the

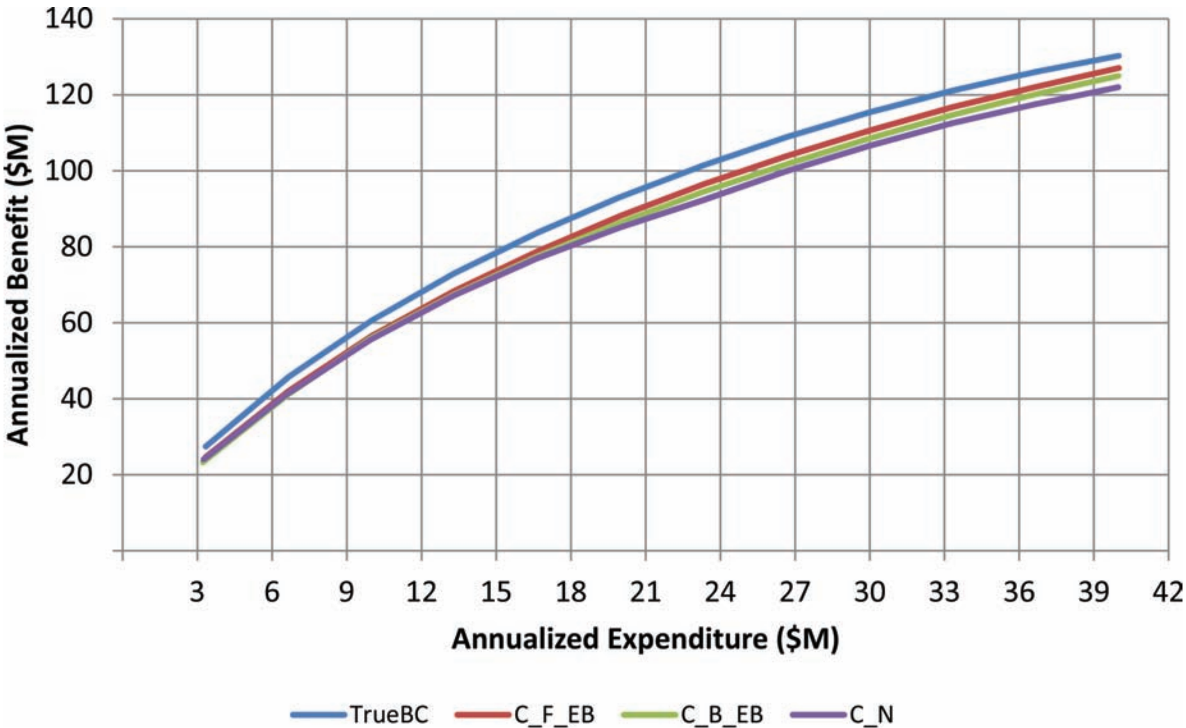

Figure I.2 Cost effectiveness of screening criteria—frequency and severity of crashes.

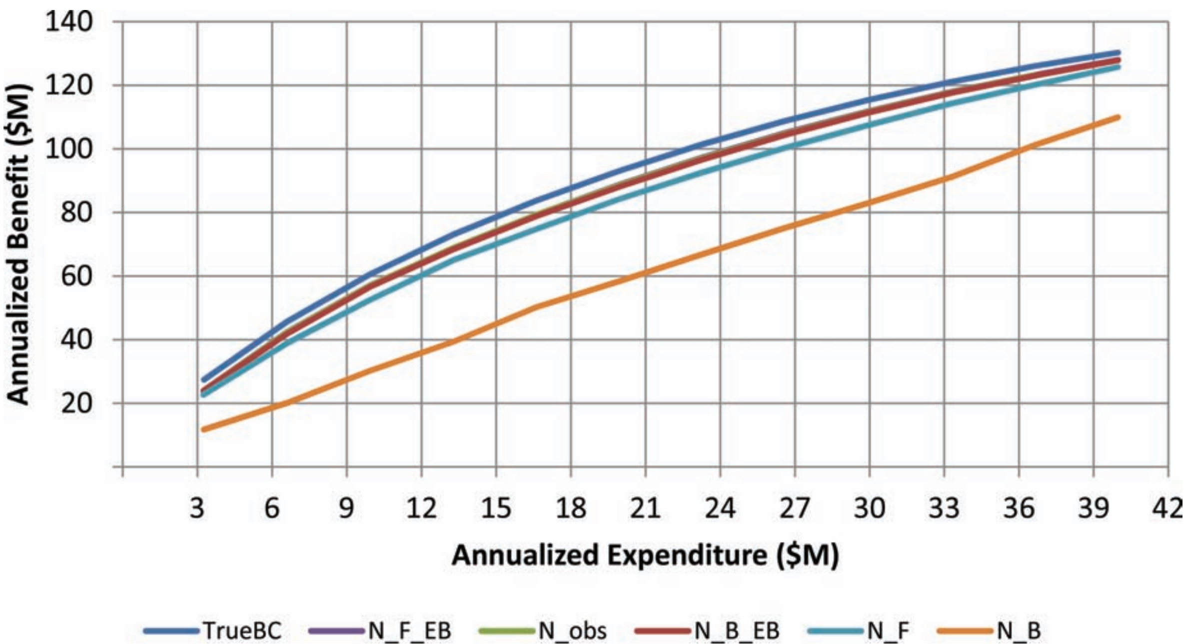

Figure I.3 Cost effectiveness of screening criteria that represent the frequency of crashes.

crash counts, which cannot be much improved with the EB method. It also is mentioned that the differences between the sorted lists of roads were not very useful as far as the overall performance if the majority of the treated roads from both lists were the same. Only the BSPF estimates performed much worse than the other method, which was not surprising because the BSPF does not include any information about safety deficiencies.

The top frequency-based screening criteria seemed to slightly outperform the crash cost criteria, which account for the severity of crashes. There are two plausible

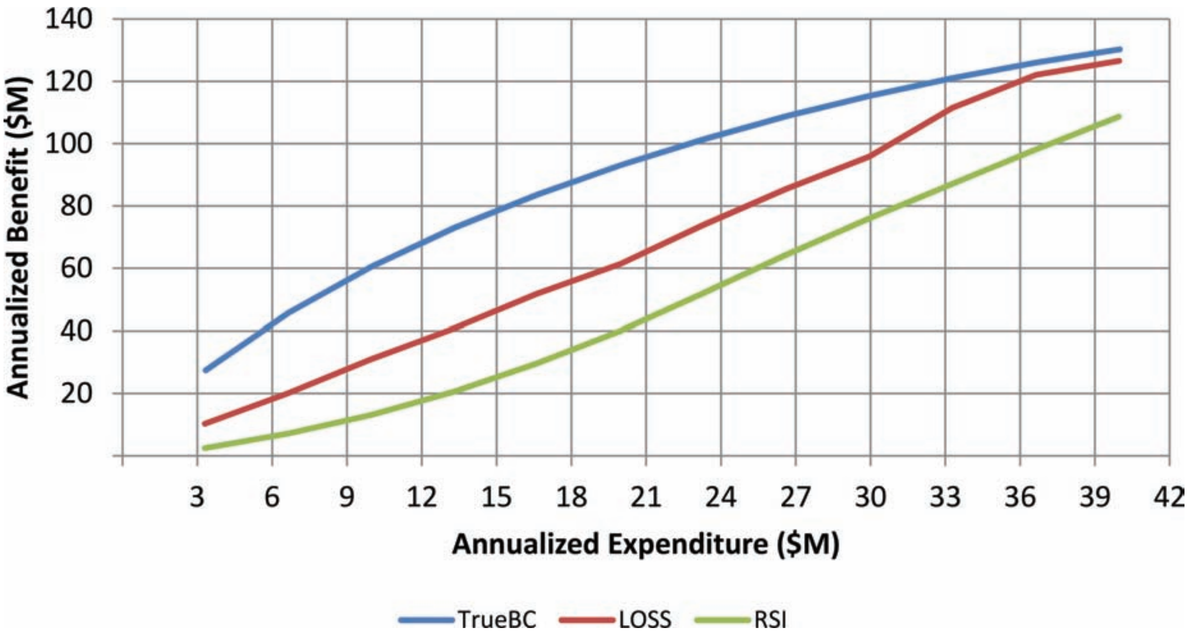

Figure I.4 Cost effectiveness of LOSS and RSI screening criteria.

explanations. First, severe crashes are much more expensive and less frequent; thus, their inclusion in the screening criteria may have introduced a large extra randomness. On the other hand, roads with a large number of crashes that were not severe represented the risk of more severe crashes well. However, this benefit of using only the crash frequency may be reduced if the network includes roads where the ratio between the severe and not severe crashes varies between roads much stronger than in the simulated example.

Figure I.4 presents two rather poorly performing screening criteria: LOSS and SRI. The performance of the LOSS criterion may have been jeopardized by the discretization of the measures in four levels, which thus reduced its sensitivity to the changes in the potential for improvement. Otherwise, this measure was comparable to the Index of Crash Severity. The SRI criterion, on the other hand, did not reflect the crash counts and only their average severity. This measure is important where the fairness of the management system (reducing the risk in a way that equalizes the risk across roads) is among the objectives and not necessarily the overall effectiveness only. This study preferred screening criteria that offered the maximum benefit without fairness being considered. From that point of view, the RSI measure therefore was inadequate.

Among all the screening measures compared, this study recommended the following for implementation in the road network screening: I_{cc}, $C_{F\text{-}EB}$, I_{cf}, $N_{Delta\text{-}B}$, and $N_{F\text{-}EB}$. Preference was given to criteria that accounted for crash severity and frequency (I_{cc} and $C_{F\text{-}EB}$) even if they performed slightly worse in the simulation than the frequency-based criteria. They appeared to be more trustworthy in general, particularly in road networks where the proportions of severe crashes in total numbers varied strongly across the roads. The criteria that measure the potential for safety improvement (I_{cc}, I_{cf} and $N_{Delta\text{-}B}$) must use BSPFs to maintain the proper reference level, which depends solely on the exposure variables. On the other hand, the criteria that reflect frequency ($N_{F\text{-}EB}$) or frequency and severity ($C_{F\text{-}EB}$) should use as much elaborated SPFs as possible.

Some of the recommended screening criteria can be found in the HSM and others in the Indiana procedures. All of them performed equally well if the SPFs they utilized were developed or properly calibrated to the conditions of the region where the screening was conducted.

ECONOMIC EVALUATION

Economic evaluation was performed to compare the benefits of potential crash reduction of a countermeasure to its implementation costs. Economic evaluation is normally conducted after the highway network is screened, the selected sites are diagnosed for potential safety needs, and potential countermeasures for reducing crash frequency or crash severity are selected. The HSM has procedures for economic evaluation of alternative safety projects (AASHTO, 2010; Kwona, Prka, Yeoa, & Chung, 2013). However, Indiana has its own procedures for economic evaluation, which were developed and implemented before the HSM procedure became available. These methods differ from each other in terms of the analysis period, the capacity constraints, and the SPF usage. Despite these differences, the two methods were reconcilable and produced identical results after making certain modifications. This chapter documents the economic analysis procedures of HSM and Indiana by showing the differences between the two methods and providing example

TABLE I.8
Comparison of economic evaluation procedures of Indiana practice and HSM.

Step	Indiana Practice	HSM
Estimate the safety without countermeasures implemented	1. Using SPFs, predict the FI, NI, and PD crash frequencies for the middle year of the crash data period. 2. Use the EB method to update the crash frequencies predicted in step 1 with the crash counts during the crash data period. 3. Calculate the EB estimate of crash frequency in the first year of the project's lifetime by adjusting for the traffic growth.	1. Using SPFs for TOT and FI, predict the crash frequency—for each year of crash data period. 2. Compute annual correction factor for each year of crash data period to reflect the change in the crash frequency due to the traffic growth. 3. Use the EB method to calculate the crash frequencies for the first year of the crash data period predicted in step 1, with the crash counts for the entire period divided by the equivalent number of years that reflect the traffic growth during the crash data period. 4. Calculate the EB estimate of all crashes in the crash data period by multiplying the EB estimate for the first year with the equivalent number of years. 5. Calculate the total number of crashes in the crash data period using the SPFs only. 6. Calculate the EB adjustment factor as the ratio of the estimates obtained in steps 4 and 5. 7. Calculate the EB estimate for each year of the analysis period as the crash frequency estimate with the SPF adjusted with the EB factors obtained in step 6.
Estimate the safety with the countermeasures implemented	4. Calculate the combined CRF that reflects the joint effect of all the applied countermeasures. 5. Calculate the crashes saved in the first year of the project lifetime by multiplying the predicted crash frequency for each crash severity level by the joint crash reduction factor.	8. For each year of the analysis period, calculate the number of crashes after the reduction caused by the countermeasure. 9. Calculate the crashes saved in each year of the analysis period as the difference between the numbers calculated in steps 7 and 8. The saved PDO crashes are the difference between the total crashes saved and the FI crashes saved. 10. Divide the saved FI crashes into the final severity (K, A, B, C) levels using the statewide proportions.
Estimate the present worth of the safety benefit	6. Estimate the present worth of the crash benefit using the crash reductions and average costs adjusted for inflation. 7. Determine the traffic growth period. 8. Calculate the total present worth of the benefit during the growth period 9. Calculate the total present worth of the benefit during the rest of the period (infinite). 10. Calculate the total present worth of the safety benefit.	11. Calculate the present worth of the benefit for each year of the analysis period. 12. Calculate the total present worth of the benefit during the analysis period.
Estimate the present worth of the agency's cost	11. Calculate the present worth of the capital cost. 12. Calculate the present worth of the difference in the maintenance costs caused by the countermeasure. 13. Calculate the present worth of the salvage value. 14. Calculate the present worth of the total agency cost.	13. Calculate the annualized construction cost.
Annualize the cost components	15. Annualize the safety benefit. 16. Annualize the agency cost.	14. Calculate the present worth of the construction cost for the analysis period.
Calculate the economic performance	17. Calculate the B/C ratio. 18. Calculate the annualized net benefit. 19. Calculate the present worth total benefit.	15. Calculate the B/C ratio based on steps 12 and 14.

calculations that demonstrate how the differences in results can be eliminated if the methods are reconciled.

Economic Evaluation Procedure

The Indiana and HSM procedures for economic evaluation of safety improvement projects are compared in Table I.8 (see Appendix E for further details). To facilitate the comparison, the procedures were summarized in the following six computational steps:

1. Estimate the safety without countermeasures implemented.
2. Estimate the safety with the countermeasures implemented.
3. Estimate the present worth of the safety benefit.
4. Estimate the present worth of the agency's cost.
5. Annualize the cost components.
6. Calculate the economic performance.

TABLE I.9
Characteristics of the example rural two-lane road segment.

Analysis Period (years)	Initial Q_i	Annual Traffic Growth Rate R (%)	Road Capacity Q_m (veh/day)	Crashes (in 3 years)			Input Traffic Growth Period GY (years)
				N_{PD}	N_{BC}	N_{FI}	
10,000	5,000	2	100,000,000	18	12	1	10,000

TABLE I.10
Properties of the countermeasures.

Countermeasure	Countermeasure 1	Countermeasure 2
Service Life SL (years)	15	30
Capital cost ($)	200,000	30,000
Maintenance cost ($)	5,000	1,000
Salvage cost ($)	1,000	–

TABLE I.11
Results of the economic evaluation.

Economic Indicator	Indiana Practice	HSM
Annualized benefit ($)	140,204	140,204
Annualized cost ($)	33,173	33,173
Annualized net benefit ($)	107,031	107,031
B/C ratio	4.2	4.2

Differences in Indiana practice and HSM Procedures

The three differences between the Indiana and HSM procedures are as follows.

1. HSM has a finite analysis period, whereas Indiana assumes an infinite analysis period. The infinite period eliminates the cut-off issue that occurs when the finite analysis period is not a multiple of all the countermeasure lifecycles.
2. Indiana assumes that the traffic grows during a certain period to reach capacity and does not grow thereafter. This assumption solves the issue of infinite traffic growth during the infinite analysis period. HSM assumes a continuous growth rate for the entire analysis period, thus allowing traffic growth beyond a reasonable limit if the period is long and traffic is already heavy.
3. The safety analyst (Harwood et al., 2010) using the HSM (AASHTO, 2010) procedure develops two sets of SPFs, one for the total and the other for the fatal and injury crashes; and in order to incorporate the costs of all injury severities, the injury severity proportions are taken from the statewide accident proportions. Indiana uses three sets of SPFs (PDO, NI, and FI) and does not depend on the statewide proportions to calculate the crash cost.

Results Reconciliation

Despite the above-mentioned differences, these two methods are reconcilable under certain conditions (i.e., relaxing capacity constraints for the traffic growth period for Indiana, assuming a long analysis period and three sets of SPF for HSM, and considering the current year being the implementation year).

In order to illustrate the procedures of the two methods, a rural two-lane road was analyzed. Thirty-one crashes of different severities occurred on the example roadway segment during the 2012–2014 analysis period. As both procedures are sensitive to the length of the analysis period and the capacity constraints, assuming a very long analysis period (10,000) and enormous capacity (100,000,000) was the best way to illustrate the procedures. The traffic growth period also was assumed to be very long for the Indiana procedure. Later in this chapter, the results of sensitivity analysis are presented for different capacity constraints (starting with the existing volume to infinity), a varied analysis period (very short to very long), and both. The roadway segment characteristics are presented in Table I.9.

Two countermeasures were implemented along the road segment to mitigate the above-mentioned crashes. The countermeasure was to be implemented in 2015, with the current year being 2015. Three percent inflation rate was assumed with an interest rate of 4 percent. The countermeasures had the characteristics presented in Table I.10.

Table I.11 shows the results of the economic evaluation. Based on the assumption of a very long analysis period (10,000 years) and with very high capacity (100,000,000), the annualized benefit, annualized cost, and benefit cost ratio of Indiana and HSM were identical.

The Effect of Analysis Period and Capacity Constraints

Sensitivity analysis was performed based on the analysis period, the traffic growth constraints, and both. Figure I.5 shows the effect of the analysis period on the Indiana and HSM B/C ratios. Indiana's B/C ratio was constant because the crash reduction benefit and countermeasures implementation costs were annualized so the analysis period duration had no effect on the B/C ratio. The HSM B/C ratio depended on the cumulative benefit of crash reduction for the analysis period, which caused the B/C ratio to be less for the shorter analysis periods and steadily growing with longer analysis periods. HSM's B/C ratio converges with the Indiana's B/C ratio when the analysis period was 150 years if everything else remained constant.

Figure I.6 shows the effect of the capacity constraints on the Indiana and HSM B/C ratios. The HSM B/C ratio was constant because of the fact that the HSM assumes that the traffic growth rate applies for an

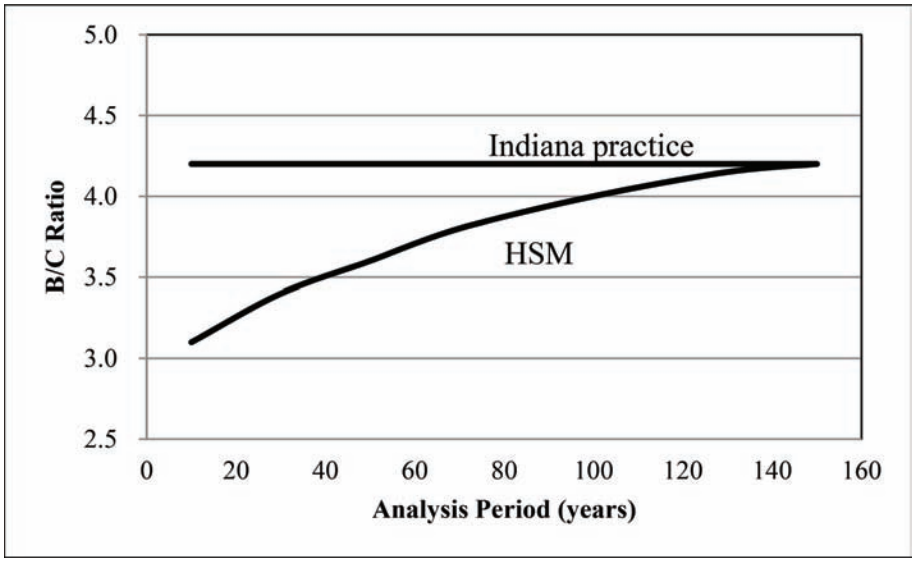

Figure I.5 Analysis period effect on B/C ratio.

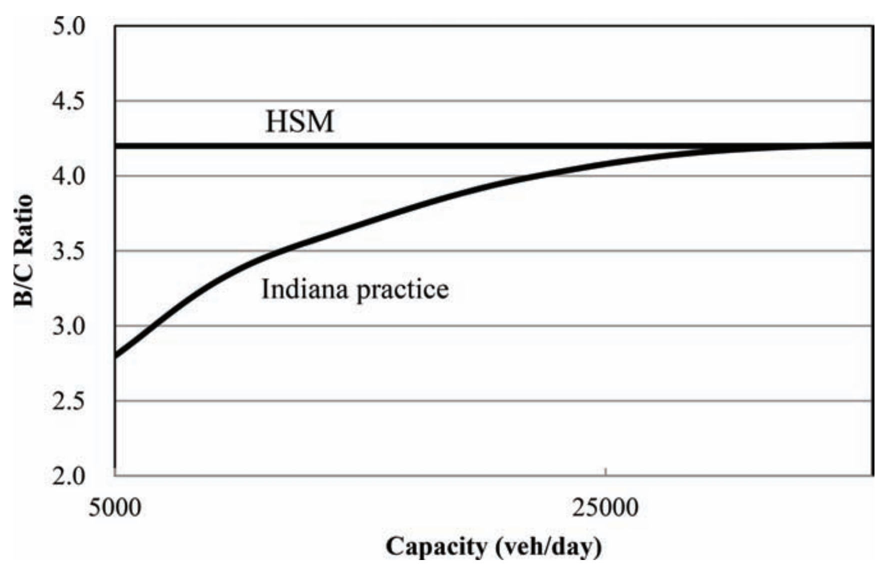

Figure I.6 Capacity constraint effect on B/C ratio.

infinite period of time; therefore, capacity constraints had no effect on the B/C ratio. Indiana, on the other hand, assumes that traffic will grow until it reaches capacity for a certain period (growth period) and thereafter will reach its capacity and remain constant for the analysis period. That is why the B/C ratio was less for low capacity and the ratio grew with higher capacity. The Indiana B/C ratio converged with the HSM B/C ratio when the capacity was sufficiently high enough (50,000) with everything else remaining constant.

A sensitivity analysis also was performed based on changing the analysis periods and capacity constraints. Figure I.7 shows the effect of changing the analysis periods and capacity constraints on the Indiana and HSM B/C ratios, which are represented by the Y axis in the figure. When the capacity was equal to the existing volume, the Indiana and HSM B/C over B/C ratio gradually decreased over the longer analysis period because the analysis period duration had no effect on the Indiana B/C, and the HSM B/C increased with the longer period. With a high capacity and shorter analysis period, the B/C over B/C ratio was much higher than 1 because the HSM B/C ratio was penalized by the shorter analysis period. For a typical analysis period (40-50 years) of any transportation safety improvement project, the Indiana B/C ratio was higher than the HSM B/C ratio for different capacity constraints. When the analysis period was longer (more than 100 years) and the capacity was high enough (50,000), the results were identical.

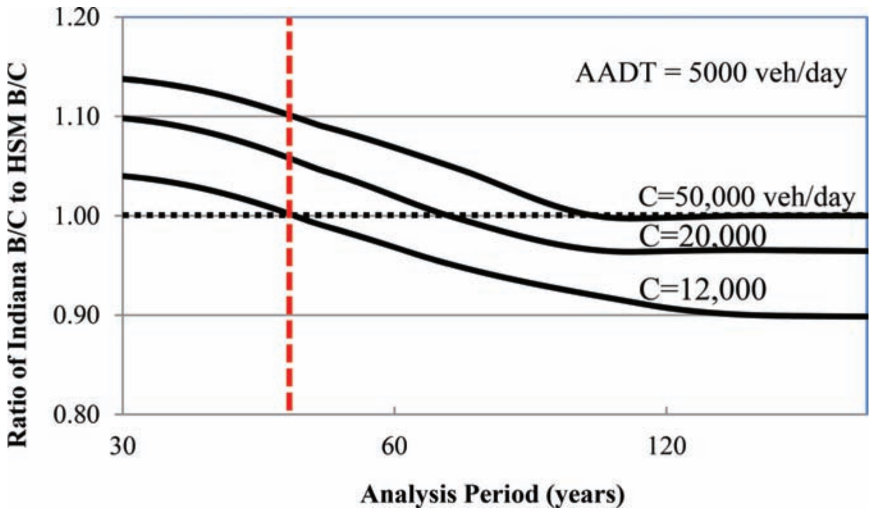

Figure I.7 Effect of the analysis period and the capacity constraint on B/C ratios.

Findings Summary

The sensitivity analysis results above show that the traffic growth period and capacity constraints were significant influencing factors that produced differences in the results of the economic evaluation of road safety improvements. Indiana's procedure was not sensitive to the analysis period because it annualizes the benefits and cost of implementing countermeasures, while the HSM procedure was highly sensitive to the analysis period as the benefits and cost of implementing countermeasures are accumulated over the analysis period. On the other hand, the Indiana procedure was very sensitive to the roadway capacity because, unlike the HSM's infinite period of traffic growth, it assumes a certain period for traffic growth. Based on the sensitivity analysis of this study, it was therefore concluded that the B/C over B/C ratio of the Indiana and HSM procedures will produce identical results for high capacity roads and longer analysis periods.

CONCLUSIONS

Indiana developed its safety management procedures before the HSM and the SafetyAnalyst became available. The considerable cost of the SafetyAnalyst and the required additional efforts to adjust the Indiana data and engineering procedures to the HSM methodology, caused Indiana to use its own safety management tools, SNIP and RoadHAT. Comparing the Indiana and HSM-based safety management methods is justified as the identified differences and similarities may help improve both methods. This study evaluated the following three key components of safety management present in both the methods: (1) Safety Performance Functions (SPFs), (2) network screening and (3) economic analysis. The comparison focused on the analytical components of the methods rather than on the implementation of these methods through computer tools.

Safety Performance Functions

This study concluded that the HSM SPFs would need to be calibrated to the Indiana conditions before they can be used. The requirement of calibrating for roads in the base conditions leads to an insufficient number of roads and, consequently, estimates that are not trustworthy. This problem is amplified by the large number of road categories and crash types in HSM (110 categories and 468 crash severity proportions), thus making the number of roads in most category too low for obtaining confident calibration results. This re-calibration process is not a one-time effort as the process must be repeated over time to keep up with the overall changes in safety.

The Indiana procedure has SPFs for 19 different types of roads and three levels of crash severity. Indiana's SPFs are calibrated for all roads in the network, not just for those in the base conditions, and therefore provides much more confident estimation of the SPFs. If needed, these average-conditions SPFs can be transformed to the base conditions using the estimated safety impacts of the road geometry.

Network Screening

An advanced statistical simulation of a safety management system that intends to maximize the total net benefit indicated that the most important element for safety management effectiveness is the selection of adequate network screening criteria.

The HSM EPDO-based measure and Indiana total cost of crashes are equivalent criteria producing the same results. They have been found the top screening criteria. HSM criteria that proved to be inadequate for road network screening included the Level of Safety Service and the Relative Severity Index. It is important that the HSM provide guidance as to which screening criteria support which screening objectives. Incorrect selection may lead to considerable losses.

Three top criteria that support the maximization of long-term cost-effectiveness of a safety management are:

1. The total cost of crashes estimated by combining the reported crashes with the predicted ones from the full SPFs (elaborated equation that includes multiple explanatory variables).
2. The potential for crash reduction calculated as the difference between the total number of crashes and the number predicted with exposure SPFs that include only the exposure variables.
3. The Index of Crash Frequency I_{cf}.

Although the total number of crashes was shown to be an effective criterion of identifying locations with high potential for safety savings, its usefulness strongly depends on the correlation between severe and less severe crashes. Nevertheless, this result indicates that any crash provides a risk of a severe outcome; thus, a large number of crashes are a good indicator of a safety problem.

It also was concluded that although the cost of crashes and the Index of Crash Cost and Frequency used separately proved to be good screening criteria in Indiana, the combined use of these two measures did not deliver any considerable improvement and its use could be abandoned.

Economic Analysis

Two major differences were found between the HSM and Indiana procedures for evaluating the benefits and costs of safety projects: the infinite period of analysis and the road capacity constraint on traffic growth. The Indiana results were sensitive to the capacity constraints while the HSM results were sensitive to the length of the analysis period. The differences between the two methods were typically quite limited and became negligible if a high road capacity in the Indiana method and a long analysis period in the HSM method were assumed.

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PART II. COLLISION DIAGRAM BUILDER

Installation

The Crash Diagram Builder (CDB) program, in its current version, is distributed as a self-contained application. Any supplementary instructions are included in the accompanying readme.txt file. The user should click on the setup.exe file to start the installation process. Once the installation is completed, the program should be accessible on the Windows Start Menu under the category *All Programs\CDB.*

Data Requirements

The CDB tool helps the user display crashes on collision diagrams and investigate the crash patterns. The current version is designed for road intersections. The tool attempts to automatically assign crashes to probable locations. To do so, it needs to access and interpret crash data found in police reports. Only crashes that occurred at a studied road intersection during a studied period should be included in input files. The following crash records should be extracted from the police reports and provided by the user in three separate text files:

- Collision data (Record Type =10)
- Unit data (Record Type=20)
- Factors data (Record Type=22)

These tables should be supplied in separate CSV files, and should follow the same specifications used by the state police system database (ARIES). These specifications are in the Section: Specifications of the Input Data Files. A near-future modified version will include a stand-alone format translator to help CDB users prepare these input files.

The tool requires a JPG image of the studied intersection to be used as a background for displayed crashes. Multiple crashes of the same type are represented by a single crash icon and a bar diagram that reflects the number of crashes. A multivehicle crash type is defined by the initial direction of travel and the traffic maneuver of the first two road users listed in the police record. A single-vehicle crash is defined by the initial direction of travel of the vehicle, its traffic maneuver and the hit object.

The image should be sufficiently large to accommodate all the icons for all occurring types of crashes. The image should include the intersection central area and part of the each approach upstream of the entry lines. Rear-end collision icons are placed right upstream of the entry lines. Including excessively long approach segments reduces the size of the displayed intersection central area where the majority of crash types occur. Figure II.1 demonstrates this issue.

The CDB checks the crash data, marks suspicious crash records, and provides a tool for correcting the data by the user. The user may provide PDF files of the original police reports and PDF (or JPG) files of the police crash diagrams. These files help the user visually confirm the correctness of crash data. These files are not required.

General Overview

The CDB creates a project folder where all the input data and the results are stored. Among the items stored in the project folder are:

- Basic project information such as the intersection street names, name of the analyst, date of the analysis, and years of crash data analyzed with the tool, and additional comments.
- A user-provided aerial image of the intersection.
- The police crash data for the studied intersection and years.
- PDF copies of original police reports (not required).
- JPG or PDF copies of collision diagrams made by an investigating police officer (not required).
- User-created elements of the intersection including leg names, entry lines, exit lines, vehicle paths, and pedestrian paths.

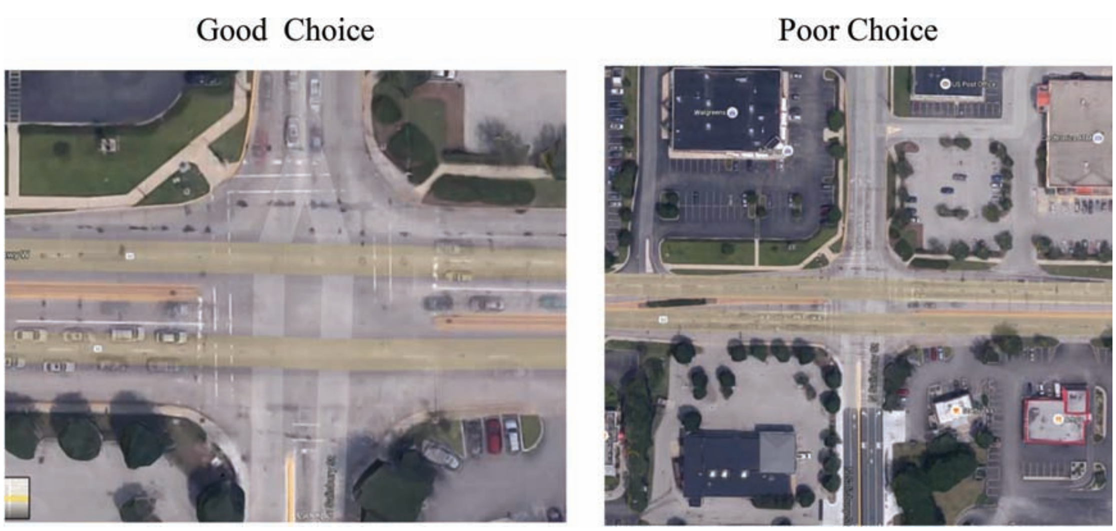


Figure II.1 Selecting proper image size.

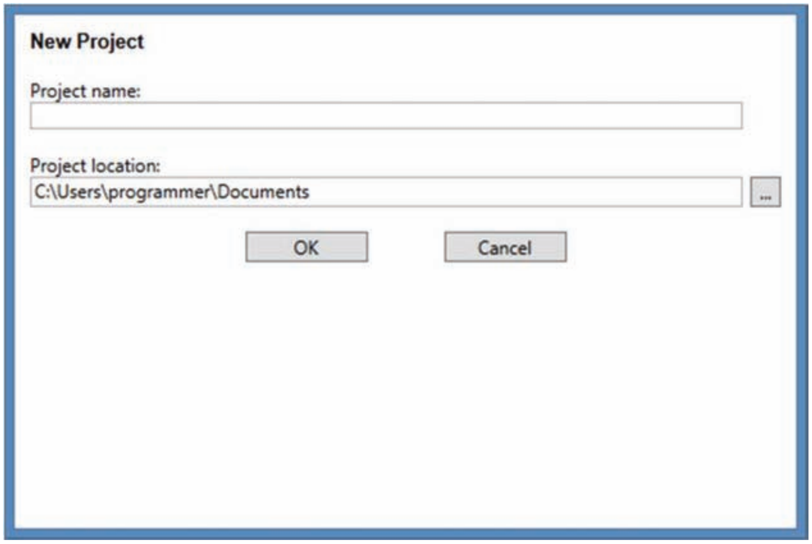


Figure II.2 Creating a project.

- User-saved collision diagrams with both the crash icons positioned at the intersection automatically or manually and the crash frequency bars by crash type and for a subset of crashes selected based on the user-defined filter.
- User-saved two-way tables of crash frequencies for user-defined variables and for a subset of crashes selected based on the user-defined filter.

Interface

The CDB interface provides commands and options in four functionality areas:

1. **Menu Bar** provides options to manage the project and its files and input data.
2. **Annotate Image Tab:** In this tab user enters the intersection elements, traffic paths, and their properties. These elements include: Leg Names, Entry Lines, Exit Lines, Vehicle Paths and Pedestrian Paths. The information entered in this tab is used by the tool to assign automatically as many crashes as possible.
3. **Assign Crashes Tab:** This tab provides a tool to examine each crash data and edit it if needed based on the available police reports and diagrams. Indicators of data consistency are provided to help identify suspicious data. After editing the data, the user may accept the revisions to let the tool perform another attempt to automatically assign the crash. Alternatively, the user can manually move the crash icon to the desired position.
4. **Analyze Crashes Tab:** This tab offers tools for analyzing and visualizing crash patterns. The user may display the crash frequencies and their distribution by selected variable directly at the intersection via vertical bars. Another possibility is to cross-tabulate the crash frequency by two variables if user choice in multiple tables. These operations may be performed for all crashes or for their subset defined by a user-set filter. The diagrams and tables can be saved for incorporation into a report.

The following sections describe details of the CDB features.

Menu Bar

The menu bar is used to manage projects including creating a new project and importing new files, opening an existing project and editing or changing some of its elements and images, and exiting the program.

The user starts a project by selecting the *Create Project/Project Name* option (Figure II.2.) The user's Documents folder is a default location where the project folder is created. It can be changed by editing the project location field.

Once a project name is assigned, the user selects three required crash data files: the collision file, the factors file, and the vehicle (units) file (Figure II.3.) Each of these three files should contain only data from crashes whose master record numbers have been previously selected as related to the intersection being studied. Then, the user is asked to select a JPG file with the intersection image (Figure II.4.) This image may be replaced later, if needed. The user is also asked to provide the paths to a folder containing PDF files of the original police reports as well as a folder containing either JPG or PDF files of the original police crash diagrams. If all documents reside in the same folder, the user should simply provide the same path twice.

By convention, a PDF file containing a police crash report should have a name that includes the master record number of the crash followed by the PDF extension. A file containing a police crash diagram should have a name that includes the master record number of the crash followed by the letter d (for diagram). The extension of this file may be either JPG or PDF depending on the format of the file. AIRES used to export diagrams as JPG files, but currently exports them as PDF files. Both versions are supported.

Once all the needed input files are imported and the project creation is completed, the image is displayed

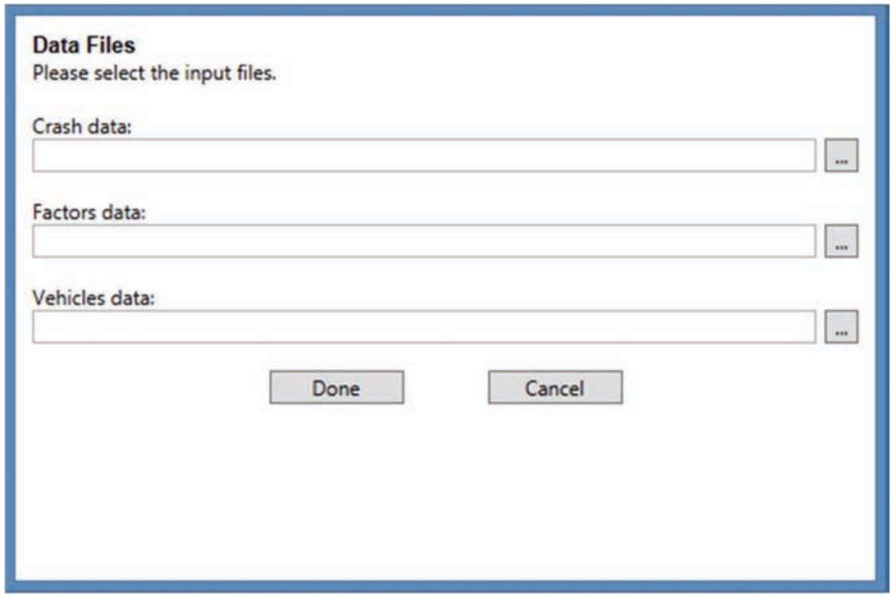


Figure II.3 Required crash data files.

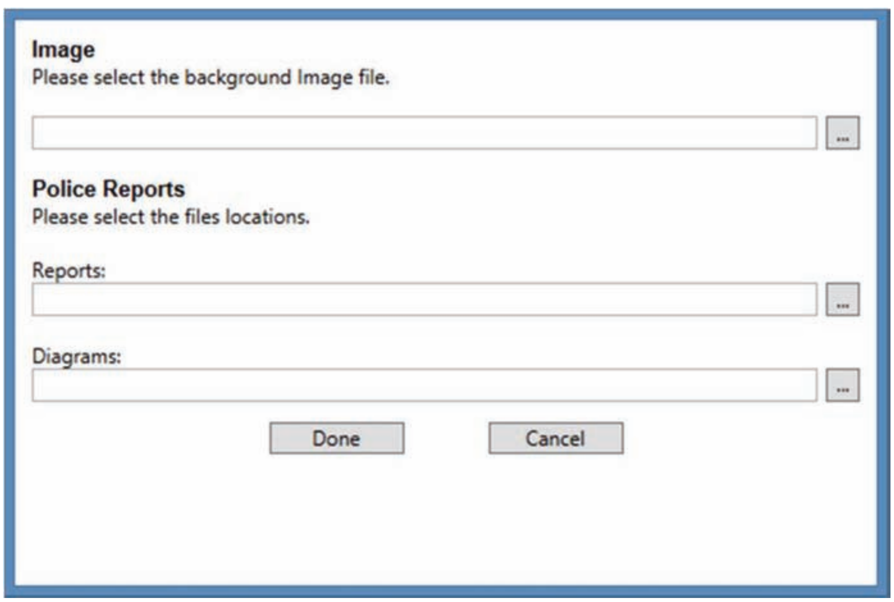


Figure II.4 Intersection image, police report and diagram PDF files.

in the interface window in the *Annotate Image Tab*. The features of the *Annotate Image Tab* are discussed in the next section.

When a project is created, the user may use the *Existing Project/Save* feature at any time to save the project. The saved project preserves all the current results of operations performed so far. The user may also open a saved project with the *Existing Project/Open* feature.

A displayed project image may be replaced with the *Existing Project/Replace Image* feature with another image read from a folder of the user choice. In this case, the new image file is copied into the project folder and it replaces the old image. Finally, the user may leave the project with the *Exit* menu option.

Annotate Image Tab

This tab is used to annotate the intersection image with elements that are needed to automatically assign crashes to adequate locations at the intersection.

The upper area of the tab window shown in Figure II.5 contains tools needed to add, display, edit and configure the settings of these elements. This area also contains zoom in/out buttons and the North arrow

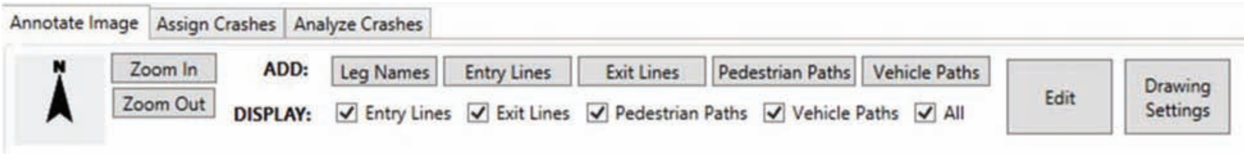


Figure II.5 Annotate image tab—element creation area.

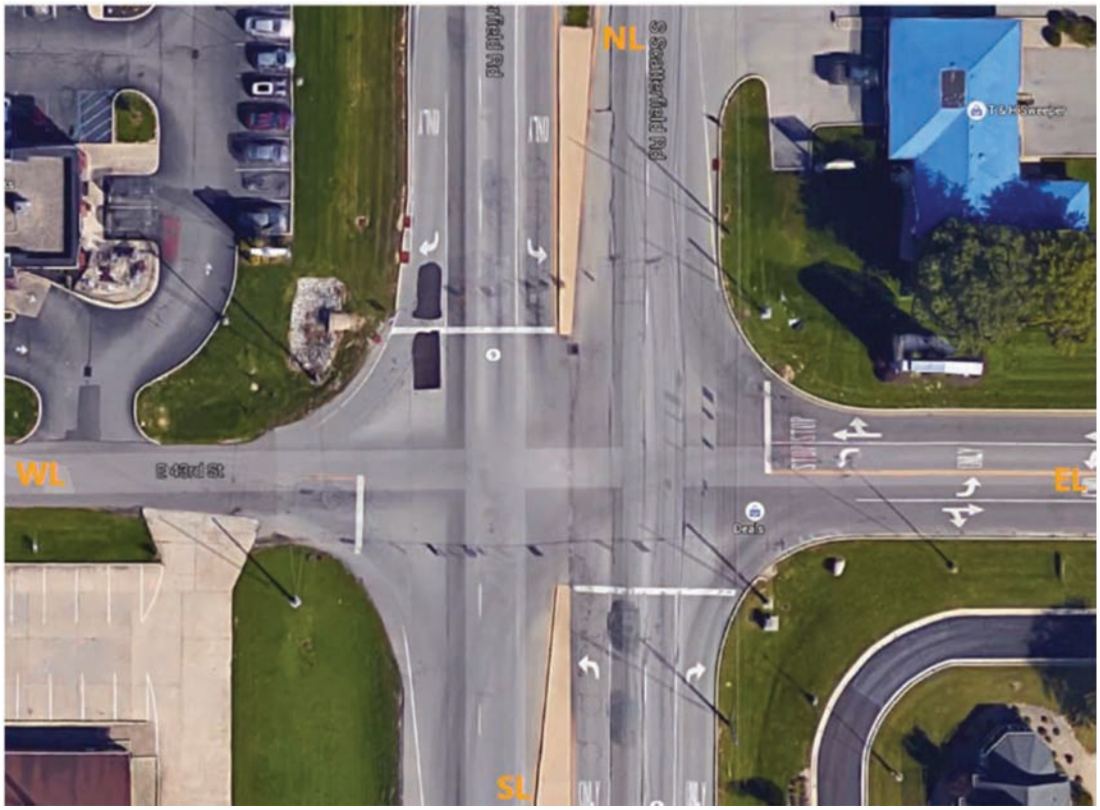


Figure II.6 Leg names.

pointing upward. The current version of the program requires that imported images are oriented consistently with this North arrow.

The rightmost area of the tab window displays the properties of the elements as entered by the user. Although these elements and their properties may be added in any sequences, there is a certain order that minimizes the user effort. This order is reflected below and it may be adjusted to the current needs as the user becomes more experienced.

Leg Names

The users should always start by entering leg names to all the intersection legs (Figure II.6.) This is done by pressing the *Leg Name* button in the *ADD:* row. The user should then place the cursor near one of the legs of the intersection and click the mouse left button. An empty text box appears. The user must click again inside the text box to start typing the name of the selected leg. The process is repeated for all legs of the intersection that the user wishes to label. The label can be moved to a new position at any time. Legs also can be renamed by clicking on the leg name with the mouse right button and entering a new name on the proper field.

Entry lines

Once all leg names are typed, the next step is adding the Entry lines. This is accomplished by first clicking on the button *Entry lines* in the *ADD:* row. This activates the drawing entry lines mode and the mouse cursor changes from an arrow to a cross. The user can then draw the entry line with the mouse, by clicking the mouse left button at two or more distinct points. A red entry line appears between the points. Clicking the mouse right button ends drawing of the current entry line but does not exit the drawing mode and another entry line can be drawn. The process should then be repeated for as many entry lines as needed.

Once all the entry lines are added (Figure II.7), the user may start editing their properties.

Clicking the Edit button changes its color to indicate that the Edit mode is active. The mouse button also

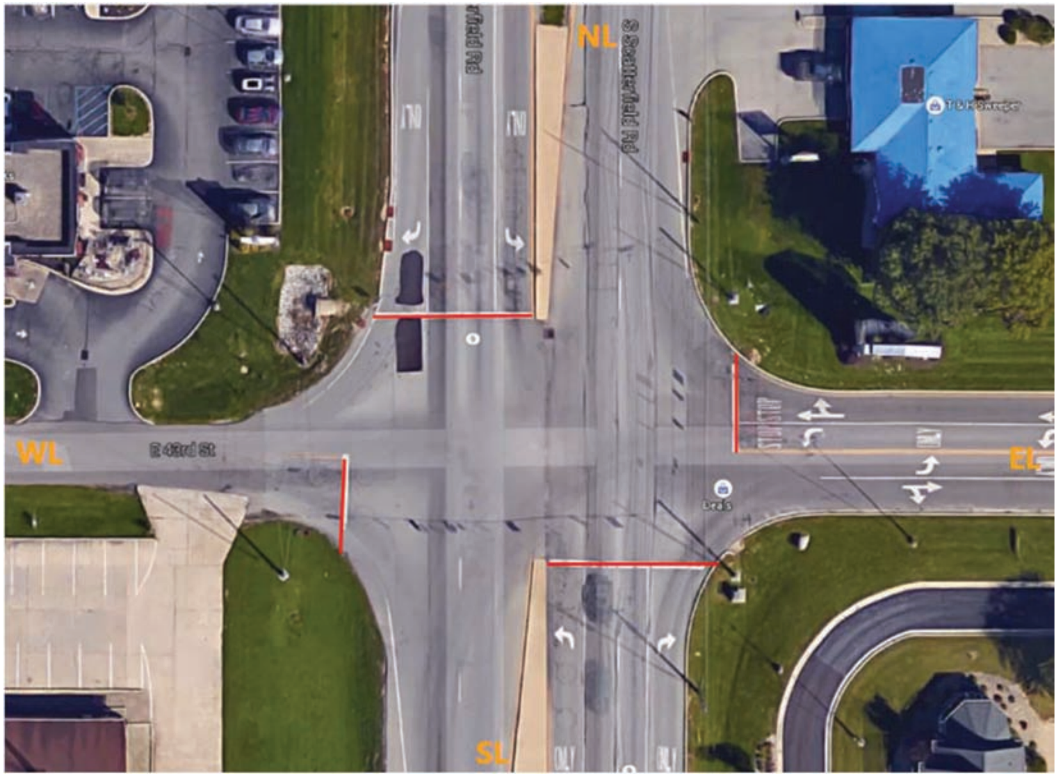


Figure II.7 Entry lines.

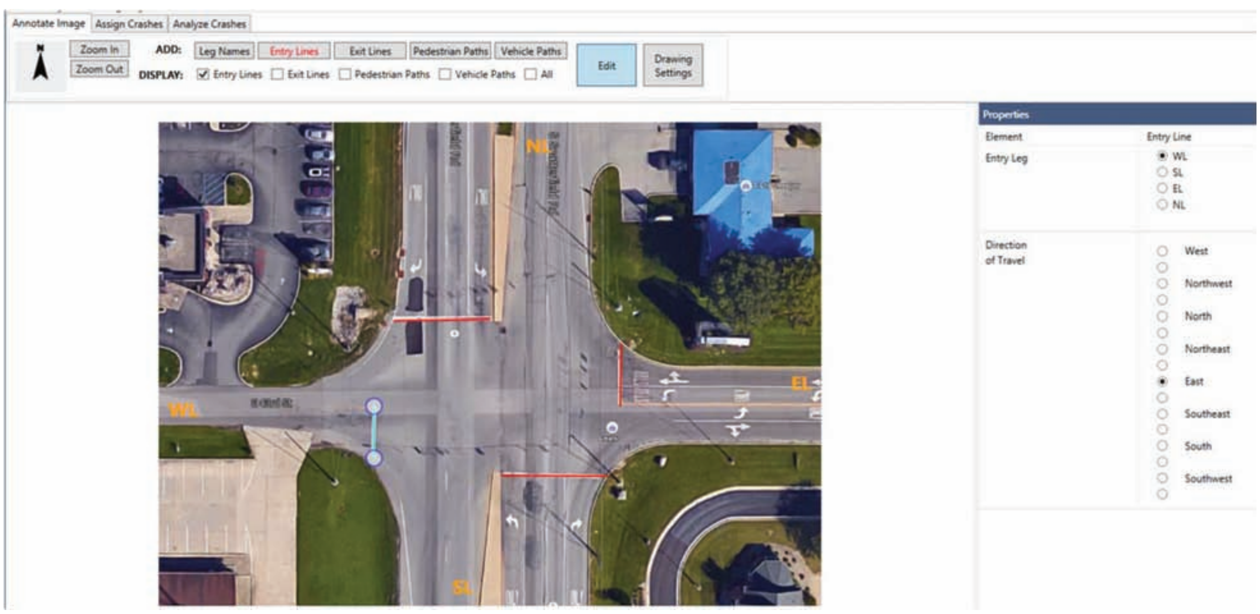


Figure II.8 Assigning properties to entry lines.

changes from an arrow to a hand. Then, the user clicks on any entry line to select it. The selected line changes color to blue and circles surround its defining points (Figure II.8.) The properties of the selected element are displayed in the right pane of the tab window. These properties include the name of the leg with the entry line and the direction of travel. The direction of travel represents the direction which is closest to the actual geometrical direction of the leg and it is used for the best visual representation of the collision icons when those are generated. The user should enter the properties of all the remaining entry lines.

The current project should be periodically saved by clicking on the *Existing Project/Save* menu option.

Exit Lines

The next step is to add Exit Lines to the intersection by clicking the *Exit Lines* button in the row labeled *ADD:*. The process is similar to the one previously described for adding entry lines. Once all the exit lines are drawn, their properties should be entered in a way similar to the already described for entry lines. The only property to enter is the Leg Name.

Vehicle Paths

The next step is adding the vehicle paths. Vehicle paths are drawn in a way similar to how the entry and exit were created. The user starts by selecting the corresponding *Vehicle Paths* button in the *ADD:* row of buttons. Then, the path is defined by clicking the mouse left button multiple times. Usually four clicks are necessary to draw a path. The middle straight segment is a "shortcut" representing the circular curve. This segment is automatically replaced with a circular curve tangent to the two end straight segments immediately after the user presses the mouse right button to end the drawing.

The tool allows drawing paths with more than one circular curve. For example, a path with two circular curves and three straight segments should be drawn as a polygon with five straight segments. The second and fourth straight segments are automatically replaced with two circular curves that are tangent to the adjacent segments. These adjacent segments remain straight as drawn by the user.

After a path is added, it is possible to tweak its curves by clicking on the edit button and selecting the path. All the defining points are emphasizes with circles. The curves are supplemented with tangency "handles" ended with squares. The path can be easily edited with a mouse by holding and moving the circles and squares (Figure II.9.) A path should intersect an entry line and an exit line.

Once the paths are drawn, their properties should be entered. The vehicle path's properties include: Entry Leg Name, Exit Leg Name, Actual Initial Direction of Travel, Coded Initial Direction of Travel, and Maneuver. If the user follows the proposed order of adding elements, then the Entry Leg Name, Exit Leg Name, Actual Initial Direction of Travel should be already transferred from the entry and exit lines. To complete entering the properties, the user should select the Coded Initial Directions of Travel which a police officer may choose when filling the crash form. Although the legs have specific directions indicated in their properties and transferred to the crossing paths as preferred directions, sometimes officers may consider the position of the vehicles when a specific maneuver was taking place at the time of a crash rather than the original direction of travel. Such miscoding is particularly probable for turning vehicles. More than one coded direction may be chosen. If additional directions are found later in the data, the user can return to this tab and add these directions.

Pedestrian Paths

The user can also add pedestrian paths and enter their properties in a process similar to the ones previously described.

The user may, at any time, move or edit an existing element or its properties by simply clicking on the edit button and selecting the desired element. An element may also be deleted by selecting it in edit mode and then pressing the Delete Key.

Property Propagation

The CDB automatically propagates the properties of entry and exit lines to the paths they cross. If the user changes the properties of an entry line or an exit line,

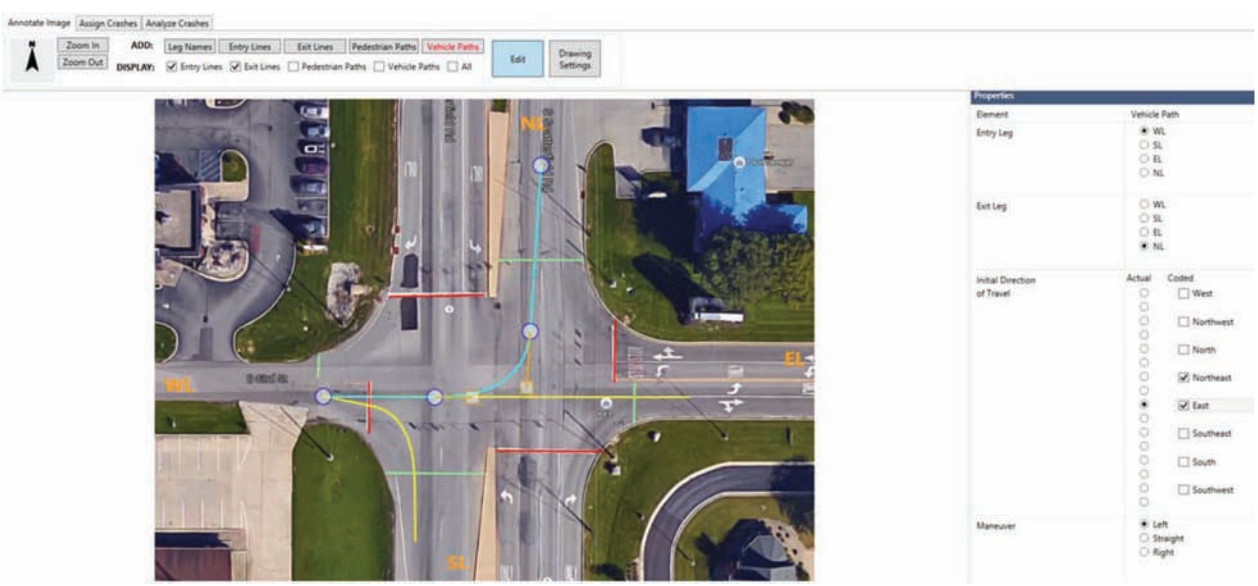


Figure II.9 Editing vehicle paths and their properties.

these changes are reflected in the properties of the intersecting paths. Reversely, if the user changes the properties of a path, the changes propagate to the intersecting approach and exit lines crossed by this path. If an element is moved by dragging it with the mouse after it has been selected in edit mode, its properties are blanked and re-imported from the other intersecting elements after the dragging movement is finished. So, after moving an object, the user should always check if the final properties are the expected ones.

Other Features

The *DISPLAY* row of check boxes allows the user to select types of element to become visible on the monitor. This feature, together with the zoom buttons, is useful if the drawing area becomes too cluttered.

Underneath the graphic area depicting the intersection there are fields for the user to enter the project's relevant information including the intersection name, analyst name, date, years of data and additional notes. These fields are also repeated on the Analyze Crashes tab.

The user has the ability to customize the line thicknesses and colors of all elements via the button *Drawing Settings*. Once all desired entry lines, exit lines, vehicle and pedestrian paths have been added to the image and all the properties and project information have been entered, the user should save the project and then should proceed to the *Assign Crashes Tab*.

Assign Crashes Tab

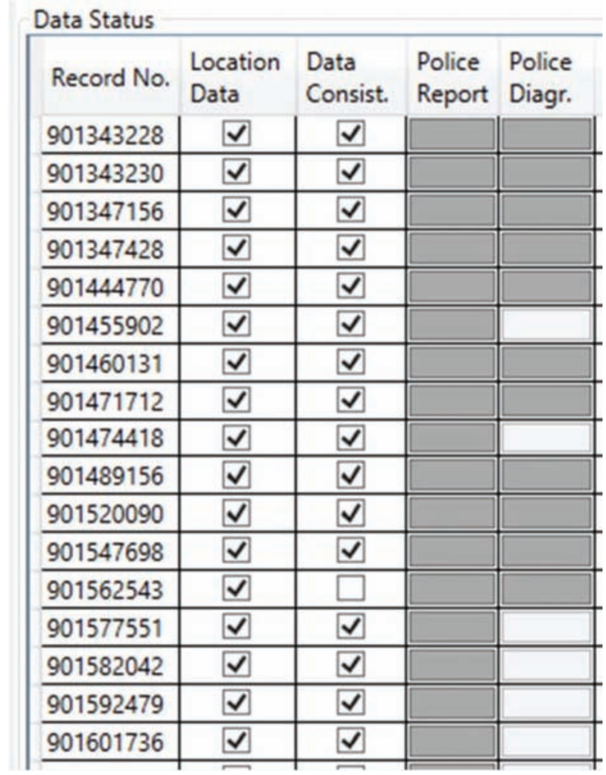
The operations available to the user while in this tab include:

- Check the availability of crash location information in the input data
- Check the consistency of the input data for each crash
- Enter, edit, and save data found to be missing or inconsistent
- Display a PDF Police report for a crash being examined
- Display a JPG or PDF Police diagram for a crash being examined
- Accept the crash locations automatically assigned by the program or manually alter these locations
- Manually assign crashes not assigned automatically to their proper locations

This tab includes the intersection image area and two additional areas: Data Status Area, and Data Editor Area.

Data Status Area

On the right of the image, there is a *Data Status Area* (Figure II.10) where useful information about the processed crash reports is presented in several columns. The first column, *Record No.*, displays the police crash master record number. The second column, *Location Data*, if checked, indicates that the data contains sufficient information for automatic crash location. The third column, *Data Consistency*, contains check boxes indicating whether the data for that crash has passed the CDB's consistency criteria. An empty box does not necessarily mean that the data is incorrect, but it may also mean that there is missing or insufficient information to assess the consistency. When the location and/or consistency boxes are not checked, the user should review the PDF police report and diagram, and perhaps edit the crash data in the *Data Editor Area.*



Data Status

Record No.	Location Data	Data Consist.	Police Report	Police Diagr.
901343228	✓	✓		
901343230	✓	✓		
901347156	✓	✓		
901347428	✓	✓		
901444770	✓	✓		
901455902	✓	✓		
901460131	✓	✓		
901471712	✓	✓		
901474418	✓	✓		
901489156	✓	✓		
901520090	✓	✓		
901547698	✓	✓		
901562543	✓			
901577551	✓	✓		
901582042	✓	✓		
901592479	✓	✓		
901601736	✓	✓		

Figure II.10 Data status area.

Pressing a button in the third column opens the Police Report for the crash in this line if the report file is available. Similarly, pressing a button in the fourth column opens the Police Diagram for inspection if the diagram file is available. The availability of a police report or diagram for a given crash is indicated by a dark grey button. If a report or diagram is not available for a given crash, the proper button on the *Data Status* grid shows in lighter color (Figure II.10.)

Data Editor Area

The area underneath the image contains a grid where selected vehicle and crash data fields are displayed for the first two vehicles listed in the police report of a multivehicle crash. The assumption is that the collision between the first and second vehicles is the only event or it is a precursor of additional collisions—all of them reported together as a single event. From the point of view of crash causality, the first collision is the most important regardless of the number of vehicles involved.

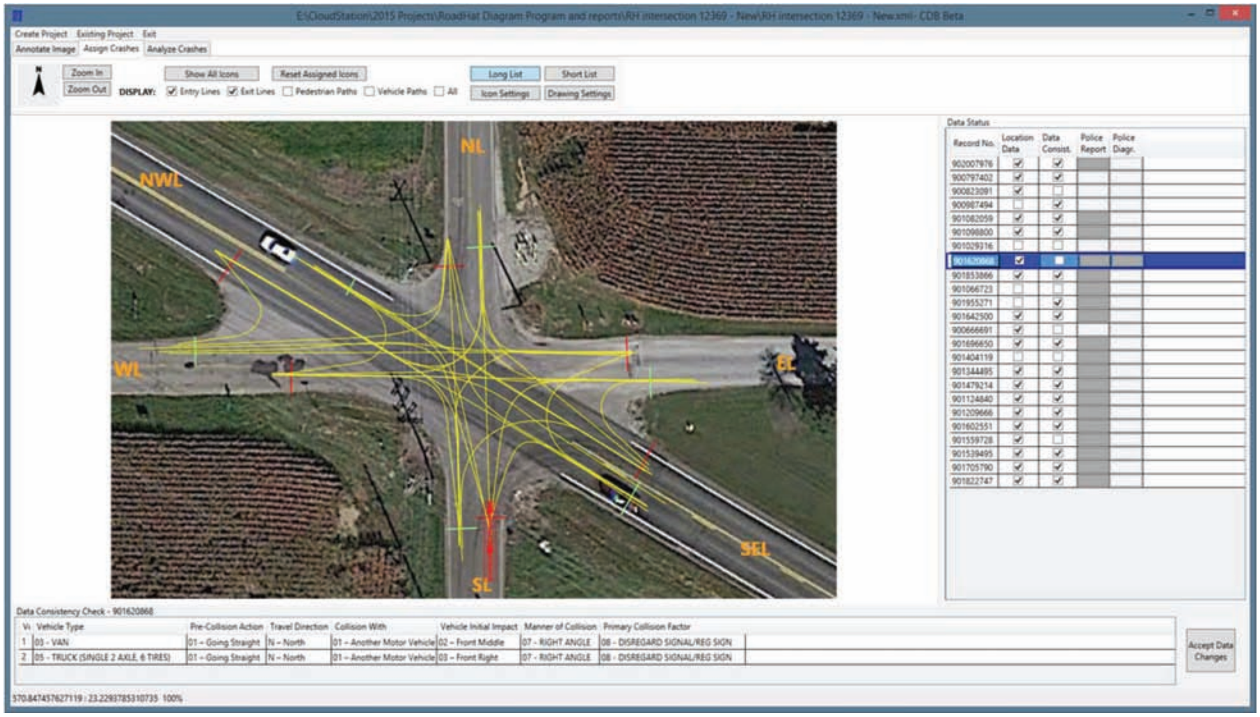


Figure II.11 Example of identified data inconsistency.

A single vehicle is present in the grid if the crash involved only one vehicle.

The variables displayed in the Data Editor area are those used to check the consistency of the data. As it has already been discussed, if the data do not pass all consistency checks, the *Data Consistency* column in the *Data Status* area will not be marked. In these cases, the user should examine the values of the relevant variables displayed in the grid of the Data Editor. Their values should be compared them with the police diagram and the police report. If changes are necessary, the variables should be edited and saved by clicking the *Accept Data Changes* button.

After the user clicks the Accept Data Changes button, the CDB updates the data and reruns the consistency checks. If the changes fix the previously identified problem, the *Data Consistency* check box for the processed crash appears checked. An example of inconsistency checking is given below.

Example

When examining the *Data Status* panel for intersection with ID 12369, the user finds that the crash with *Record No.* 901620868 has the *Location Data* check box marked but not the *Data Consistency* check box (Figure II.11.)

Examination of the data on the Data Consistency Check grid shows that the data indicate that both the vehicles were moving northbound. This is inconsistent with another Police entry indicating that the manner of collision was a right-angle collision. The CDB flags this case as a possible inconsistency. Since the location data were sufficient for assigning this crash, the CDB assigns the location near the entry line of the northbound approach lane.

The user examines the data from the police report by opening the corresponding crash report (Figure II.12). Examining the report, the user finds that indeed both the vehicles were coded going north as indicated in the data fields of the *Data Editor* grid. Nevertheless, further inspection of the detailed narrative (Figure II.13) indicates clearly that the ambulance was driving eastbound, while the second vehicle was driving northbound. The police diagrams reinforces this finding (Figure II.14). Both sources point to the manner of collision being a right-angle colliosion.

The user decides to alter the value in the crash data for the first vehicle and he replaces the Travel Direction value from North to East. After effecting the change in the grid (Figure II.15), the user presses the Accept Data Changes button. After reprocessing the data, the Data Consistency Checkbox for that crash shows that the data is consistent (Figure II.16). Furthermore, the CDB regenerates the crash icon as a right-angle collision and places it at the correct spot (Figure II.17.)

Reviewing Crash Assignments

When the user clicks with the mouse on a crash from the *Data Status Area*, the row of the selected crash is highlighted in dark blue. If the *Location Data* permits, the icon corresponding to the crash is also displayed at its assigned location. The data corresponding to the crash is displayed for review in the *Data Editor Area.*

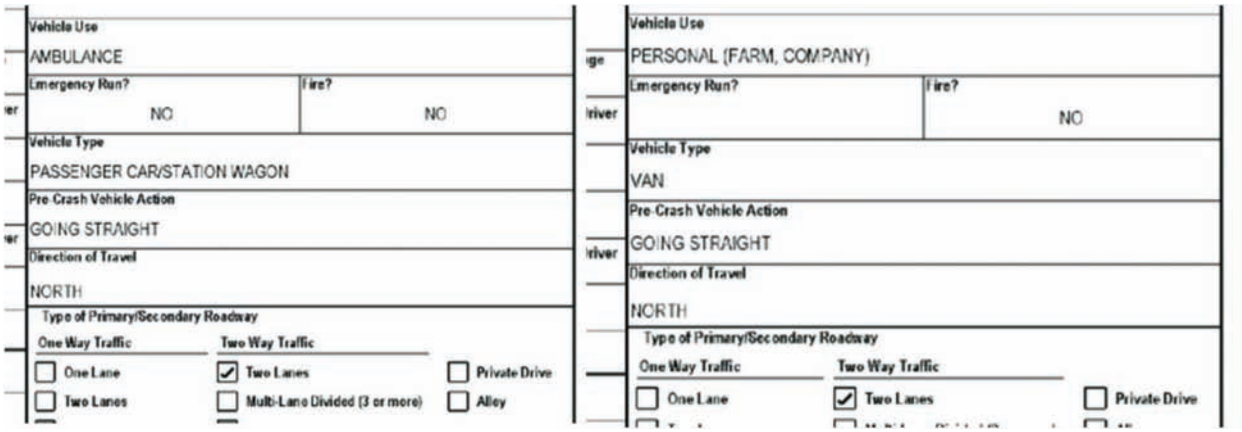
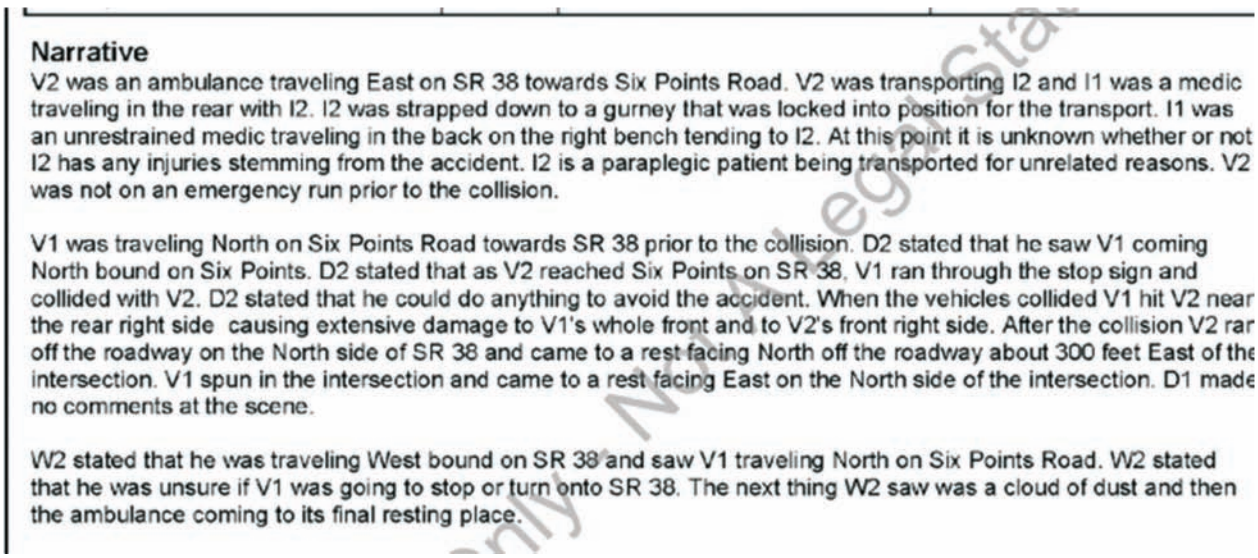


Figure II.12 Example—directions from PDF police report.



Narrative

V2 was an ambulance traveling East on SR 38 towards Six Points Road. V2 was transporting I2 and I1 was a medic traveling in the rear with I2. I2 was strapped down to a gurney that was locked into position for the transport. I1 was an unrestrained medic traveling in the back on the right bench tending to I2. At this point it is unknown whether or not I2 has any injuries stemming from the accident. I2 is a paraplegic patient being transported for unrelated reasons. V2 was not on an emergency run prior to the collision.

V1 was traveling North on Six Points Road towards SR 38 prior to the collision. D2 stated that he saw V1 coming North bound on Six Points. D2 stated that as V2 reached Six Points on SR 38, V1 ran through the stop sign and collided with V2. D2 stated that he could do anything to avoid the accident. When the vehicles collided V1 hit V2 near the rear right side causing extensive damage to V1's whole front and to V2's front right side. After the collision V2 ran off the roadway on the North side of SR 38 and came to a rest facing North off the roadway about 300 feet East of the intersection. V1 spun in the intersection and came to a rest facing East on the North side of the intersection. D1 made no comments at the scene.

W2 stated that he was traveling West bound on SR 38 and saw V1 traveling North on Six Points Road. W2 stated that he was unsure if V1 was going to stop or turn onto SR 38. The next thing W2 saw was a cloud of dust and then the ambulance coming to its final resting place.

Figure II.13 Example—crash narrative.

The CDB keeps track of all crashes examined by the user by displaying them in the grid with a light blue color. The user has the option of marking any crash for further review by changing the color to orange, or unmark it back to white by simply right-clicking on its respective row consecutively until the desired color is achieved (Figure II.18.)

The user has a number of options when choosing the order in which crashes are reviewed:

- **Sequential order:** the *Data Status* area lists all crashes associated with the intersection and the user reviews them following the order in which they appear on the grid. When the grid is listing all crashes it is said to be in *Long List* mode.
- **By type of crash:** The CDB permits the user to change the list of crashes displayed in the Data Status area in such a way that only crashes corresponding to a given icon are listed. This filtered list of crashes is denominated Short List. There are two ways to enter the Short List mode: (1) The user clicks the Short List button. In this case the program lists only crashes with the same icon as the currently selected crash (highlighted in dark blue). (2) The user clicks on the button Show All Icons to display the icons of all crashes and subsequently right-clicks on any one of the icons exhibited. In such case, the program will list only crashes with the same icon as the one right-clicked by the user. Figure II.19 shows a short list of southbound rear end crashes. Clicking on the long list button switches the grid back to long list mode.
- Combining both methods: The user may alternate the use of the above methods as desired.

Regardless of the order in which the user decides to review the list of crashes, the CDB will preserve the status of all visited crashes by highlighting them in light blue, whether they are displayed in short or long list mode.

Assigning Crashes Manually

In some cases, combination of data and user defined elements do not allow the CDB to automatically identify

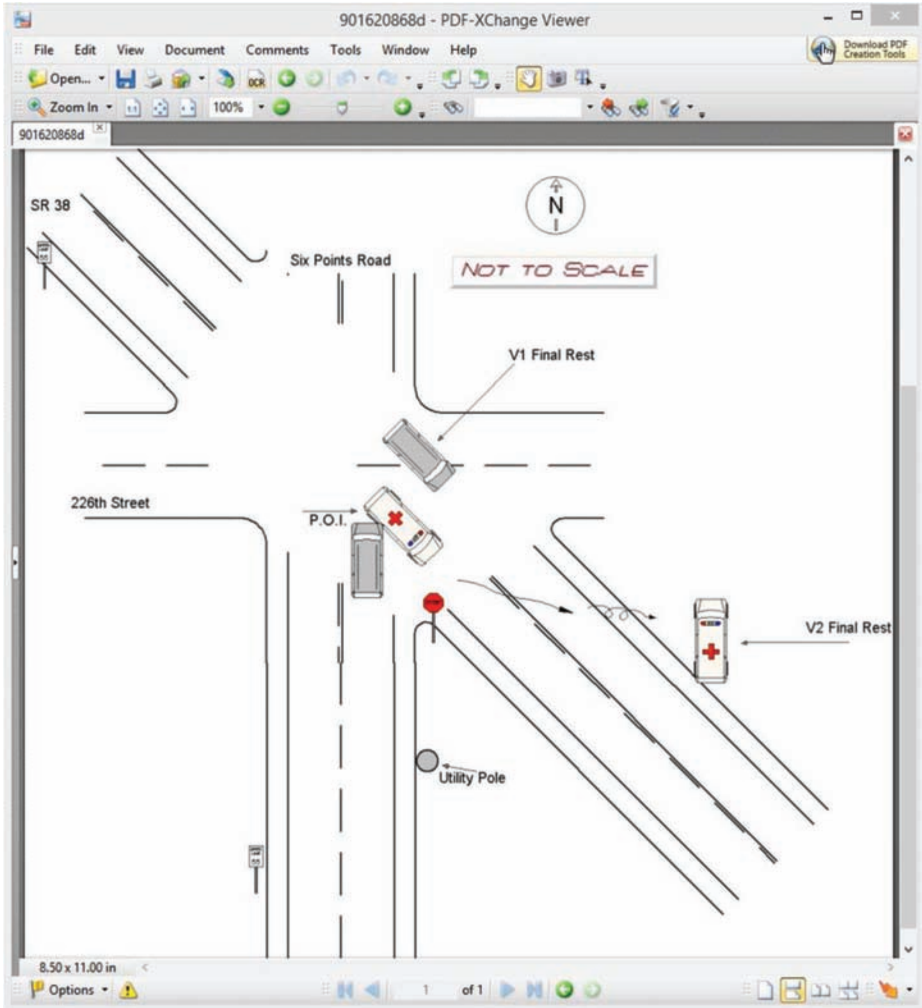


Figure II.14 Example—police diagram.

Before Change

Data Consistency Check - 901620868

Ve	Vehicle Type	Pre-Collision Action	Travel Direction
1	03 - VAN	01 – Going Straight	N – North
2	05 - TRUCK (SINGLE 2 AXLE, 6 TIRES)	01 – Going Straight	N – North

After Change

Data Consistency Check - 901620868

Ve	Vehicle Type	Pre-Collision Action	Travel Direction
1	03 - VAN	01 – Going Straight	E – East
2	05 - TRUCK (SINGLE 2 AXLE, 6 TIRES)	01 – Going Straight	N – North

Figure II.15 Example—changing direction of travel.

the crash location. Consequently, an icon representing the unassigned crash is displayed outside of the intersection image on its left side (Figure II.20).

Crashes with animals, fixed objects or running off the road are usually not automatically assignable. Both incomplete entries for paths possible directions and the inclusion of too many possible directions in complex intersections may also be possible factors that prevent the automatic assignability of certain crashes. When the user believes that a certain crash should have been automatically assigned, it may prove useful to review the properties of the paths involved.

When a crash cannot be automatically assigned, the users should review the police crash report and diagram to determine the most probable position of the crash. The crash icon may be selected with the mouse left button and dragged to its position while keeping the mouse left button depressed. The manual assignment is remembered by the CDB and other crashes of the same type are assigned to this location automatically.

In summary, the user should inspect the status of each crash on the consistency check list; examine the data if needed, and accept the automatically assigned locations or make manual adjustments to either the data or the location assignment. If some crashes cannot be confidently assigned even after checking the police reports and diagrams, their icons may be left outside of the image area. They are excluded from further analysis.

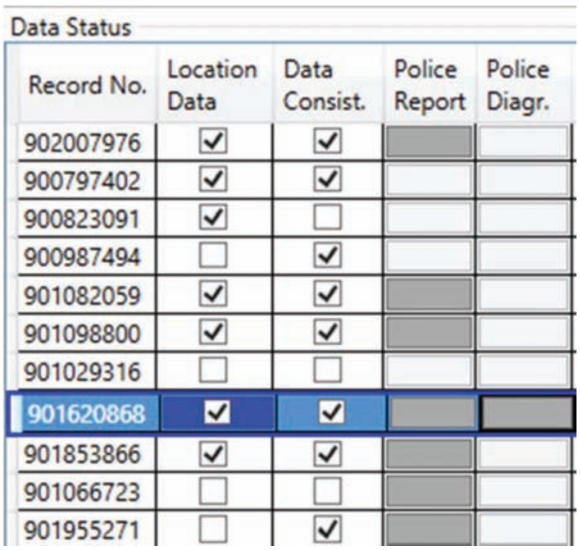
There are occasions when the user may decide to erase and redraw a number of paths. The reason may be the replacement of the background image by a better one, or simply an attempt to better represent the traffic flow at the intersection. At such times, rather than having to revise the position of all crashes previously manually adjusted, the user may simply press the *Reset Assigned* button. This action discards any existing assignments (Figure II.21), allowing the program to attempt to reassign all crashes locations based on the new paths.

The user may at any time use the button *Icon Settings* to change the size, color and transparency of the icons associated with the crashes. Once a satisfactory icon size is achieved, the size ratio between the crash icons and the intersection image is preserved if the user makes use of the zoom buttons to magnify or reduce the size of the image.

After processing all the crashes, the user proceeds to the *Analyze Crashes* Tab.

Analyze Crashes Tab

This tab is used to analyze the crash patterns represented with the crash frequency distribution in space



Data Status

Record No.	Location Data	Data Consist.	Police Report	Police Diagr.
902007976	✓	✓		
900797402	✓	✓		
900823091	✓			
900987494		✓		
901082059	✓	✓		
901098800	✓	✓		
901029316				
901620868	✓	✓		
901853866	✓	✓		
901066723				
901955271		✓		

Figure II.16 Example—inconsistency removed.

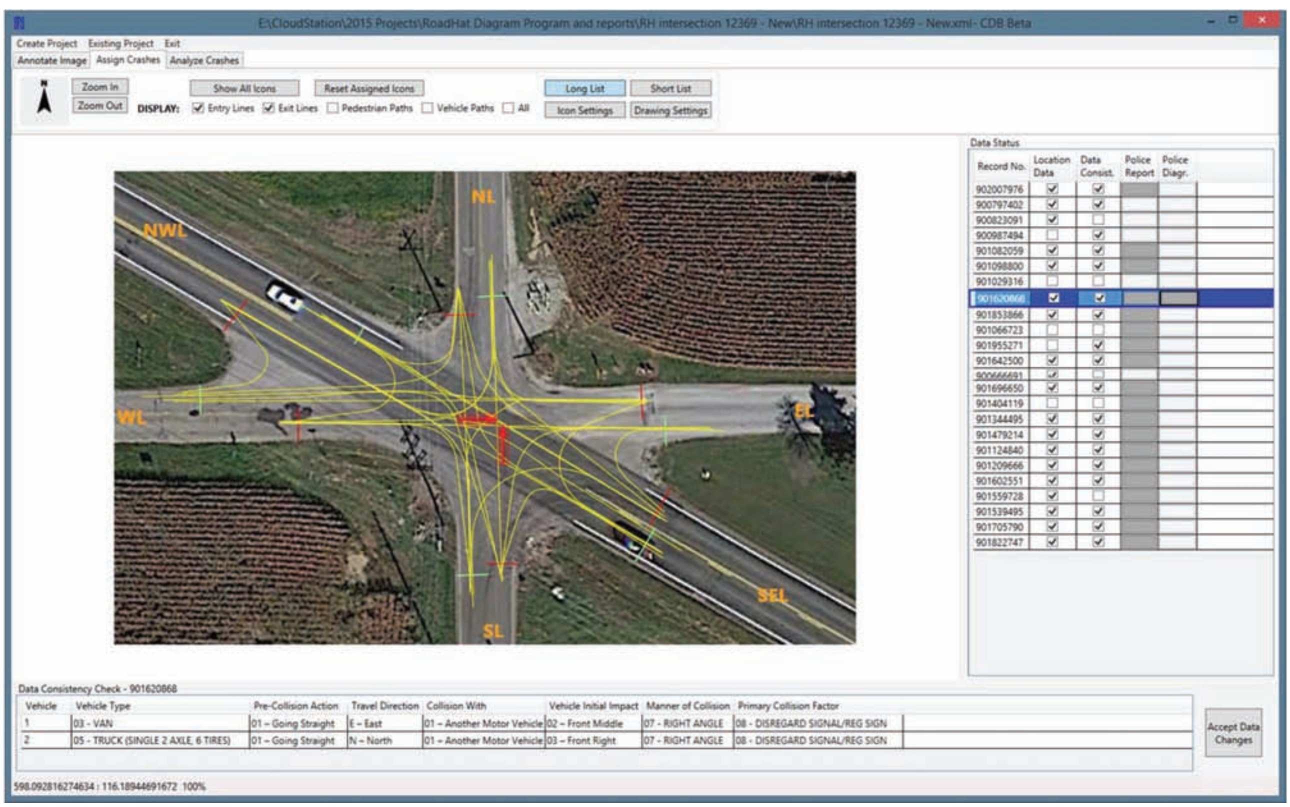
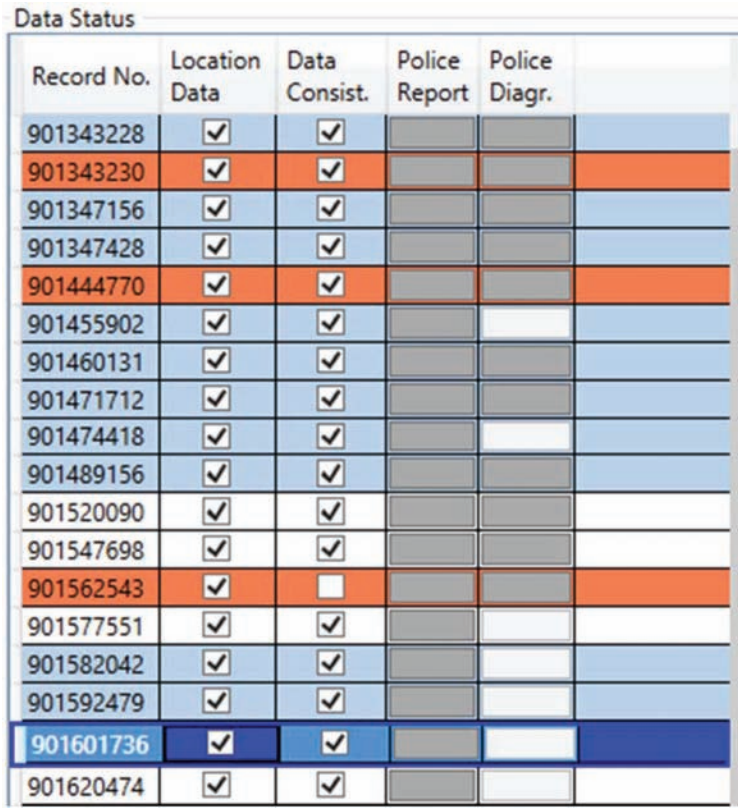


Figure II.17 Example—automatic location re-assignment.



Data Status

Record No.	Location Data	Data Consist.	Police Report	Police Diagr.
901343228	✓	✓		
901343230	✓	✓		
901347156	✓	✓		
901347428	✓	✓		
901444770	✓	✓		
901455902	✓	✓		
901460131	✓	✓		
901471712	✓	✓		
901474418	✓	✓		
901489156	✓	✓		
901520090	✓	✓		
901547698	✓	✓		
901562543	✓			
901577551	✓	✓		
901582042	✓	✓		
901592479	✓	✓		
901601736	✓	✓		
901620474	✓	✓		

Figure II.18 Data status color scheme.

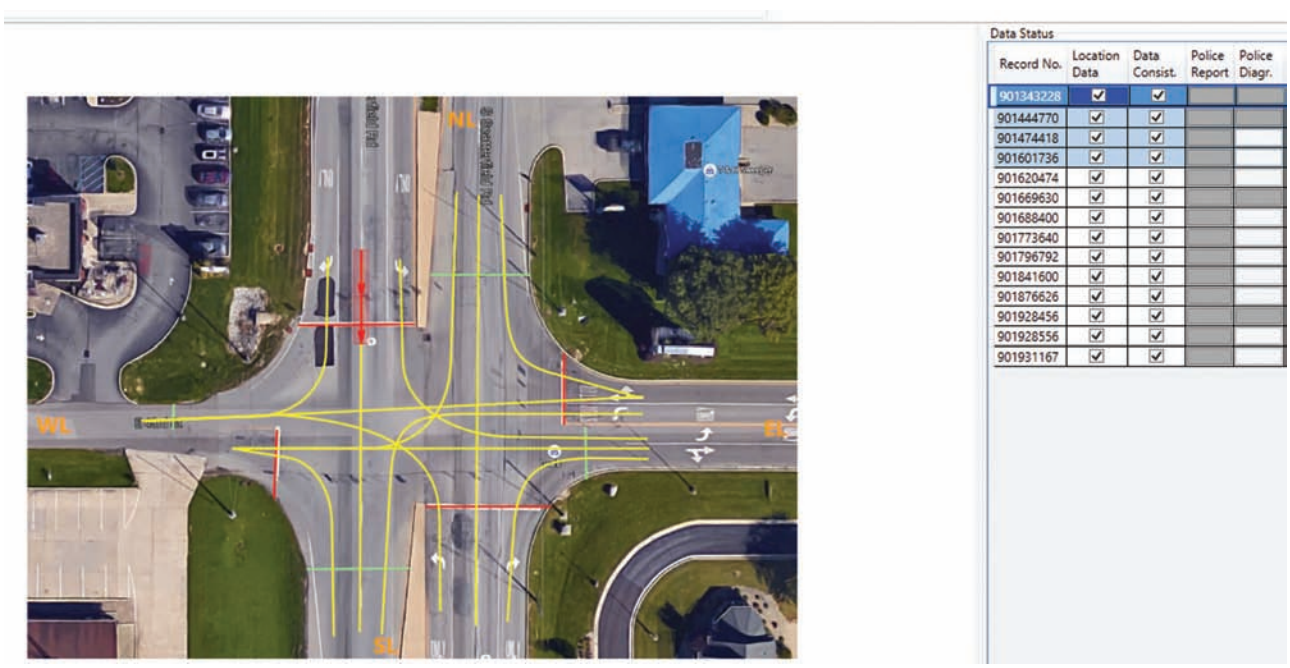


Figure II.19 Short list of rear end crashes.

and according to user-defined criteria. The possible tasks available to the user while in this tab include:

- Display the distribution of crash frequency at their locations with a bar diagram (Figure II.22) according to a user-selected variable (Figure II.23). The angle, scale, and width of the bar diagrams are controlled by the user (Figure II.24).
- Tabulate two-way distribution of crash frequency by user-selected two variables. Multiple tables can be displayed simultaneously.

Figure II.20 Unassigned crash locations.

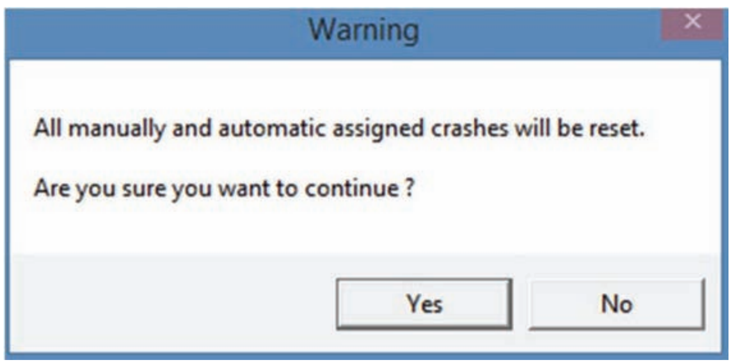


Figure II.21 Resetting all assigned crashes.

- Perform the above analysis on all assigned crashes or on a subset defined by a user-set filter (Figure II.25).
- Save the results of the above analysis for incorporation to a report later.

The program offers some flexibility as to how the bars are displayed by allowing the user to change the bar angle, scale(length) and width (Figure II.23). These adjustments may prove useful if the intersection diagram becomes too busy with overlaping bars. The user may select how the crash freaquency are broken down and displayed on bars by selecting the desired option from the *Variable* pull down menu in the *CHART* control row (Figure II.23).

The bars displaying the frequencies breakdown according to the selected variables may further be controlled by applying one of the filters available in the *Filter* pull down menu (Figure II.25). A filter selection forces the frequency bars to display a breakdown of the crashes according to the selected variable only for the crashes satisfying the selected filters. The user may disable any filters by selecting the option *None* from the menu.

Color legends for the selected bar variables and the list of selected filters are displayed to the right of the image (Figure II.26.)

The user may also generate tabulations by clicking on the *New Table* button (Figure II.27). This action creates a table which cross-tabulates the crash frequencies according to two user selected variables. These variables may be selected independently of the variables used in the bar chart or in other tables (Figure II.27). It is important to note that all the results dispalyed on the image and in the tables apply to the subset of crashes defined by the current filter. Changing the filter automatically updates the bar chart as well as any open table. The active filters are always displayed underneath the tables.

The user saves the current bar charts by selecting *the Existing Project/Save Image* menu option (Figure II.28). The user selects the folder where the image is to be saved and types the name of the file. The intersection

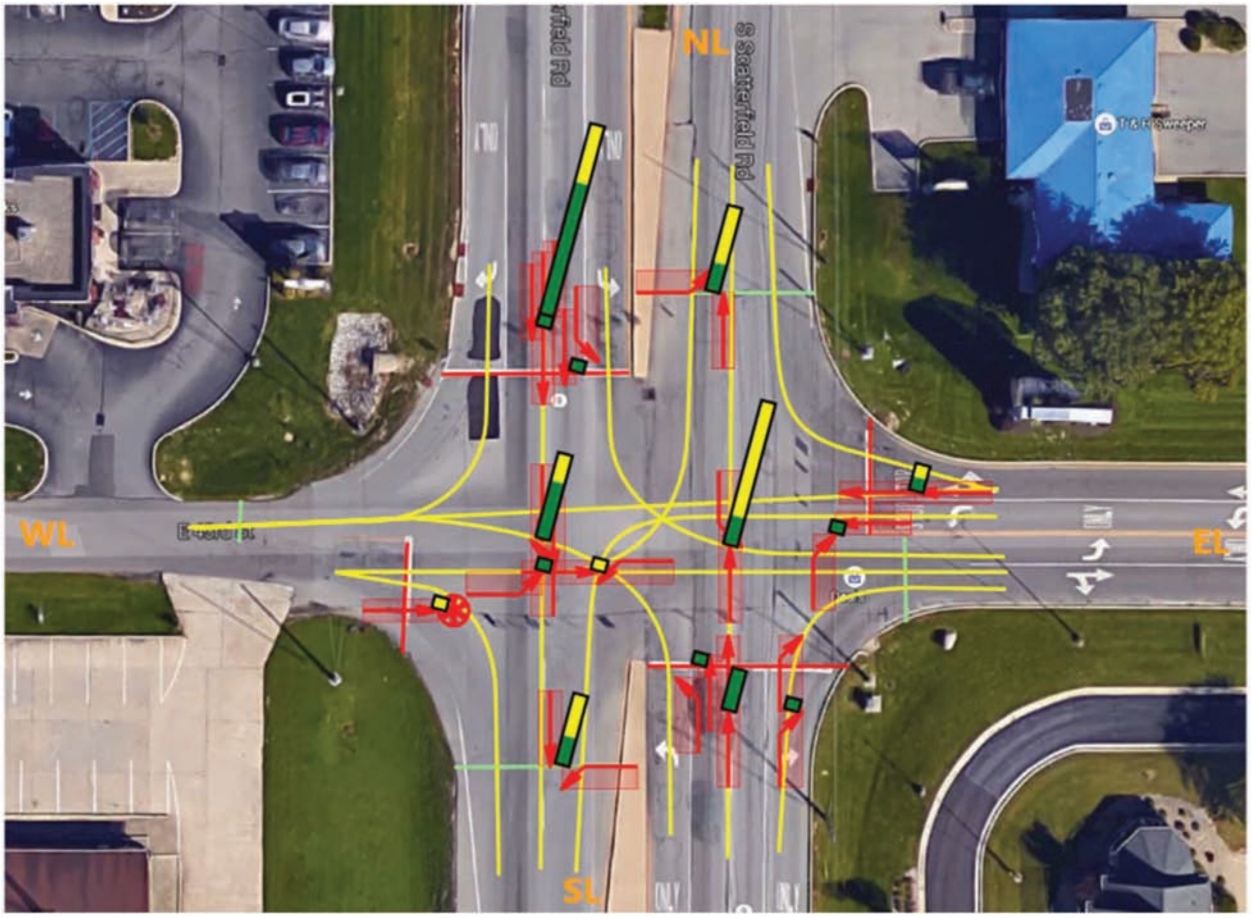


Figure II.22 Crash frequency bars for each assigned location.

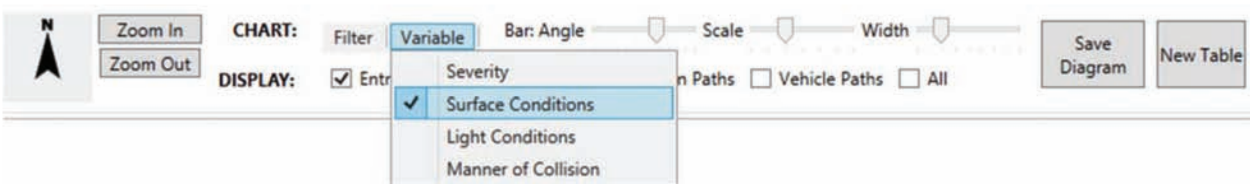


Figure II.23 Pull down menu for bar variable selection.

Figure II.24 Analyze crashes frequency bar and tabulation controls.

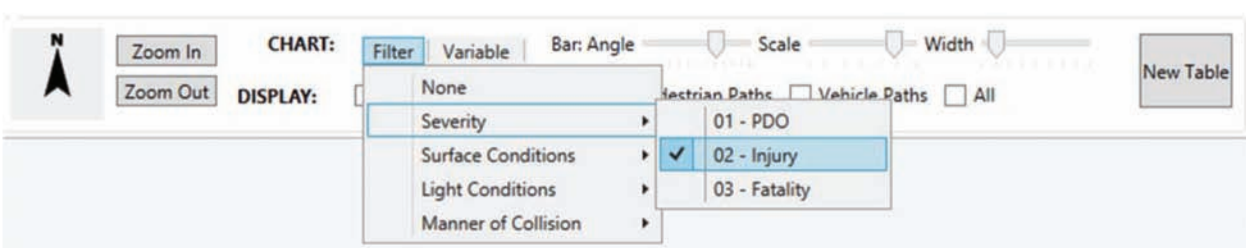


Figure II.25 Pull down menu for filter selection.

image with the currently displayed bar charts is saved along with the legend of the variables and the status of the applied filter (Figure II.28). The saved image also includes the basic information about the project, as entered by the user when the project was created. The collision diagrams are saved in the html format that can be easily edited and imported into documents.

To save a displayed table, the user should click on the Save Table button present on the top left of the table window. The user may then select the folder where to save the file and type its name. Similarly to images, the saved table includes the basic information about the project and it is saved in the html format (Figure II.29).

Specifications of the Input Data Files

The program reads three csv files using the same original format as provided by the ARIES system. These tables' data formats are shown in Table II.1.

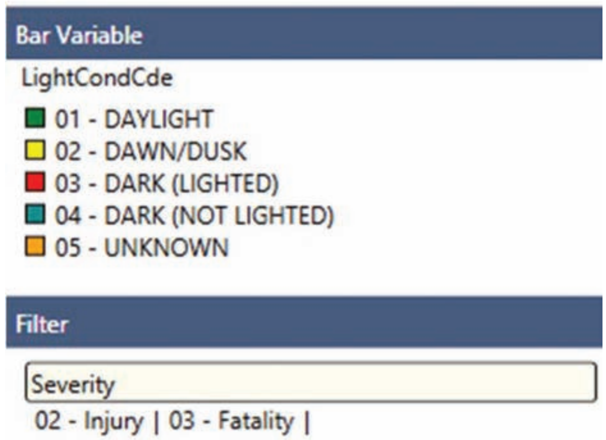


Figure II.26 Color legends for bar variables and filter.

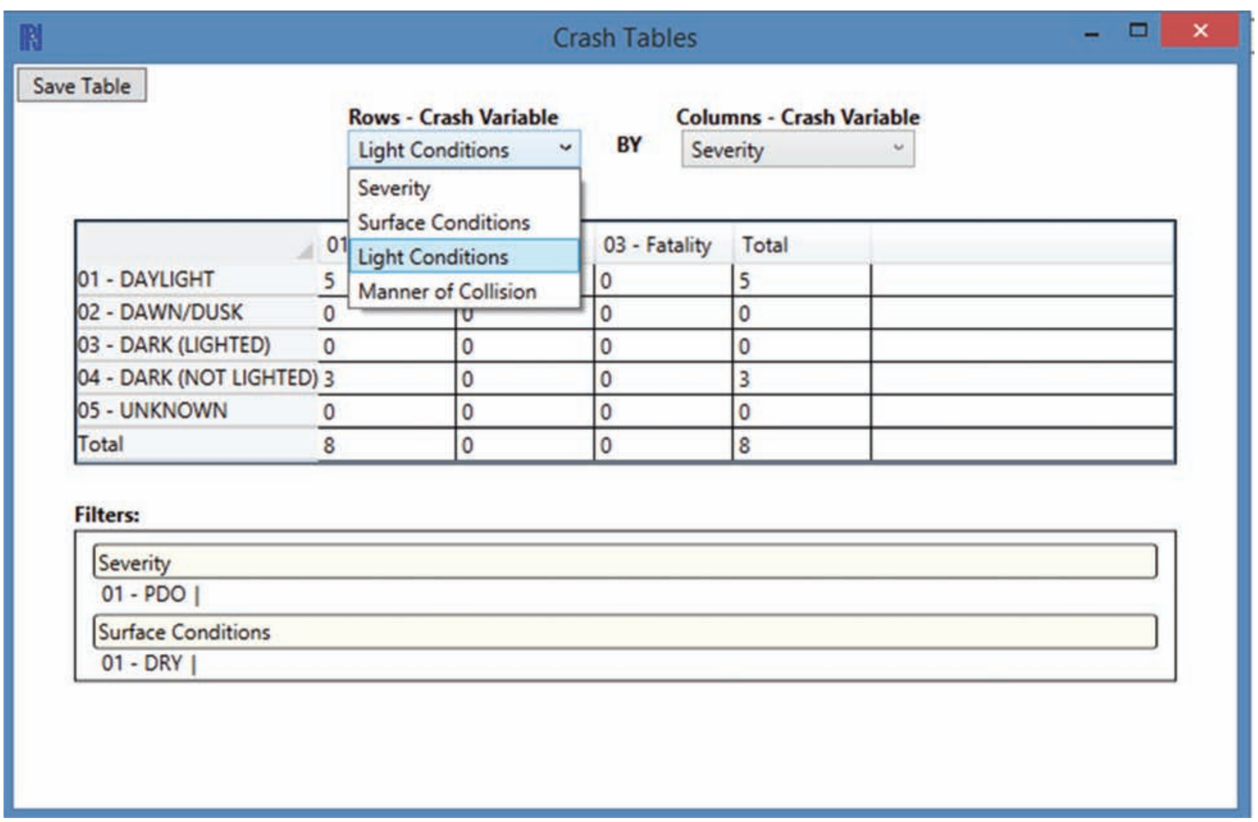
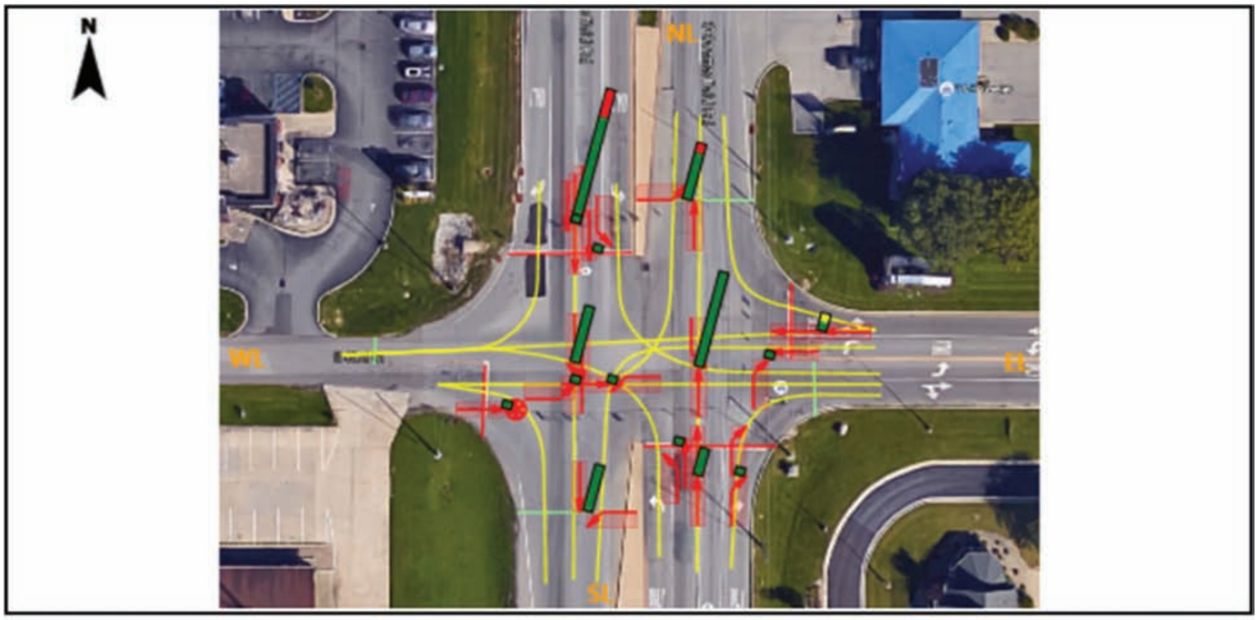


Figure II.27 Tables allow independent selection of variables.



Bar Variable : LightCondCde
01 - DAYLIGHT
02 - DAWN/DUSK
03 - DARK (LIGHTED)
04 - DARK (NOT LIGHTED)
05 - UNKNOWN

Filters:
Severity
01 - PDO|02 - Injury|03 - Fatality|

Intersection:	43rd and Scatterfield Rd
Analyst:	JET
Date:	December 1. 2015
Year Of Data:	2011-2013
Notes:	

Figure II.28 Saved image and attached project information.

	01 - PDO	02 - Injury	03 - Fatality	Total
01 - REAR END	0	5	0	5
02 - HEAD ON	0	1	0	1
03 - REAR TO REAR	0	0	0	0
04 - SAME DIRECTION SIDESWIPE	0	0	0	0
05 - OPPOSITE DIRECTION SIDESWIPE	0	0	0	0
06 - RAN OFF ROAD	0	0	0	0
07 - RIGHT ANGLE	0	6	0	6
08 - LEFT TURN	0	8	0	8
09 - RIGHT TURN	0	0	0	0
10 - LEFT/RIGHT TURN	0	0	0	0
11 - BACKING CRASH	0	0	0	0
12 - OTHER - EXPLAIN IN NARRATIVE	0	4	0	4
13 - NON-COLLISION	0	0	0	0
Total	0	24	0	24

Filters:
Severity
02 - Injury|03 - Fatality|

Intersection:	43rd and Scatterfield Rd
Analyst:	JET
Date:	August 1, 2015
Year Of Data:	2011-2013
Notes:	There are no notes at this time

Figure II.29 Saved table and attached project information.

TABLE II.1
Data formats.

Collision (Record Type = 10)						
Field	**Description**	**Length**	**Start Pos**	**End Pos**	**Type**	**Values**
1	Record Type	2	1	2	Text	10
2	MstrRecNbrTxt	9	3	11	Text	
3	StatusCde	2	12	13	Code	
4	StatusDte	8	14	21	Date	YYYYMMDD
5	AgencyORITxt	7	22	28	Text	
6	LocalCodeTxt	20	29	48	Text	
7	CountyCde	3	49	51	Code	
8	TownshipCde	5	52	56	Code	
9	CityCde	5	57	61	Code	
10	CollDte	8	62	69	Date	YYYYMMDD

(Continued)

TABLE II.1
(Continued)

Collision (Record Type = 10)						
Field	**Description**	**Length**	**Start Pos**	**End Pos**	**Type**	**Values**
11	CollDayWeekCde	1	70	70	Code	
12	CollTimeTxt	4	71	74	Text	
13	CollTimeAMPMTxt	1	75	75	Text	
14	CollTimeMilitaryTxt	4	76	79	Text	
15	MotorVehInvolvedNmb	2	80	81	Number	
16	TrailersInvolvedNmb	2	82	83	Number	
17	InjuredNmb	3	84	86	Number	
18	DeadNmb	3	87	89	Number	
19	DeerNmb	2	90	91	Number	
20	RdwyHouseNbrTxt	5	92	96	Text	
21	RdwyNameTxt	30	97	126	Text	
22	RdwySuffixTxt	4	127	130	Text	
23	RdwyNumberTxt	8	131	138	Text	
24	RdwyInterchangeTxt	4	139	142	Text	
25	RdwyRampTxt	1	143	143	Text	
26	RdwyIDTxt	47	144	190	Text	
27	InterNameTxt	30	191	220	Text	
28	InterSuffixTxt	4	221	224	Text	
29	InterNumberTxt	8	225	232	Text	
30	InterMilemarkNmb	5	233	237	Number	###.#
31	InterInterchangeTxt	4	238	241	Text	
32	InterRampTxt	1	242	242	Text	
33	InCorpLimitInd	1	243	243	Y/N	
34	PropDamageCde	2	244	245	Code	
35	FeetFromPointNmb	4	246	249	Number	
36	DirFromPointCde	1	250	250	Code	
37	MilesFromCorpNmb	6	251	256	Number	##.###
38	DirFromCorpCde	1	257	257	Code	
39	LatDegreesNmb	3	258	260	Number	
40	LatMinNmb	6	261	266	Number	###.##
41	LatDecimalNmb	12	267	278	Number	##.#########
42	LongDegreesNmb	3	279	281	Number	
43	LongMinNmb	6	282	287	Number	##.###
44	LongDecimalNmb	12	288	299	Number	##.#########
45	RdwyClassCde	2	300	301	Code	
46	TrafficCntlOpInd	1	302	302	Y/N	

(Continued)

TABLE II.1
(Continued)

Field	Description	Length	Start Pos	End Pos	Type	Values
Collision (Record Type = 10)						
47	AggressiveDriveInd	1	303	303	Y/N	
48	HitRunInd	1	304	304	Y/N	
49	LocalityCde	1	305	305	Code	
50	SchoolZoneInd	1	306	306	Y/N	
51	RumbleStripInd	1	307	307	Y/N	
52	ConstructInd	1	308	308	Y/N	
53	ConstructTypeCde	2	309	310	Code	
54	LightCondCde	2	311	312	Code	
55	WeatherCde	2	313	314	Code	
56	SurfaceCondCde	2	315	316	Code	
57	MedianTypeCde	2	317	318	Code	
58	RdwyJunctionCde	2	319	320	Code	
59	RdwyCharCde	2	321	322	Code	
60	SurfaceTypeCde	2	323	324	Code	
61	PrimaryFactorCde	2	325	326	Code	
62	DamageEstimateCde	2	327	328	Code	
63	MannerCollCde	2	329	330	Code	
64	TimeNotifiedTxt	4	331	334	Text	
65	TimeNotifiedAMPMTxt	1	335	335	Text	
66	TimeNotifiedMilitaryTxt	4	336	339	Text	
67	TimeArrivedTxt	4	340	343	Text	
68	TimeArrivedAMPMTxt	1	344	344	Text	
69	TimeArrivedMilitaryTxt	4	345	348	Text	
70	InvestCompleteInd	1	349	349	Y/N	
71	PhotosTakenInd	1	350	350	Y/N	
72	OfficerNameLastTxt	30	351	380	Text	
73	OfficerNameFITxt	1	381	381	Text	
74	OfficerIDTxt	5	382	386	Text	
75	DocIDCollRptNmb	10	387	396	Text	
76	DocIDSupplNmb	10	397	406	Number	
77	SubmissionTypeCde	2	407	408	Code	
78	TrafficCntrlCde	2	409	410	Code	
79	UniqueLocationID	100	411	510	Text	
78	CommercialUnitsNmb	2	511	512	Number	
79	WitnessesInd	1	513	513	Y/N	
79	NonMotoristsNmb	1	514	514	Number	

(Continued)

TABLE II.1
(Continued)

Unit (Record Type = 20)						
Field	**Description**	**Length**	**Start Pos**	**End Pos**	**Type**	**Values**
1	Record Type	2	1	2	Text	20
2	MstrRecNbrTxt	9	3	11	Text	
3	StatusCde	2	12	13	Code	
4	UnitNmb	2	14	15	Number	
5	UnitTypeCde	2	16	17	Code	
6	VehicleNmb	2	18	19	Number	
7	VehYearTxt	4	20	23	Text	
8	VehMakeTxt	25	24	48	Text	
9	VehModelTxt	25	49	73	Text	
10	OccupsNmb	3	74	76	Number	
11	VehLicYearTxt	4	77	80	Text	
12	VehLicNbrTxt	20	81	100	Text	
13	VehLicStateCde	2	101	102	Code	
14	AxelsTxt	2	103	104	Text	
15	SpeedLimitTxt	2	105	106	Text	
16	TowedInd	1	107	107	Y/N	
17	VehUseCde	2	108	109	Code	
18	RoadTypeCde	2	110	111	Code	
19	TravDirCde	2	112	113	Code	
20	EmergencyRunInd	1	114	114	Y/N	
21	FireInd	1	115	115	Y/N	
22	EventCollWithCde	2	116	117	Code	
23	PreCollActCde	2	118	119	Code	
24	TrafficCntlCde				Code	
25	InitialImpactCde	2	120	121	Code	
26	VehColorTxt	8	122	129	Text	
27	VehStyleTxt	2	130	131	Text	
28	EnforcementInd	1	132	132	Y/N	
29	DrugAlcoholInd	1	133	133	Y/N	
30	CommVehInd	1	134	134	Y/N	
31	TrailerInd	1	135	135	Y/N	
32	TowDueToDamageInd	1	136	136	Y/N	
33	TowedToTxt	25	137	161	Text	
34	TowedByTxt	25	162	186	Text	
35	EventCollWithCde2	2	187	188	Code	
36	EventCollWithCde3	2	189	190	Code	

(Continued)

TABLE II.1
(Continued)

Unit (Record Type = 20)						
Field	**Description**	**Length**	**Start Pos**	**End Pos**	**Type**	**Values**
37	EventCollWithCde4	2	191	192	Code	
38	InsurerNameTxt	30	193	222	Text	
39	InsurerPhoneTxt	10	223	232	Text	
40	InsPolicyNbrTxt	100	233	332	Text	
41	VINTxt	21	333	353	Text	
Factors (Record Type = 22)						
Field	**Description**	**Length**	**Start Pos**	**End Pos**	**Type**	**Values**
1	Record Type	2	1	2	Text	22
2	MstrRecNbrTxt	9	3	11	Text	
3	StatusCde	2	12	13	Code	
4	UnitNmb	2	14	15	Number	
5	FactorCde	2	16	17	Code	

APPENDICES

Appendix A: Glossary

AADT: Annual Average Daily Traffic

AASTHO: American Association of State Highway and Transportation Officials

B/C ratio: Benefit Cost Ratio

BSPF: Base Safety Performance Function

CDB: Collision Diagram Builder

CMF: Crash Modification Factor

CRF: Crash Reduction Factor

CRS: Center for Road Safety

CSV: Comma Separated Values

DOT: Department of Transportation

EB: Empirical Bayes

EPDO: Equivalent Property Damage Only

FC: Functional Class

FI: Fatal and Incapacitating Injury Crash

FSPF: Full Safety Performance Function

HCM: Highway Capacity Manual

HSM: Highway Safety Manual

INDOT: Indiana Department of Transportation

MM: Method of Moments

ML: Maximum Likelihood

MOE: Measure of Effectiveness

NI: Non-incapacitating and Possible Injury Crash

PD: Property Damage Crash

RoadHAT: Roadway Hazard Analysis Tool

SE: Standard Error

SPF: Safety Performance Function

SNIP: Safety Needs Identification Program

TOT: Total Number of Crash

TSPF: True Safety Performance Function

ρ^2: Coefficient of Determination

Appendix B: Segment and Intersection SPFs of HSM

The following SPFs are available in the HSM 2010 for different types of segments and intersections.

Urban and Suburban Arterial

For 5 different segment types	Number of SPFs
Multiple vehicle crash non-driveway-related	15 (Total, F&I, PDO crashes)
Single vehicle crash	15 (Total, F&I, PDO crashes)
Multiple vehicle crash driveway-related	35 (Total) (provided proportions for F&I, PDO)
Total	65

Adjustments factors for pedestrian and bicyclist and proportions (around 100) by collision are provided.

For 4 different intersection types	Number of SPFs
Multiple vehicle crash	12 (Total, F&I, PDO crashes)
Single vehicle crash	12 (Total, F&I, PDO crashes)
Vehicle pedestrian collision on signalized intersection	2
Total	26

Adjustments factors for pedestrian and bicyclist and proportions (88) by collision type are provided.

Rural Multilane

For 2 different Segment types	Number of SPFs
Undivided segments	3 (Total, F&I, KAB crashes)
Divided segments	3 (Total, F&I, KAB crashes)
Total	6

Proportions (48) by collision type are provided.

For 3 different intersection types	Number of SPFs
3 different Intersection types	9 (Total, F&I, KAB crashes)
Total	9

Proportions (72) by collision type are provided.

Rural Two-Lane

Entity	Number of SPFs
Rural Two-Lane Two-Way Segment	1 (Total)
3 different Intersection types	3 (Total)
Total	4

Proportions (160) by collision type are provided.

Appendix C: Safety Performance Functions in the Safety Management Simulation

True Safety Performance Functions for Different Severity Levels

	True SPF-KA	True SPF-BC	True SPF-PDO
Parameter	Estimate	Estimate	Estimate
Intercept	Rural=-7.38; Urban=-10.66	Rural=-6.91; Urban=-0.32	Rural=-4.91; Urban=-7.01
LogAADT	Rural=0.59; Urban=0.88	Rural=0.72; Urban=1.09	Rural=0.63; Urban=0.88
T_indicator	Rural=-0.65; Urban=-0.51	Rural=-0.60; Urban=-0.62	Rural=-0.42; Urban=-0.53
CMF101	0.735849	0.744493	0.738707
CMF102	0.472668	0.59411	0.431795
CMF103	0.489228	0.679447	0.565902
CMF104	0.36708	0.507264	0.407653
CMF105	0.404974	0.532451	0.474734
CMF106	0.403215	0.410941	0.534406
CMF107	0.787939	0.798594	0.761119
CMF108	0.631332	0.541646	0.538969
CMF109	0.632729	0.485901	0.52395
CMF110	0.85912	0.78522	0.792868
CMF111	0.407172	0.429331	0.560982
CMF112	0.500942	0.355522	0.428206
CMF113	0.624641	0.656937	0.477939
CMF114	0.586234	0.664424	0.658187
CMF115	0.546732	0.562114	0.538522
CMF116	0.479974	0.387537	0.413271
CMF117	0.509696	0.455417	0.620684
CMF118	0.653105	0.440904	0.519652
CMF119	0.448481	0.486934	0.527589
CMF120	0.510596	0.58227	0.369942
CMF121	0.379727	0.265774	0.461994
CMF122	0.694363	0.533447	0.542116
CMF123	0.623027	0.521377	0.632566
CMF124	0.352932	0.523823	0.355596
CMF125	0.451183	0.587368	0.490811
CMF126	0.354798	0.372552	0.446995
CMF127	0.412074	0.477226	0.534797
CMF128	0.61803	0.485264	0.52823
CMF129	0.70058	0.710111	0.57997
CMF130	0.46873	0.348958	0.489157

Basic Safety Performance Functions for Rural Areas

	Rural					
	PD		BC		KA	
Parameter	Estimate	Std Err	Estimate	Std Err	Estimate	Std Err
Intercept	-4.3958	0.1367	-6.4526	0.2249	-7.166	0.2932
T_indicator	-0.4082	0.0301	-0.5777	0.0469	-0.5976	0.0576
logADT	0.6512	0.016	0.6897	0.0259	0.6597	0.0335
Dispersion	2.0788	0.0383	3.5491	0.1286	2.8879	0.1977

Basic Safety Performance Functions Urban Areas

	Urban					
	PD		BC		KA	
Parameter	Estimate	Std Err	Estimate	Std Err	Estimate	Std Err
Intercept	-6.4438	0.1848	-10.471	0.3353	-10.019	0.5065
T_indicator	-0.571	0.0332	-0.7207	0.0525	-0.5491	0.076
logADT	0.8893	0.0202	1.1105	0.0362	0.8735	0.054
Dispersion	1.993	0.0378	3.4358	0.1255	2.5558	0.2811

Full Safety Performance Functions for Rural Areas

	Urban					
	PD		BC		KA	
Parameter	Estimate	Std Err	Estimate	Std Err	Estimate	Std Err
Intercept	-3.687	0.1281	-5.5493	0.213	-6.4103	0.2872
T_indicator	-0.4054	0.0277	-0.5931	0.0437	-0.5941	0.0562
logADT	0.6584	0.0149	0.6971	0.0245	0.6559	0.0327
Def02	-0.6638	0.031	-0.6708	0.0523	-0.5432	0.0681
Def05	-0.5784	0.0308	-0.8689	0.0539	-0.7239	0.0709
Def14	-0.6031	0.031	-0.8171	0.0539	-0.4497	0.0674
Def24	-0.7713	0.0317	-1.0095	0.0565	-0.8017	0.0733
Def25	-0.7701	0.0308	-1.309	0.0581	-0.6398	0.0683
Dispersion	1.5484	0.031	2.0293	0.0852	2.0271	0.1543

Full Safety Performance Functions Urban Areas

	Urban					
	PD		BC		KA	
Parameter	Estimate	Std Err	Estimate	Std Err	Estimate	Std Err
Intercept	-5.6573	0.1733	-9.4342	0.3151	-9.2927	0.4974
T_indicator	-0.572	0.0303	-0.7167	0.0483	-0.5395	0.0744
logADT	0.8876	0.0189	1.0992	0.034	0.8705	0.0529
Def02	-0.6263	0.0336	-0.5935	0.0562	-0.4679	0.0892
Def05	-0.5994	0.0334	-0.9002	0.0585	-0.7646	0.0952
Def14	-0.6552	0.0343	-0.8523	0.0596	-0.5616	0.093
Def24	-0.7144	0.0342	-0.8645	0.0598	-0.5823	0.0932
Def25	-0.8395	0.0337	-1.4251	0.0643	-0.6813	0.0927
Dispersion	1.4957	0.0306	2.0237	0.0851	1.7298	0.2165

Appendix D: Performance Measures of Network Screening Evaluation

After generating the crash counts by using deterministic SPFs and Gamma random effect, the next step of the simulation was to compare different methodologies to screen a road network. We compared 10 methodologies (six RoadHAT and four HSM); and every methodology was based on different performance measures and their objective was to estimate the potential of safety improvement for each intersection.

The HSM uses crash counts and expected crash counts (BSPFs) to generate the LOSS. In the Index of Crash Frequency and Index of Crash Cost, we used a variance which depends on observed and expected crash counts.

Total Crash Cost

The total crash cost for an intersection "k" is going to be equal to the sum of the crash count times the average crash cost at three different severity levels:

$$CrashCost = \left(N_{pd} \cdot C_{PD}\right) + \left(N_{bc} \cdot C_{BC}\right) + \left(N_{ka} \cdot C_{KA}\right)$$

Empirical Bayes Estimate

Instead of using the crash count directly from the database, we calculated the performance measures based on the Empirical Bayes (EB) estimate for each crash severity. In our case, the EB was obtained thorough the following calculations applied to crashes at each severity level:

$$c_0 = 1/d_0$$

$$n_0 = 1/(d_0 a_0)$$

$$c_2 = c_0 + N_1$$

$$n_2 = n_0 + Y$$

$$a_2 = c_2/n_2$$

where:
d_0: SPFs over-dispersion parameter;
a_0: Expected number of crashes from SPF;
N_1: Crash count;
Y: Number of years analysis (3).

Once we had the three EB adjustments for each severity level, we applied the same methodology as before in the total crash cost as follows:

$$C_{nEB} = \left(N_{pd_{EB}} \cdot C_{pd}\right) + \left(N_{bc_{EB}} \cdot C_{bc}\right) + \left(N_{ka_{EB}} \cdot C_{ka}\right)$$

Index of crash cost (Icc). The index of crash cost equation is presented below.

$$I_{CC} = \frac{Observed\ Crash\ Cost - Expected\ Crash\ Cost}{\sqrt{Observed\ Crash\ Cost\ Variance + Expected\ Crash\ Cost\ Variance}}$$

where:

$$Observed\ Crash\ Cost = C_{PD} \cdot (N_{PD}) + C_{BC} \cdot (N_{BC}) + C_{KA} \cdot (N_{KA})$$

$$Expected\ Crash\ Cost = C_{PD} \cdot (a_{PD}) + C_{BC} \cdot (a_{BC}) + C_{KA} \cdot (a_{KA})$$

Observed Crash Cost Variance

$$= C_{PD}^2 \cdot (N_{PD}+1) + C_{BC}^2 \cdot (N_{BC}+1) + C_{KA}^2 \cdot (N_{KA}+1)$$

Expected Crash Cost Variance

$$= C_{PD}^2 \cdot a_{PD}^2 \cdot d_{PD} + C_{BC}^2 \cdot a_{BC}^2 \cdot d_{BC} + C_{KA}^2 \cdot a_{KA}^2 \cdot d_{KA}$$

where:

Npd = Number of observed property damage only (PDO) crashes during Y years;
Nbc = Number of observed non-incapacitating/possible injury (BC) crashes during Y years;
Nka = Number of observed fatal and incapacitating injury (KA) crashes during Y years;
a_{PD}= Typical PDO crash frequency (3 yr expected crash count) estimated from SPF;
a_{BC} = Typical BC crash frequency (3 yr expected crash count) estimated from SPF;
a_{KA} = Typical KA crash frequency (3 yr expected crash count) estimated from SPF;
d_{PD}, d_{NI}, d_{FI} = Over-dispersion parameters taken from SPF models;
C_{PD} = Average cost of PDO crashes, in dollars, estimated using crash data from State of Indiana;
C_{BC} = Average cost of BC crashes, in dollars, estimated using crash data from State of Indiana;
C_{KA} = Average cost of KA crashes, in dollars, estimated using crash data from State of Indiana;

Adjusted Index of Crash Cost (Ica)

For the basic and full SPFs the Ica is going to be calculated as:

$$U = \sum N_k C_k$$

where:
U = Total crash cost per intersection;
N = Number of crashes;
C = Unit cost.

$$m = \sum a_k(e) C_k$$

where:
m = Estimate of the crashes or cost expected for the exposure;
SPF (e) = Estimated expected crash count on a location for exposure e.

$$v_1 = \sum (N_k + 1) C_k^2$$

$$v_2 = \sum d_k m_k^2 c_k^2$$

$$v = v_1 + v_2$$

where:
v = variance of the m estimate;
d = dispersion parameter.
Then, the F value was calculated as follows:

$$F = Gamma.Dist\left(U, \frac{m^2}{v}, \frac{v}{m}, 1\right) \ldots \text{ Excel}$$

$$F = \text{CDF}\left(\text{gamma}, U, \frac{m^2}{v}, \frac{v}{m}\right) \ldots SAS$$

Finally, the Ica index is going to be equal to:

$$I_{ca} = \frac{(\ln(F) - \ln(1-F))}{1.7}$$

Average Crash Frequency

The average crash frequency is basically the total number of crashes for each location, which can be sorted by the total number of crashes at the three severity levels, for PDO crashes only or by injury and fatal crashes. The locations were sorted by the total number of crashes.

$$N_{observed,i} = N_{pd,i} + N_{bc,i} + N_{ka,i}$$

Relative Severity Index (RSI)

The RSI compares the crash cost of a single location against the crash costs of a reference population. Unsignalized rural and urban state-local intersections were used for this simulation purpose), so the reference population was all intersections in that type and the calculation procedure was:

$$RSI_i = \frac{N_{pd,i} \cdot C_{PD,i} + N_{bc,i} \cdot C_{BC,i} + N_{ka,i} \cdot C_{KA,i}}{N_{pd,i} + N_{bc,i} + N_{ka,i}}$$

where RSI_i applies to intersection i.

$$RSI_p = \frac{\sum_{k=1}^{12308} \left(N_{pd,k} \cdot C_{PD,i} + N_{bc,k} \cdot C_{BC,i} + N_{ka,k} \cdot C_{KA,i}\right)}{\sum_{k=1}^{12308} \left(N_{pd,i,k} + N_{bc,i,k} + N_{ka,i,k}\right)}$$

The RSI revealed a safety problem when RSI_i was higher than RSI_p. Then, the crash costs were sorted by average RSi_i cost. RSI was calculated based on the crash counts not in the SPFs as explained in the HSM 2010.

Expected Average Crash Frequency with EB

According to the method described in the HSM 2010, the expected average crash frequency with EB must be calculated based on the basic SPFs and the crash counts. The procedure followed from the Fundamentals of Roadway Safety Management (unpublished class notes of Dr. Tarko) and it is:

$$ExpectedCrashes_{EB} = (N_{PD\,EB}) + (N_{BC\,EB}) + (N_{KA\,EB})$$

And the estimated EB was calculated as described above using BSPFs.

EPDO average crash frequency with EB. To calculate the EPDO, we previously calculated the EB for the FSPFs at three severity levels. Then, all the crashes were converted into PD crashes:

$$EPDO = N_{PD\,EB} + N_{BC\,EB}\left(\frac{C_{BC}}{C_{PD}}\right) + N_{KA\,EB}\left(\frac{C_{KA}}{C_{PD}}\right)$$

Level of Service of Safety (LOSS)

Following the procedure described in the HSM 2010, the LOSS was calculated as follows:

$$N_{predicted} = a_{pd} + a_{bc} + a_{ka}$$

where a is the predicted number of crashes according to the basic SPFs.

$$ó = \sqrt{dN^2_{predicted}} = \sqrt{d_{pd} \cdot a^2_{pd} + d_{bc} \cdot a^2_{bc} + d_{ka} \cdot a^2_{ka}}$$

The level of service of safety threshold was as follows:

LOSS	Condition
I	$N_{obs} < (N_{pred} - 1.5 \cdot ó)$
II	$(N_{pred} - 1.5 \cdot ó) \leq N_{obs} < N_{pred}$
III	$N_{pred} \leq N_{obs} < (N_{pred} + 1.5 \cdot ó)$
IV	$N_{obs} \geq (N_{pred} + 1.5 \cdot ó)$

Appendix E: Comparison of Economic Evaluation Procedure

Steps	Indiana Practice	HSM
Estimate safety without road improvements	1. Crash reduction factor for the countermeasure $CRF_{total} = 1 - \Pi\ (1 - CRF_i)$ 2. Traffic Growth Period $GF = Q_m/Q$ $GQ = \log_{(1+R/100)}GF$ $Y_2 = IY - (BY + LY)/2; Y_4 = IY - PY$ $GT = \min\ (GQ - Y_2,\ GY - Y_4)$ 3. EB adjusted estimated crash frequency in the implementation year using 3 sets of SPF for PD, NI and FI $a_{PD} = 2.763 \times 10^{-3} \times Q_i^{.674} L^{.809}$ $a_{NI} = 7.945 \times 10^{-4} \times Q_i^{.668} L^{.815}$ $a_{FI} = 2.763 \times 10^{-4} \times Q_i^{.593} L^{.767}$ $a_1 = \frac{\frac{1}{D} + k}{\frac{1}{D \times a} + Y} \left(1 + \frac{R}{100}\right)^{z \times Y_2}$	1. Using 2 sets of SPF for TOT, FI calculate per mile predicted crash frequency for each year of crash data period $a_{TOT} = cy_{TOT} \times pct_{TOT} \times e^{\hat{a}} \times Q_i^{\hat{a}QTOT}$ $a_{FI} = cy_{FI} \times pct_{FI} \times e^{\hat{a}} \times Q_i^{\hat{a}QFI}$ cy_{TOT}, cy_{FI} = calibration factor pct_{TOT}, pct_{FI} =proportion of total and FI crashes of a specific type 2. Compute yearly correction factor for each year of crash data period $A_{y(TOT)} = \frac{a_{y(TOT)}}{a_{1(TOT)}}\ A_{y(FI)} = \frac{a_{y(FI)}}{a_{1(FI)}}$ 3. Calculate EB weight for crash data period $w_{(TOT)} = \frac{1}{1 + d_{TOT} \times \sum_{y=1}^{y} a_{TOT} \times L}$ $w_{(FI)} = \frac{1}{1 + d_{FI} \times \sum_{y=1}^{y} a_{FI} \times L}$ 4. EB adjusted expected crash for 1st year of crash data period $a_{EB(TOT)} = w_{(TOT)} \times L \times a_{1(TOT)} + \left(1 - w_{(TOT)}\right) \times \frac{k}{\sum_{y=1}^{y} A_{y(TOT)}}$ $a_{EB(FI)} = w_{(FI)} \times L \times a_{1(FI)} + \left(1 - w_{(FI)}\right) \times \frac{k}{\sum_{y=1}^{y} A_{y(FI)}}$ 5. Calculate the sum of the EB-adjusted expected number of accidents for the for crash data period $a_{H(TOT)} = \sum_{y=1}^{y} a_{EB(TOT)} \times A_{y(TOT)}$ $a_{H(FI)} = \sum_{y=1}^{y} a_{EB(FI)} \times A_{y(FI)}$ 6. Without countermeasure EB adjusted expected crash for each year of the analysis period $a_{F(TOT)} = \frac{a_{H(TOT)}}{\sum_{y=1}^{y} a_{TOT}} \times cy_{TOT} \times pct_{TOT} \times e^{\hat{a}} \times (Q_i \times GF^n)^{\hat{a}}$ $a_{F(FI)} = \frac{a_{H(FI)}}{\sum_{y=1}^{y} a_{FI}} \times cy_{FI} \times pct_{FI} \times e^{\hat{a}} \times (Q_i \times GF^n)^{\hat{a}}$ Here, n=Implementation year - Last year of crash data period + Year in the analysis period-1

(Continued)

(Continued)

Steps	Indiana Practice	HSM
Estimate safety with road improvements	4. Estimate the present worth of crash benefit based on crash severity $B_p = \frac{1}{\left(1+\frac{I}{100}\right)^{Y_4}} \times a_1 \times \frac{CRF}{100} \times C_p$ $C_p = \left(1+\frac{F}{100}\right)^{Y_3} \times C_{cy}$ $Y_3 = PY - CY$	7. Countermeasure (v) with EB adjusted expected crash for each year of the analysis period $a_{Fv(TOT)} = \frac{a_{H(TOT)}}{\sum_{y=1}^{y} a_{TOT}} \times \left(cy_{TOT} \times pct_{TOT} \times e^{\hat{a}} \times (Q_i \times GF^n)^{\hat{a}} \times CMF_{TOT}\right)$ $a_{Fv(FI)} = \frac{a_{H(FI)}}{\sum_{y=1}^{y} a_{FI}} \times \left(cy_{FI} \times pct_{FI} \times e^{\hat{a}} \times (Q_i \times GF^n)^{\hat{a}} \times CMF_{TOT}\right)$ Here, n=Implementation year - Last year of crash data period + Year in the analysis period-1
Estimate the PW of safety benefit:	5. Calculate present worth of benefit for the countermeasures $PWB_1 = \frac{B_p \times \left(1+\frac{R}{100}\right)^{z} \times [1 - \frac{\left(1+\frac{R}{100}\right)^{z \times GT}}{\left(1+\frac{I}{100}\right)^{GT}}]}{\left(1+\frac{I}{100}\right) - \left(1+\frac{R}{100}\right)^{z}}$ $PWB_2 = \frac{B_p \times \left(1+\frac{R}{100}\right)^{z \times GT}}{\left(1+\frac{I}{100}\right) \times \left(1+\frac{I}{100}\right)^{GT}}$ $PWB = PWB_1 + PWB_1$ Annualized benefit for the countermeasures $EUAC = PWB \times \left(\frac{I}{100}\right)$	8. Calculate the reduced number of crashes because of countermeasure for each year of the analysis period $AR_{TOT} = a_{F(TOT)} - a_{Fv(TOT)}$ $AR_{FI} = a_{F(FI)} - a_{Fv(FI)}$ $AR_{PDO} = AR_{TOT} - AR_{FI}$ 9. Present value of safety benefits of countermeasure $AC_{FI} = P_F AC_F + P_{II} AC_{II} + P_{SI} AC_{SI} + P_{MI} AC_{MI}$ $P_F, P_{II}, P_{SI}, P_{MI}$ = Statewide proportions of fatal, incapacitating, serious and minor injury, which are stored in the Master SafetyAnalyst Accident distribution defaults by severity level file. $AC_F, AC_{II}, AC_{SI}, AC_{MI}$ = Relative costs for fatal, incapacitating, serious, and minor injury, which are stored in the Master SafetyAnalyst Accident Costs defaults file. Calculate present worth of benefit for each year of the analysis period $PWB = \sum_{n=1}^{N} \frac{AR_{PD} \times AC_{PD}}{(1+R)^n} + \sum_{n=1}^{N} \frac{AR_{FI} \times AC_{FI}}{(1+R)^n}$
Estimate the PW of cost for countermeasure implementation	7. Present worth of countermeasure implementation cost by taking into account the present worth of capital cost and the present worth of maintenance cost, minus the present worth of salvage value $PWCC = \frac{1}{\left(1+\frac{I}{100}\right)^{Y_4}} \sum_i (CC_i \times \frac{\left(1+\frac{I}{100}\right)^{SL_i}}{\left(1+\frac{I}{100}\right)^{SL_i} - 1})$ $PWC = PWCC + PWM - PWS$ $EUAC = PWC \times \left(\frac{I}{100}\right)$	10. Present worth of countermeasure implementation cost: a. Annual construction cost for countermeasure $ACC = C \times \frac{R\left(1+\frac{R}{100}\right)^{SL_i}}{\left(1+\frac{R}{100}\right)^{SL_i} - 1})$ b. Present value of construction cost for the analysis period $PWC = ACC \times \frac{\left(1+\frac{R}{100}\right)^{N} - 1}{R \times \left(1+\frac{R}{100}\right)^{N}})$
Calculate Net benefit	8. Calculate B/C ratio	11. Calculate B/C ratio

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

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The recommended citation for this publication is:

Tarko, A. P., Romero, M., Thomaz, J., Ramos, J., Sultana, A., Pineda, R., & Chen, E. (2016). *Updating RoadHAT: Collision diagram builder and HSM elements* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2016/11). West Lafayette, IN: Purdue University. http://dx.doi.org/10.5703/1288284316334