New Tool and Safety Performance Measure for Highway Safety Evaluation

A Thesis
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Abstract

This thesis describes the development of a new geographic information system (GIS) tool to evaluate the safety effectiveness of roadway safety projects. The tool calculates four standard safety performance measures and compiles the results into a report. The tool was demonstrated with a case study of nineteen projects that began between 2013 and 2015 and were completed by 2016 throughout the state of Idaho. Ten of the projects experienced reductions in crash frequency; eleven experienced reductions in crash rate; eight experienced reductions in annual economic cost; and ten experienced reductions in severe crash proportion. Four projects experienced reductions in all four safety measures.

The thesis also introduces a new safety performance measure based on the concept of expected utility. The new measure, called expected cost, was demonstrated in three example applications: network screening, safety effectiveness evaluation, and route choice navigation. For network screening, ten intersections and ten segments were ranked according to their expected costs and compared to rankings formed by the four standard measures. Two intersections and two segments were then analyzed using expected cost to test its performance in safety effectiveness evaluation. The results were again compared to those generated by the standard performance measures to see if expected cost offers a new perspective in this application. Lastly, the expected cost was used to calculate routes that optimized safety rather than travel time.

Acknowledgments

I first would like to thank Dr. Lowry for his outstanding mentorship. Working as a research assistant for Dr. Lowry has opened so many doors in my life, helping me to pursue a master’s degree and get a job that I want. This thesis truly would not have been possible without his support and encouragement. I also want to thank the Idaho Transportation Department for funding this project.

Dedication

This thesis is dedicated to my parents for all their support throughout my educational career. They taught me to always question the world around me and to appreciate education in an ever-progressing world. It is difficult to picture myself being where I am today without them in my corner.

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Chapter 1: Introduction

Problem Statement

The Highway Safety Improvement Program (HSIP) is a Federal-aid program started in 2005 to reduce fatalities and serious injuries from motor vehicle traffic. The program allocates money to each state Department of Transportation (DOT) for projects that will help improve highway safety (e.g., installation of metal guard rails, rumble strips, and new lighting). To track the efforts of the program, State DOTs must submit an annual report to the federal government explaining how their HSIP funds were spent and how effective those projects were at improving safety.

Currently, the Idaho Transportation Department (ITD) only provides an overall evaluation of statewide crash statistics in their HSIP Annual Reports. They do not have tools available to perform before/after crash analyses for individual projects, which makes it difficult to evaluate the effectiveness of the countermeasures that were implemented. There are existing tools, such as those in AASHTOWare Safety, that can be used to help gather crash and volume data from project locations, but the tools do not automatically calculate safety performance measures. Instead, the analyst must calculate these metrics, which for numerous sites can be a substantial amount of work.

This thesis presents a new geographic information systems (GIS) tool to help ITD evaluate HSIP projects. The new tool can reduce the time and cost to complete this phase of the safety management process. Furthermore, this thesis introduces a new safety performance measure that can be used for safety analysis. The four traditional safety performance measures are *crash frequency*, *crash rate*, *annual economic cost*, and *severe crash proportion*. These measures possess certain strengths and limitations. Consequently, they are more useful when observed comprehensively to gain a more robust understanding of safety conditions. Likewise, the new safety performance measure described in this thesis provides additional insight into safety conditions.

Objectives

The objectives of this research were to:

1) Create a GIS <u>tool</u> to evaluate safety effectiveness of safety improvement projects.
2) Perform a <u>case study</u> evaluation for HSIP projects in Idaho.
3) Invent a <u>new safety performance measure</u> and demonstrate potential applications for transportation safety analysis.

Organization

Chapter 2 provides background information about safety analysis. Chapters 3 and 4 focus on the work that was done for ITD related to safety effectiveness evaluation. Chapter 3 introduces the new GIS tool and describes the data sources, which include ITD's published data for Annual Average Daily Traffic (AADT) and crashes. Chapter 4 summarizes the results for the case study evaluation for nineteen HSIP projects that were completed between 2014 and 2016. ITD provided the project list and project information from their project database called OTIS (Office of Transportation Investment Systems). Chapter 5 introduces the new safety performance measure and demonstrates usefulness with three applications: network screening, safety evaluation, and route choice navigation. Chapter 6 concludes with a discussion of the strengths and limitations of the new tool and safety performance measure.

Chapter 2: Background on Safety Analysis

Safety Management Process

The Safety Management Process is a six-step cycle presented in the HSM to help state DOTs identify and prioritize site-level safety improvement projects (AASHTO, 2010). Figure 2.1 shows the steps: Network Screening, Diagnosis, Select Countermeasures, Economic Appraisal, Prioritize Projects, and Safety Effectiveness Evaluation.

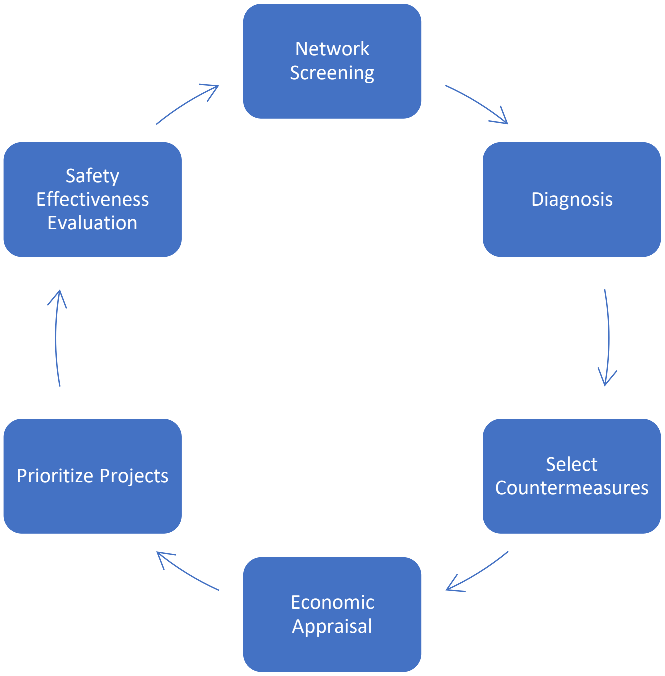


Figure 2.1 Safety Management Process Steps

The first step is *Network Screening*. This is the process of scanning segments and intersections throughout the state to rank-order locations where roadway improvements might be able to reduce crashes. Network screening is done separately for sites that are segments and sites that are intersections. Dr. Ezra Hauer, a safety expert who helped develop the HSM, emphasized that network screening is the crucial first step to identify “sites with promise” (Hauer, 1997). Sites are ranked using *safety performance measures*, such as *crash frequency* which is the average number of crashes per year over an analysis period (typically five years for Network Screening).

The second step is *Diagnosis*. This involves identifying the root cause of the crashes at the site and determining the extent of the problem. This is done through detailed investigation of crash data, including summarizing the contributing circumstances (e.g., Excessive Speed) and harmful events

(Rear-End Collision) as reported by law enforcement. The outcome of the diagnosis step is a clear understanding of what went wrong and why, which is critical in developing effective solutions and preventing similar incidents from happening in the future.

The third step is *Select Countermeasures*. This involves identifying and choosing the most appropriate solutions to address identified safety risks. A countermeasure is a specific strategy taken to reduce collisions and improve road safety. This could include measures such as installing roundabouts, adding road signs and traffic signals, increasing road visibility, improving road surfaces, creating pedestrian and cyclist paths, and implementing traffic calming measures. The goal of these countermeasures is to minimize the likelihood and severity of crashes and create safer conditions for all road users. This step in the Safety Management Process requires a thorough evaluation of various options, taking into consideration their feasibility, cost-effectiveness, and potential impact on safety. The goal is to select countermeasures that effectively mitigate the identified risks.

The fourth step is *Economic Appraisal.* This is an assessment of the costs and benefits associated with implementing countermeasures at a particular site. This step involves estimating the financial impact of potential safety measures, including both the costs of implementing the measures and the benefits that may result from reduced vehicle collisions. The goal of the Economic Appraisal step is to ensure that the most cost-effective safety measures are selected and implemented, while taking into consideration both financial and non-financial factors such as regulatory requirements and public perception. The results of the Economic Appraisal are used to inform the decision-making process and support the development of a safety management plan.

The fifth step is *Prioritize Projects*. This involves prioritizing potential safety improvement projects based on a variety of factors, including crash frequency and severity, target population, and cost-effectiveness. This step allows agencies to focus their limited resources on the projects that will have the greatest impact on reducing crashes and improving safety for all road users. The prioritization process also helps to ensure that limited funding is allocated to the most pressing safety concerns and that projects are aligned with overall transportation and safety goals.

The sixth step is *Safety Effectiveness Evaluation.* This is the evaluation of completed safety improvement projects. One approach is to compare safety performance measures, such as crash frequency, before and after project completion. For Safety Effectiveness Evaluation, the before and after analysis period is typically three years. This information helps to determine the effectiveness of the implemented countermeasures, guide decision-making for future projects, and allocate resources effectively. The Safety Effectiveness Evaluation step is an ongoing process that enables agencies to continuously monitor and evaluate their safety programs to ensure they are achieving their desired outcomes and making progress towards reducing crashes and improving safety on the road. The interested reader should consult *Chapter 9 Safety Effectiveness Evaluation* of the Highway Safety Manual (HSM), for additional information about safety evaluation. Another essential resource is the *Highway Safety Improvement Program Manual* published by FHWA to provide state DOTs guidance for integrating HSM methods with their state HSIP effort (Herbel et al., 2010). A few years later, FHWA launched a series of reports called *Reliability of Safety Management Methods* to provide additional explanations and examples. The report authored by Srinivasan et al. (2016) is focused on evaluation and provides examples using simulated data.

Safety Performance Measures

Safety performance measures are metrics for (1) Network Screening to rank-order sites and (2) Safety Effectiveness Evaluation to determine if the implemented countermeasures improved safety. Four commonly used safety performance measures are *crash frequency*, *crash rate*, *annual economic cost*, and *severe crash proportion*. Each performance measure conveys a different safety aspect, so it is beneficial for the analyst to examine all four comprehensively. The HSM recommends calculating these performance measures for a three-year analysis period, N = 3. (The analyst can choose to use other durations but should be aware that statistical bias increases for analysis periods less than three years and more than five years. For Safety Effectiveness Evaluation, the “before period” should be the same duration as the “after period”).

Crash frequency is calculated as follows:

$$Crash\ Frequency = \frac{1}{N}\sum_{n} X_n \tag{1}$$

where $X_n$is the number of crashes in year n for N years. Crash frequency is expressed as *crashes/year*.

Crash Rate is the number of crashes per vehicle volume. For segments the calculation is:

$$Segment\ Crash\ Rate = \frac{1{,}000{,}000 * \sum_n X_n}{365 \sum_n LA_n} \tag{2}$$

where $X_n$is the number of crashes in year n, L is the length of the segment in miles, and A_n is the Annual Average Daily Traffic (AADT) for year n. The denominator is Vehicle Miles Traveled (VMT). Crash Rate for a segment is expressed as *crashes/Million VMT*. When AADT varies across a segment, then A_n is a length-weighted average.

For intersections, the calculation for crash rate is:

$$Intersection\ Crash\ Rate = \frac{1{,}000{,}000 * \sum_n X_n}{365 \sum_n \sum_i d_i * A_{n,i}} \tag{3}$$

where $X_n$is the number of crashes in year n. is the AADT for year n on leg i. If leg *i* is a two-way road, then d_i = ½; if leg *i* is a one-way road approaching the intersection, then d_i = 1; and if leg *i* is one-way road leaving the intersection, then d_i = 0. For two-way roads, AADT is divided by 2 because AADT is the total volume in both directions. The denominator in Equation 3 is Total Entering Vehicles (TEV). Crash Rate for an intersection is expressed as *crashes/Million EV*.

Annual Economic Cost is based on the concept of cost “equivalence” for each severity type. Table 2.1 shows economic cost equivalent values for each severity type in 2021-USD. The calculation for the performance measure is:

$$Annual\ Economic\ Cost = \frac{1}{N} \sum_n \sum_s X_{n,s} * C_s \tag{4}$$

where N is the number of years, $X_{n,s}$ is the number of crashes in year n for severity s and C_s is the economic cost equivalent for severity s. Annual Economic Cost is expressed as *dollars/year*. (Sometimes this performance measure is divided by the equivalent cost associated with Property Damage Only crashes, in which case the value is a unitless index relative to PDO).

Table 2.1 Crash Severity Equivalent Economic Cost (ITD, 2022)

KABCO	Severity	Cost
K	Fatalities	$11,800,000
A	Suspected Serious Injury	$564,335
B	Suspected Minor Injury	$153,707
C	Possible Injuries	$78,488
O	No Injuries (Property Damage Only)	$3,976

Severe crash proportion is the percentage of crashes that are categorized as either fatal or serious injury crashes. This calculation is:

$$Severe\ Crash\ Proportion = \frac{\sum_n \sum_{s\in KA} X_{n,s}}{\sum_n \sum_{s\in KABCO} X_{n,s}} \tag{5}$$

where $X_{n,s}$ is the number of crashes in year n for severity s. The numerator is a summation of fatal (K) and serious injury (A) crashes. The denominator is a summation of all crashes. Severe crash proportion is expressed as a percentage.

Example Safety Effectiveness Evaluation Calculations

For example, Table 2.2 shows crash data for two intersection projects and two segment projects (these projects were selected from the case study). The data is for a three-year analysis period. Traffic volume is in units of million TEV for intersections and million VMT for segments. The intersection projects involved one intersection each (it is possible to have multiple intersections associated with a single HSIP project). The first segment project is one continuous segment 84 miles long. The second segment project is four segments totaling 10 miles. The segment projects have more crashes because of the long geographic distance.

Table 2.2 Example Before and After Crash Data

		Before							**After**						
ID	**Project Type**	**Volume**	**K**	**A**	**B**	**C**	**O**	**Total**	**Volume**	**K**	**A**	**B**	**C**	**O**	**Total**
1	Intersection	35.33	0	2	3	2	15	22	41.85	1	1	3	6	13	24
2	Intersection	11.50	0	1	4	1	5	11	13.59	0	0	1	2	12	15
3	Segment	182.69	5	8	28	43	276	360	248.11	6	12	20	32	123	193
4	Segment	36.72	0	3	10	14	48	75	35.50	0	3	11	9	37	60

Table 2.3 shows the safety performance measure results. This example illustrates the value of calculating and examining all four comprehensively. For example, Project 1 exhibits an increase in crash frequency but a decrease in crash rate. This mixed result is because although the number of total crashes increased by two, the volume increased by 18%. In addition, this location showed a significant increase in annual economic cost, but this is due to the high weight given to the one fatality that occurred in the after period. Yet, the severe crash proportion (K and A crashes) dropped by nearly 1%.

Project 2 shows an increase in crash frequency and crash rate but a decrease in annual economic cost and severe crash proportion. Project 3 exhibits the opposite trend. Finally, project 4 shows improvement in the first three performance measures but not for severe crash proportion. For this set of example projects, a comprehensive examination of all four safety performance measures provides more robust insight into safety effectiveness.

Table 2.3 Example Safety Performance Measure Results

	Crash Frequency (per year)		**Crash Rate (per volume)**		**Annual Economic Cost (per year)**		**Severe Proportion (percent)**	
ID	**Before**	**After**	**Before**	**After**	**Before**	**After**	**Before**	**After**
1	7.3	8.0	0.62	0.57	$602,136	$4,449,357	9.1%	8.3%
2	3.7	5.0	0.96	1.10	$425,844	$119,465	9.1%	0.0%
3	120.0	64.3	1.97	0.78	$24,096,945	$27,882,275	3.6%	9.3%
4	25.0	20.0	2.04	1.69	$1,506,585	$1,412,429	4.0%	5.0%

Analysis Enhancements

Safety analysis can be improved through various enhancements. First, the analysis is more statistically sound if a group of projects are analyzed together rather than individual projects. The *potential* issue with analyzing projects individually is a statistical phenomenon called Regression to the Mean (RTM) bias. Figure 2.2 illustrates the possibility of RTM bias for crash frequency. Note that the number of crashes fluctuates from year to year. Sometimes by coincidence, a three-year analysis period will capture a low or high average crash frequency. Evaluation of a group of projects reduces the chance of RTM bias because some locations would be experiencing a natural high while others are experiencing a natural low, such that the average across the group more accurately represents the before or after periods. An even better enhancement is to also evaluate a group of locations that did not receive any safety improvement treatments. This collection of untreated locations is called a “comparison group” and acts as a control for the safety analysis. The locations in the comparison group must be similar to the locations that received the treatment (safety improvement) in terms of characteristics such as the number of lanes, speed limit, vehicle volume, adjacent land use, intersection geometry, traffic control type, and urban/rural designation.

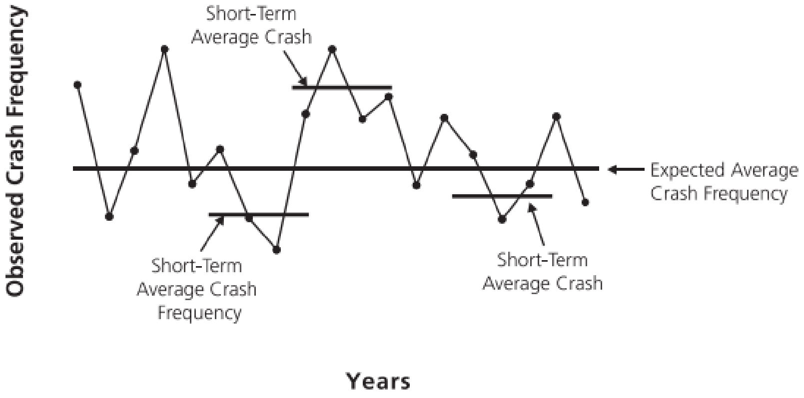


Figure 2.2 Example of RTM Bias (AASHTO, 2010)

Another enhancement is only to include specific, or targeted, crash types in the calculation. For example, the analyst could calculate crash frequency only for crashes that involved “Head-On Turning”. This new performance measure can be called “Head-On Turning Crash Frequency”. In a similar way, the analyst may want to calculate one of the other safety performance measures for specific crash types (i.e., crash rate, annual economic cost, or severe crash proportion). In some situations, this enhancement can provide additional insight into safety effectiveness. However, this approach requires identifying the crash type(s) that were targeted by the HSIP project, and in the case of annual economic cost, the calculation requires additional data—cost equivalents by crash type. Sometimes, isolating specific crash types provides no added value. For locations that experience low crash numbers, there is generally no added value to evaluate an even smaller subset of crashes.

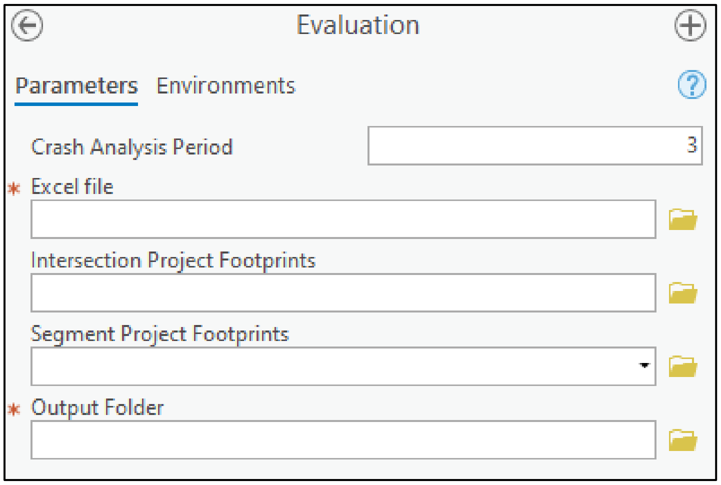
A third enhancement is to use Safety Performance Functions (SPF) in the analysis. SPFs are mathematical models for predicting crash frequencies for intersections or along roadway segments. These models are comprised of one or multiple variables which describe the site’s characteristics like vehicle volume and speed limit. One way to use an SPF is to compare the observed crash frequency with the predicted crash frequency, utilizing the predicted crash frequency as a control like in the comparison group enhancement. Another way to use SPFs is through a procedure called the Empirical Bayes (EB) Method in which the observed crash frequency and predicted crash frequency are combined using a formula that produces the “expected crash frequency” (the formula is provided in Appendix A).

There are more than one hundred SPFs in the HSM, and researchers are frequently publishing new SPFs. Analysts can follow a procedure in the HSM to *calibrate* an SPF that was created with data from somewhere else. For example, the SPF shown in Equation 6 was created using data from Florida. Calibration would adjust this SPF for use in Idaho (Srinivasan et al., 2013). Abdel-Rahim and Sipple (2015) calibrated three SPFs from the HSM for use in Idaho. They showed that the HSM SPFs without calibration consistently predicted crash frequency higher than the observed crash frequency. Furthermore, they also created Idaho-specific versions of these SPFs and showed that Idaho-specific SPFs provided better crash predictions. Loudon and Schulte (2016) demonstrated evaluation using one of the Idaho-specific SPFs. One relevant recommendation by Loudon and Schulte (2016) is to develop automated or semi-automated evaluation methods (One of the main objectives of the present research study).

Chapter 3: New GIS Tool for Safety Evaluation

Evaluation Method

Figure 3.1 shows the tool interface and Table 3.1 lists the evaluation tasks. The first task for the analyst is to decide the length of the analysis period for calculating before and after safety performance measures. The HSM recommends an analysis period between three and five years. Less than three years increases the possibility of RTM bias (see Chapter 2 for more information about RTM bias). More than five years increases the possibility of bias from a change in the surrounding land use and traffic patterns. Five years provides more time to monitor crash conditions, which is important for many locations in Idaho with low crash occurrence compared to states with densely populated areas. However, five years involves analysis too far back in the past: Some projects are under construction for two or three years and official publication of AADT and crash data can be as much as two years behind. Consequently, for some projects a three-year analysis period means the start of the before period is 11 years in the past and for a five-year analysis period, the start of the before period can be as far back as 15 years ago. There is too much that can change in terms of driver behavior, vehicle technology, and surrounding environment. We recommend using a three-year analysis period for Safety Effectiveness Evaluation and a five-year analysis period for Network Screening.



Crash Analysis Period 3

* Excel file

Intersection Project Footprints

Segment Project Footprints

* Output Folder

Figure 3.1 Evaluation tool interface.

Table 3.1 Recommended Methodology

Task	Description	Comment
Analyst: Task 1	Decide analysis period.	3 to 5 years. HSM recommends three-year analysis period.
Analyst: Task 2	Identify Key Numbers of HSIP-funded projects.	Completed two years plus analysis period in the past.
Analyst: Task 3	Query OTIS for project information: district, category, description.	Future tool could query online geodatabase (see Chapter 5 Recommendations).
Analyst: Task 4	Create geographic footprint for projects.	Future tool could query online geodatabase (see Chapter 5 Recommendations).
Analyst: Task 5	Open and run GIS tool.	
Tool: Task 1	Align project footprint with links and nodes of the AADT network.	Should be updated with ITD’s AADT (see Chapter 5 Recommendations).
Tool: Task 2	Calculate vehicle volume for before and after analysis period.	VMT for segment projects, TEV for intersection projects.
Tool: Task 3	Buffer project footprint.	100 ft for segment projects, 300 ft for intersection projects.
Tool: Task 4	Clip crash data for before and after analysis period.	ITD's online crash data. Keep only intersection related crashes for intersection project.
Tool: Task 5	Calculate before and after crash frequency.	
Tool: Task 6	Calculate before and after crash rate.	Per million vehicles.
Tool: Task 7	Calculate before and after annual economic cost.	Uses ITD's economic cost equivalent data. (Should be updated annually).
Tool: Task 8	Calculate before and after severe crash proportion.	KA/KABCO
Tool: Task 9	Create charts for safety performance measures	Four charts.
Tool: Task 10	Create chart for prominent contributing factors.	10 most frequent contributing factors.
Tool: Task 11	Create chart for prominent harmful events.	10 most frequent harmful events.
Tool: Task 12	Calculate performance measures for group evaluation.	Segment and Intersection projects. Future tool could include additional groupings.
Tool: Task 13	Create charts for group evaluation.	Segment projects and Intersection projects.
Tool: Task 14	Create map of project footprint and crash points.	Image file exported from ArcGIS.
Tool: Task 15	Get Google Street View image.	Located at latitude, longitude starting point of first segment/intersection centroid.
Tool: Task 16	Create output Excel file.	
Tool: Task 17	Create output GIS files.	An ArcGIS Map Project and geodatabase with project footprints and crash points.
Tool: Task 18	Create output Word and PDF report.	
Analyst: Task 6	Extract info for HSIP Annual Report.	From Word or Excel files.
Analyst: Task 7	Select projects for further investigation.	Optional.

The analyst identifies the HSIP-funded projects that are to be evaluated (Analyst Task 2). For the current version of the tool, the analyst must query the OTIS database for project information and create GIS files for project footprints (Analyst Tasks 3 and 4). ITD currently does not maintain an adequate geodatabase of project footprints, especially not for projects that occurred so long ago (the case study includes projects that began between 2013 and 2015). Consequently, the analyst must provide an Excel file with project information and GIS files for project footprints. The evaluation procedure is automatic (Tool Tasks 1 to 18).

The tool is an open-source Python script for ArcGIS Pro 2.9. It runs directly from a folder on a hard drive or USB storage device without the need for installation. The computer code can be edited using any integrated development environment (IDE), such as Spyder.

Tool Task 1 is to align the project footprints with a GIS file that has AADT values for all roads in Idaho to extract the appropriate volume data. Tool Task 2 calculates vehicle volume passing through the project footprint for the analysis period. For HSIP projects that involve segments (GIS polylines), the volume calculation is VMT. A project’s footprint might terminate anywhere along a roadway link (a “link” is the roadway between intersections, whereas a “segment” might span across multiple links). The calculation uses the length-weighted summation of AADT for all links or portions of links that underlie the project segment or segments (one Key Number can have multiple segments). This value is multiplied by 365 and summed for all years in the analysis period. The calculation for VMT is shown in Chapter 2 as the denominator of Equation 2.

The volume calculation for intersections (GIS points) is TEV. The calculation is the summation of entering AADT for every approach leg. AADT is divided by two for two-way roads because AADT is the total volume in both directions. This value is multiplied by 365 and summed for all years in the analysis period. The calculation for TEV is shown in Chapter 2 as the denominator of Equation 3.

Next, the tool identifies crashes within a certain distance of the project footprints (Tool Tasks 3 and 4). The search distance, or buffer distance in GIS terminology, is 100 feet for segment projects and 300 feet for intersection projects. This search distance is an example of code modification that could be done. For intersection projects, only intersection related crashes are kept.

The tool calculates safety performance measures for the before and after period (Tool Tasks 5 to 8). These four safety performance measures are crash frequency, crash rate, annual economic cost, and severe crash proportion (equations in Chapter 2). Next, charts are made for each safety performance measure (Tool Task 9). This is followed by creating charts for contributing factors and harmful events (Tool Tasks 10 and 11). These charts only include the 10 most frequent items.

Tool Task 12 calculates the average safety performance measure for groups of projects. For the current version of the tool, group evaluation is only done for project type: segment projects and intersection projects. Tool Task 13 creates charts for the group evaluation.

Next, the tool creates a map image for each project footprint showing the crash locations (Tool Task 14). The tool connects to Google's online Street View database to get a representative image for each project (Tool Task 15). For segment projects, the image is taken from the latitude and longitude of the starting point of the first segment associated with that Key Number. For intersection projects, the image is taken from the latitude and longitude of the centroid of the first intersection associated with that Key Number. Finally, the tool creates the output files (Tool Tasks 16 to 18). The output includes an Excel file, GIS database, and a report in Word and PDF format. These are described in the next section.

When the tool has completed, the analyst can proceed to use the information as needed (Analyst Tasks 6 and 7). The analyst might choose to extract information from the Word document or the Excel file to include in the Annual HSIP Report (noting that this evaluation pertains to projects done in the past). The analyst may want to investigate some projects further. For example, they may want to look closer at the original project documentation to better understand the goals of the project or examine the police reports to better understand the nature of the crashes that occurred. If possible, the analyst could try to identify a comparison group to check how much the results differ compared to locations with similar characteristics (see Chapter 2).

Tool Output

The tool creates the following output:

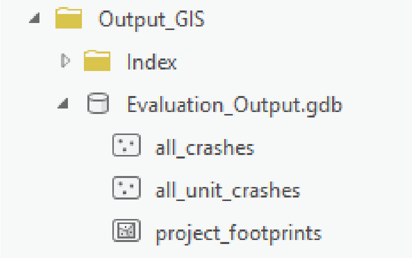
- Excel file with safety performance measure data for each project.
- GIS files with crash data and project footprints.
- Word and PDF formatted report.

The Excel file contains all relevant information. The fields are shown in Table 3.2. The data for the first eight fields are copied from the input that the analyst uploads to the tool. The data for the remaining fields are created by the tool.

Table 3.2 Output Excel Fields

Source	**Excel Field**	**Description**
Input	Key_No	Key Number Unique identifier.
Input	Project_Type	Intersection or Segment
Input	Project_Start_Year	Program Year from OTIS
Input	Project_End_Year	Finl_Est_Year from OTIS
Input	District	District ID (1 through 6)
Input	Location	Location title from OTIS
Input	Category	SubClass category from OTIS
Input	Description	Description from OTIS
Tool	Features	Number of geographic features
Tool	Latitude	Centroid for intersection projects or starting point for segment projects
Tool	Longitude	Centroid for intersection projects or starting point for segment projects
Tool	Volume_Before	TEV for intersection projects or VMT for segment projects
Tool	Volume_After	TEV for intersection projects or VMT for segment projects
Tool	K_Before	Number of fatal crashes in before period
Tool	K_After	Number of fatal crashes in after period
Tool	A_Before	Number of suspected serious injury crashes in before period
Tool	A_After	Number of suspected serious injury crashes in after period
Tool	B_Before	Number of suspected minor injury crashes in before period
Tool	B_After	Number of suspected minor injury crashes in after period
Tool	C_Before	Number of possible injury crashes in before period
Tool	C_After	Number of possible injury crashes in after period
Tool	Pdo_Before	Number of property damage only crashes in before period
Tool	Pdo_After	Number of property damage only crashes in after period
Tool	Total_Before	Number of all reportable crashes in before period
Tool	Total_After	Number of all reportable crashes in after period
Tool	Frequency_Before	Crash frequency for before period
Tool	Frequency_After	Crash frequency for after period
Tool	Economic_Before	Annual economic cost for before period
Tool	Economic_After	Annual economic cost for after period
Tool	Rate_Before	Crash rate for before period
Tool	Rate_After	Crash rate for after period
Tool	Severe_Before	Severe crash proportion for before period
Tool	Severe_After	Severe crash proportion for after period

The GIS files are stored in a geodatabase as shown in Figure 3.2. The crash points and unit crash points (one point for each vehicle involved) are labeled with the associated Key Number and analysis period designation: before or after. The project footprints are the polygon buffer that surrounds the project centroid or centerline. Figure 3.3 shows an example project footprint and the associated crash data.



Output_GIS
Index
Evaluation_Output.gdb
all_crashes
all_unit_crashes
project_footprints

Figure 3.2 Output geodatabase.

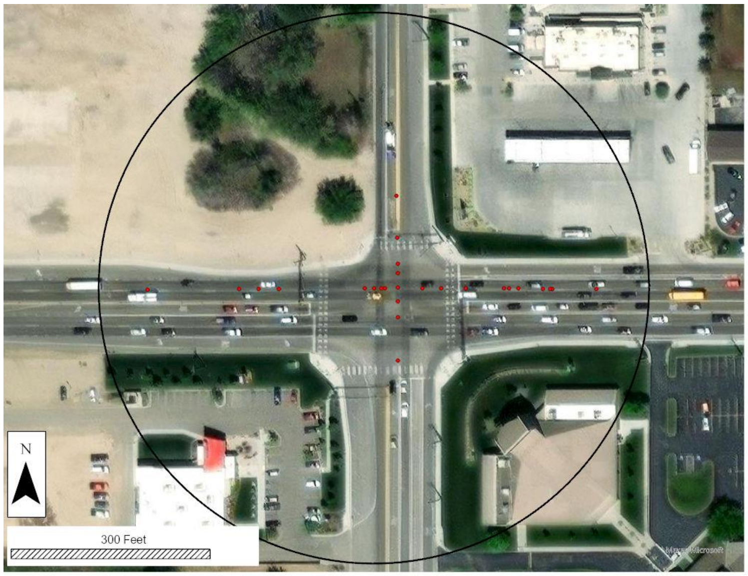
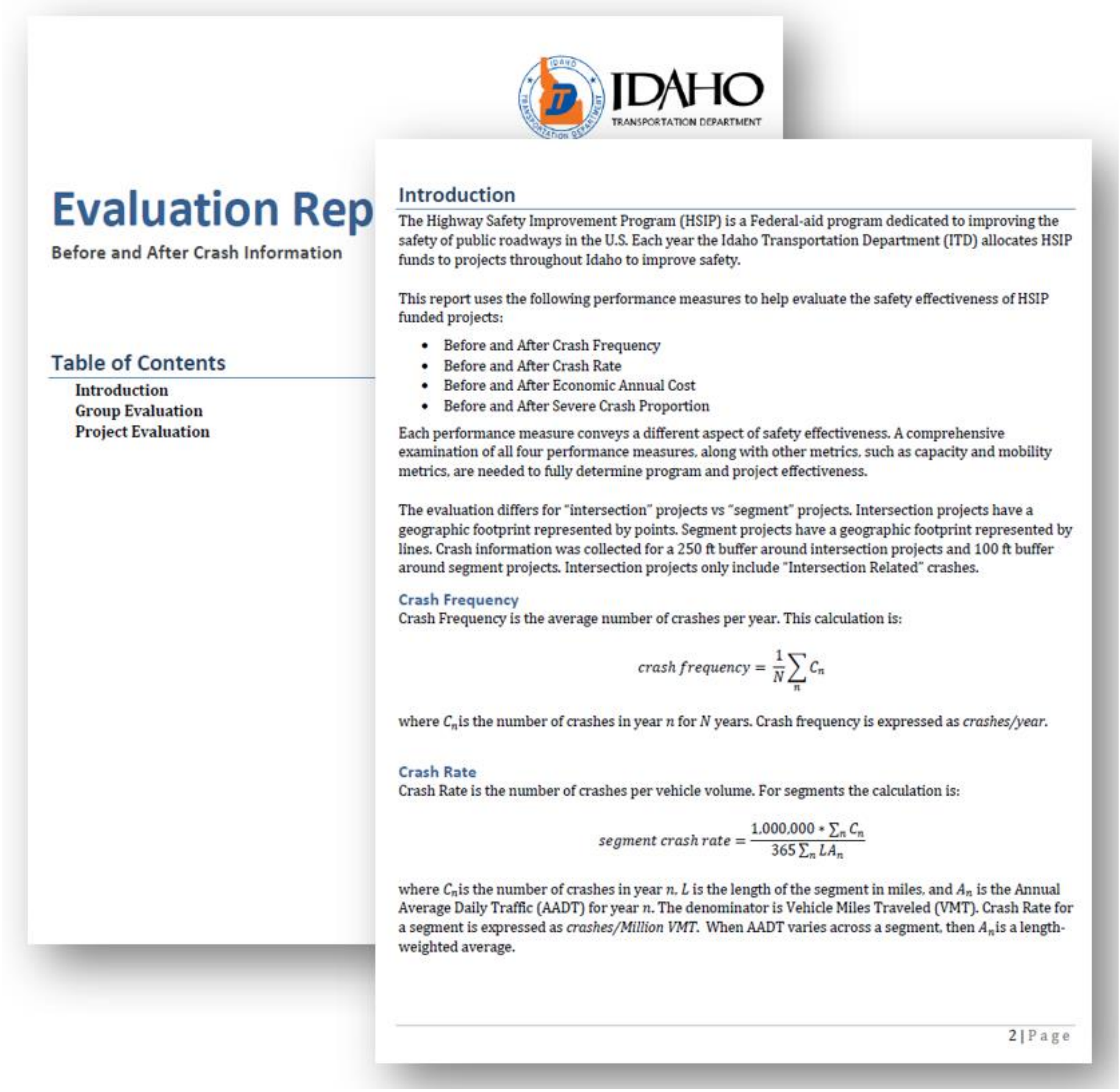


Figure 3.3 Example output project footprint and crash data.

The report is produced in Word and PDF formats. The PDF for the case study is provided as Attachment 1 to this research report. Figure 4.4 shows the cover page and an introduction page. There are three sections in the report. The Introduction describes the safety performance measures and provides the equations. The next section is Group Evaluation. For the current version of the tool, group evaluation is only done for project two types: segment projects and intersection projects. The group evaluation includes group averages for each safety performance measure. An example of group evaluation is provided in the next chapter.



IDAHO
TRANSPORTATION DEPARTMENT

Evaluation Rep

Before and After Crash Information

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Introduction
Group Evaluation
Project Evaluation

Introduction

The Highway Safety Improvement Program (HSIP) is a Federal-aid program dedicated to improving the safety of public roadways in the U.S. Each year the Idaho Transportation Department (ITD) allocates HSIP funds to projects throughout Idaho to improve safety.

This report uses the following performance measures to help evaluate the safety effectiveness of HSIP funded projects:

- Before and After Crash Frequency
- Before and After Crash Rate
- Before and After Economic Annual Cost
- Before and After Severe Crash Proportion

Each performance measure conveys a different aspect of safety effectiveness. A comprehensive examination of all four performance measures, along with other metrics, such as capacity and mobility metrics, are needed to fully determine program and project effectiveness.

The evaluation differs for "intersection" projects vs "segment" projects. Intersection projects have a geographic footprint represented by points. Segment projects have a geographic footprint represented by lines. Crash information was collected for a 250 ft buffer around intersection projects and 100 ft buffer around segment projects. Intersection projects only include "Intersection Related" crashes.

Crash Frequency

Crash Frequency is the average number of crashes per year. This calculation is:

$$crash\ frequency = \frac{1}{N}\sum_n C_n$$

where C_n is the number of crashes in year n for N years. Crash frequency is expressed as *crashes/year*.

Crash Rate

Crash Rate is the number of crashes per vehicle volume. For segments the calculation is:

$$segment\ crash\ rate = \frac{1{,}000{,}000 * \sum_n C_n}{365 \sum_n LA_n}$$

where C_n is the number of crashes in year n. L is the length of the segment in miles, and A_n is the Annual Average Daily Traffic (AADT) for year n. The denominator is Vehicle Miles Traveled (VMT). Crash Rate for a segment is expressed as *crashes/Million VMT*. When AADT varies across a segment, then A_n is a length-weighted average.

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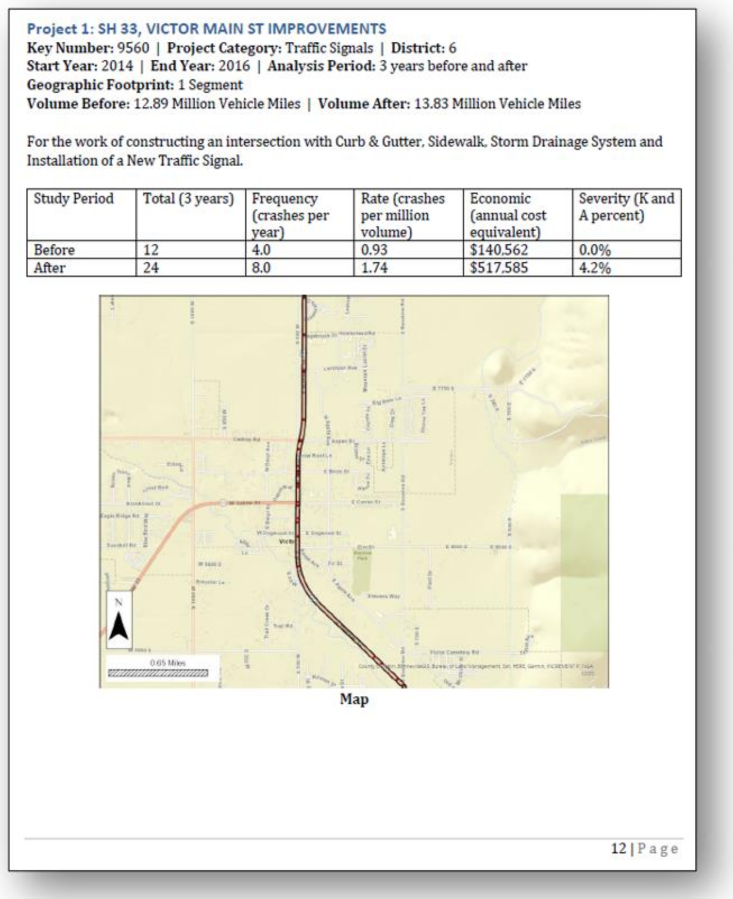
Figure 3.4 Cover and Introduction pages of the report created by the evaluation tool.

The final section of the report provides individual project evaluation for all the projects. There are three pages for each project. Figure 3.4. shows an example first page for a project. At the top is general information about the project, including the project category, years of construction, and before and after vehicle volume. Next is a table showing the four performance measures. This page also provides a map of the project location.



Project 1: SH 33, VICTOR MAIN ST IMPROVEMENTS
Key Number: 9560 | **Project Category:** Traffic Signals | **District:** 6
Start Year: 2014 | **End Year:** 2016 | **Analysis Period:** 3 years before and after
Geographic Footprint: 1 Segment
Volume Before: 12.89 Million Vehicle Miles | **Volume After:** 13.83 Million Vehicle Miles

For the work of constructing an intersection with Curb & Gutter, Sidewalk, Storm Drainage System and Installation of a New Traffic Signal.

Study Period	Total (3 years)	Frequency (crashes per year)	Rate (crashes per million volume)	Economic (annual cost equivalent)	Severity (K and A percent)
Before	12	4.0	0.93	$140,562	0.0%
After	24	8.0	1.74	$517,585	4.2%

Map

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Figure 3.5 Example first page of project evaluation.

Figure 3.6 shows an example of the second page for a project. For each project there is one image from Google Street View. For intersection projects, the image is taken at the latitude and longitude of the first intersection. For the segment projects, the image is taken at the latitude and longitude of the start of the first segment. Next, there are charts for each safety performance measure. The chart axis scale is automatically adjusted for each project (i.e., the axis scales are different for each project). The red bars are the before period and the blue bars are for the after period. Figure 3.7 shows an example of the third page for a project. There are two charts: harmful events and contributing circumstances. The red bars are the before period and the blue bars are for the after period.

Street View

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Figure 3.6 Example second page of project evaluation.

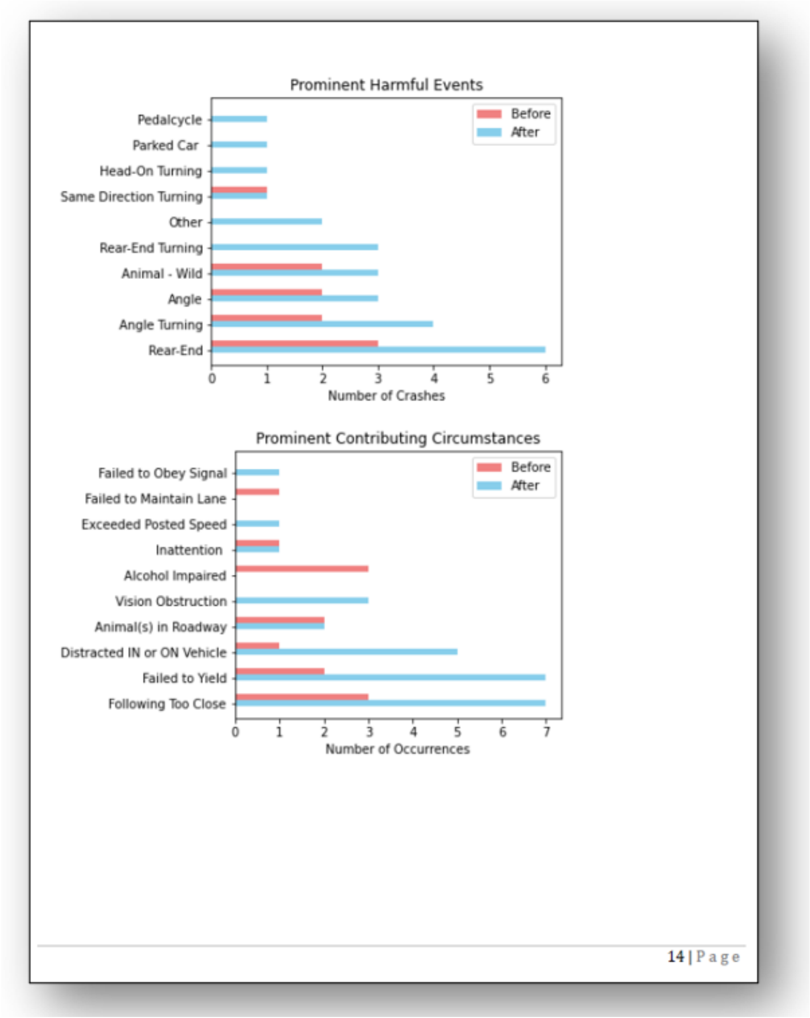

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Figure 3.7 Example third page of project evaluation.

Chapter 4: Case Study Evaluation

Case Study Data

Table 4.1 presents the case study projects provided by ITD. These HSIP projects began between 2013 and 2015 and were completed by 2016. There are ten segment projects and nine intersection projects. We used a three-year analysis period before and after project completion.

Table 4.1 Case Study Projects

Key	Start	End	Project Type	Location	Project Category
09560	2014	2016	Segment	SH 33, VICTOR MAIN ST IMPROVEMENTS	Traffic Signals
11570	2013	2014	Segment	STATE, FY13 D3 SIGN UPGRADES	Signing Improvements
11668	2013	2014	Segment	SUNNYSIDE RD TO LOMAX, IDAHO FALLS, BONNEVILLE COUNTY.	Pavement Rehabilitation
12046	2014	2016	Intersection	SH 55, INT KARCHER & MIDDLETON RDS, NAMPA	Miscellaneous
12398	2014	2015	Intersection	US 26, JCT SH 46 TRAFFIC SIGNAL, GOODING	Traffic Signals
12401	2013	2014	Intersection	SH 50, INT 3800 E RD, TWIN FALLS CO	Miscellaneous
12428	2014	2016	Intersection	US 91, YELLOWSTONE AVE & PEARL ST, POCATELLO	Traffic Signals
13022	2015	2015	Segment	STATE, FY15 D3 GUARDRAIL UPGRADE	Metal Guard Rail
13131	2013	2013	Segment	I 15, FY13 D6 CONTROLLED ACCESS FENCING	Miscellaneous
13413	2013	2015	Segment	I 90B, NORTHWEST BLVD SIGNAL UPGRADES, CDA	Traffic Signals
13418	2014	2015	Segment	LOCAL, UPRIVER & W RIVER DR SFTY UPGRADES	Signing Improvements
13420	2014	2015	Intersection	LOCAL, INT IMPR FLASHING BEACONS, POST FALLS HD	Miscellaneous
13446	2014	2015	Intersection	LOCAL, INT FLASHING ARROW SIGNALS, LEWISTON	Miscellaneous
13502	2014	2016	Intersection	STP-8213, INT MIDDLETON RD & FLAMINGO AVE, NAMPA	Traffic Signals
13543	2014	2014	Segment	STC-2752, 3900 N ROADWAY IMPR, TWIN FALLS HD	Signing Improvements
13574	2014	2016	Intersection	STATE, I 15 AND US 20 RAMP IMPROVEMENTS	Safety Improvement
13599	2014	2015	Intersection	SMA-7276, 1ST & AMMON SIGNALIZATION, IDAHO FALLS	Traffic Signals
13993	2015	2015	Segment	STC-2755, 200 N RD; 500 W TO US 93, JEROME CO	Signing Improvements
13995	2015	2015	Segment	STC-2713, 3700 N RD INTERSECTIONS; US 93 TO KIMBERLY	Signing Improvements

Results

Table 4.2 shows that crash frequency and crash rate decreased for segment projects. However, annual economic cost and severe crash proportion increased. For the intersection projects, the crash rate and severe crash proportion decreased. The mixed results demonstrate the need to group projects in other ways. A more meaningful way to group projects is by countermeasures or similar roadway characteristics (See Chapter 2).

Figures 4.1 and 4.2 show the ten most prominent harmful events and contributing factors for segment projects. Figures 4.3 and 4.4 show the ten most prominent harmful events and contributing factors for intersection projects. It still needs to be determined why there is such a dramatic change in the harmful events and contributing factors between the before and after periods.

Table 4.2 Group Evaluation Results

	Crash Frequency		**Crash Rate**		**Annual Economic Cost**		**Severe Proportion**	
Group	**Before**	**After**	**Before**	**After**	**Before**	**After**	**Before**	**After**
Segment Projects	413.3	350	1.61	1.08	$68,255,490	$89,292,413	6.00%	7.50%
Intersection Projects	65	68	0.64	0.60	$4,953,222	$16,187,183	6.70%	5.90%

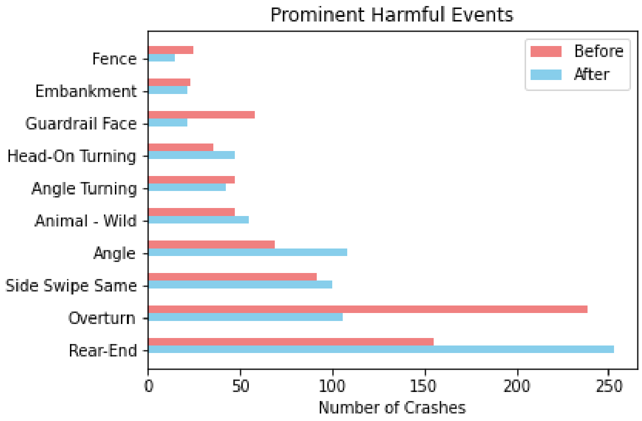


Figure 4.1 Prominent harmful events for the group of segment projects.

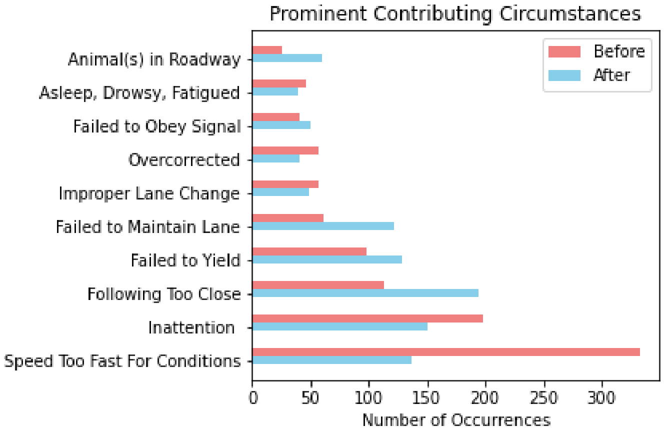


Figure 4.2 Prominent contributing circumstances for the group of segment projects.

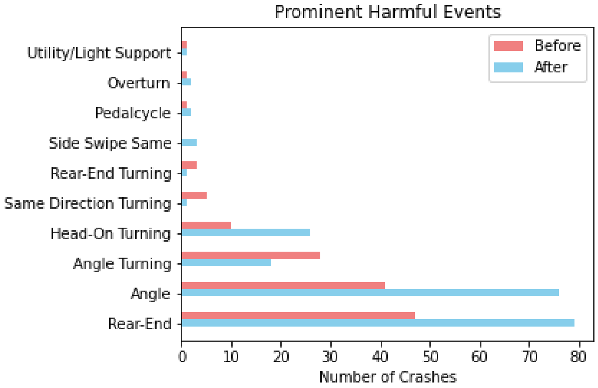


Figure 4.3 Prominent harmful events for the group of intersection projects.

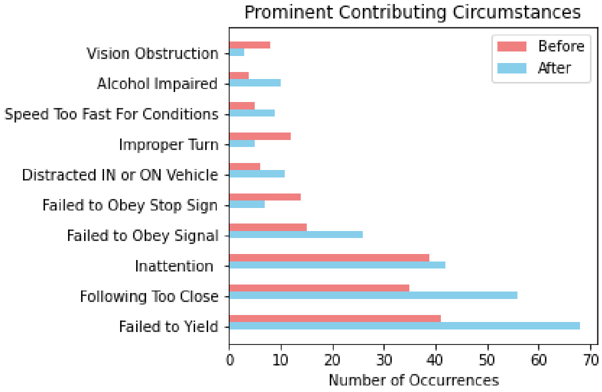
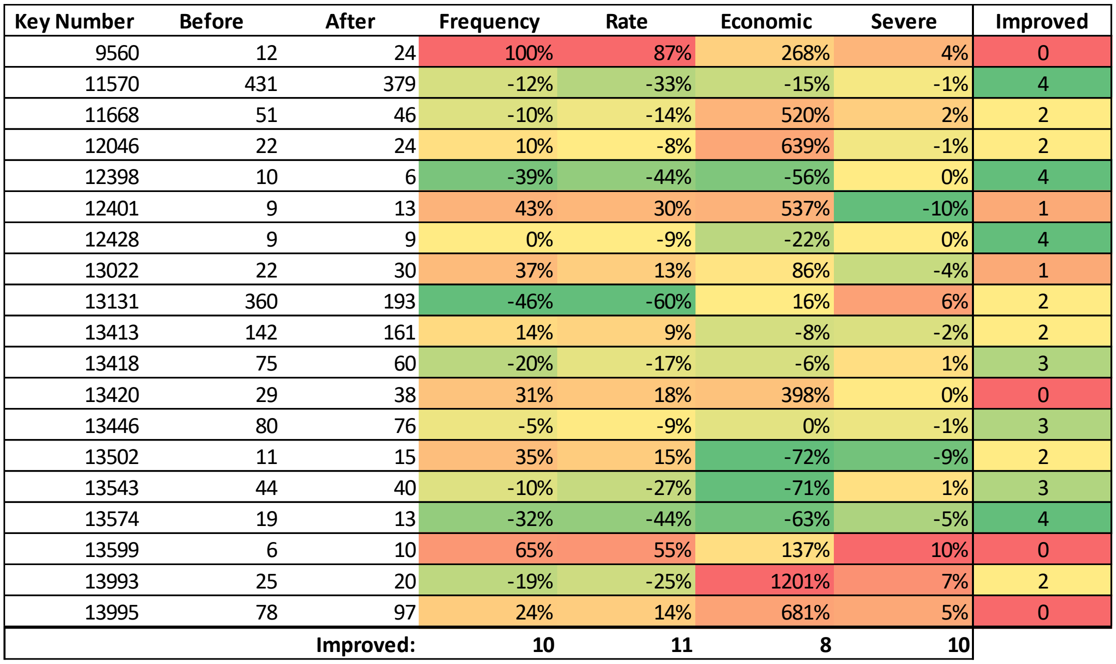


Figure 4.4 Prominent contributing circumstances for the group of intersection projects.

Figure 4.5 shows the change in safety performance measure for each project. The results are colored on a scale from green to red, representing a decrease in the safety performance measure or an increase in the safety performance measure, respectively. A positive percentage (reddish hues) indicates the safety performance measure was worse in the after period. Conversely, a negative percentage (greenish hues) indicates the safety performance measure improved in the after period.



Key Number	Before	After	Frequency	Rate	Economic	Severe	Improved
9560	12	24	100%	87%	268%	4%	0
11570	431	379	-12%	-33%	-15%	-1%	4
11668	51	46	-10%	-14%	520%	2%	2
12046	22	24	10%	-8%	639%	-1%	2
12398	10	6	-39%	-44%	-56%	0%	4
12401	9	13	43%	30%	537%	-10%	1
12428	9	9	0%	-9%	-22%	0%	4
13022	22	30	37%	13%	86%	-4%	1
13131	360	193	-46%	-60%	16%	6%	2
13413	142	161	14%	9%	-8%	-2%	2
13418	75	60	-20%	-17%	-6%	1%	3
13420	29	38	31%	18%	398%	0%	0
13446	80	76	-5%	-9%	0%	-1%	3
13502	11	15	35%	15%	-72%	-9%	2
13543	44	40	-10%	-27%	-71%	1%	3
13574	19	13	-32%	-44%	-63%	-5%	4
13599	6	10	65%	55%	137%	10%	0
13993	25	20	-19%	-25%	1201%	7%	2
13995	78	97	24%	14%	681%	5%	0
		Improved:	**10**	**11**	**8**	**10**	

Figure 4.5 Safety Performance Measures for individual projects.

The final column tallies how many of the safety performance measures showed improvement. Zero indicates none of the safety performance measures improved. Four case study projects showed improvement in every safety performance measure (green). However, there were also four projects with worse safety performance measures in the after period (red). The bottom row of the figure provides a tally of how many projects improved for each safety performance measure. There was improvement for roughly half of the projects for each performance measure.

Table 4.3 and Table 4.4 describe the evaluation results for the segment and intersection projects, respectively. ITD, like most state DOTs, did not begin using a data-driven project selection process, like Network Screening, until about 2015. Consequently, it is not surprising that the evaluation results are weak.

Table 4.3 Evaluation Description for Segment Projects

Key Number	**Evaluation Description**
9560	This project was a major improvement to an intersection, including a new traffic signal. A project of this magnitude would be expected to exhibit significant safety benefits. However, it was worse in all performance measures. This project should be investigated further to understand the reason for this poor performance.
11570	This project improved in all performance measures.
11668	Crash frequency and crash rate declined, but a fatality in the after period caused a huge increase in annual economic cost. This project was primarily for pavement rehabilitation, so significant safety improvements are not expected.
13022	Improvement was only seen in severe crash proportion. While there were less failures to maintain lane after construction, there was a great increase of instances of inattention contributing to crashes.
13131	This project involved installing a fence along various highway segments, protecting the traveling public from livestock. While the crash frequency and rate indicate an improvement in safety, the performance measures weighted by severity (severe crash proportion and economic cost) indicate otherwise. There was a large decrease in instances of overturning, jackknifing, and speeding in the crashes along this section of road, but it is difficult to say with the given information if the repair of the fence contributed to this occurrence. Crashes only involved with livestock obstruction or other things meant to be kept behind the fence line should be analyzed for this project.
13413	This project had worse crash frequency and crash rate, but there was decline in annual economic cost and severe crash proportion. This project involved upgrading 6 signalized intersections. It was evaluated as a segment project along the corridor. Additional evaluation should be done as an intersection project.
13418	This project was for the installation of traffic control devices (signs/chevrons) and shoulder line markings. Safety improvements were seen all but severe proportion, which experienced a slight increase.
13543	Description was not found in ProjectWise. Economic Cost showed improvement after construction for this location, but only slightly so in terms of crash rate and severe crash proportion. Crash frequency increased slightly after construction. For some reason, not many contributing circumstances in the "after" period were reported.
13993	This project was for more advance warning signs, larger stops signs, and more speed limit signs along a road segment. No improvement was observed in any of the recorded performance measures except severe crash proportion.
13995	This project was for adding speed limit signs, stop bars, short lane markings, and larger stop signs along a road segment. No improvement was observed in any of the recorded performance measures. However, crashes caused by inattention and failure to yield noticeably decreased after construction. The segment is very long and perhaps would be better evaluated in smaller sections, or with a sliding window technique.

Table 4.4 Evaluation Description for Intersection Projects

Key Number	**Evaluation Description**
12046	Improved crash rate and severe proportion. Worse crash frequency and economic cost. This project was a major improvement to an intersection, including a new traffic signal. This project should be investigated further to understand the reason for this poor performance.
12398	This project was for the signalization of Jct of SH-46/US26. All the safety performance measures indicate a discernible improvement in safety at this location.
12401	This project involved adding a 12' acceleration lane to the roadway. While a project of this sort is expected to exhibit safety improvements, no discernible improvement was observed. All performance measures showed significant lack of improvement after construction except severe crash proportion. Prominent contributing circumstances after construction included failure to yield, failure to obey stop sign, alcohol impairment, and inattention. This project should be investigated further.
12428	This project was related to pedestrian improvements, such updating to ADA compliance. An evaluation focused on pedestrians should be done. Angle-turning crashes likely caused by failures to yield, and improper turns have gone down, but the number of rear-end crashes caused by speeding, inattention, and tailgating has increased at this site.
13420	This project was for the installation of new flashing beacons and stop signs at various intersections. No improvement was observed in any of the performance measures used. This project should be investigated further to understand the poor performance.
13446	This project improved in all performance measures.
13502	This project involved the design and installation of a traffic signal at an intersection. Crash frequency and rate did not improve at this location, but economic cost and severe crash proportion showed improvement. This was likely due to one less A-Injury crash in the period after construction.
13574	This project was for improving the safety of the on-ramp at an interchange. Improvement was observed in all performance measures, but the collection of data in this case might have been flawed. First, there looks to be data from crashes that occur nearby the intersection (such as on the neighboring freeway or at the adjacent off-ramp), but not at the location of interest.
13599	This project was for the installation of a signal and ADA improvements to an intersection. No improvement was observed in any of the recorded performance measures. This project should be investigated further to understand the reason for this poor performance.

Chapter 5: New Safety Performance Measure

Introduction

Crash frequency is the most used safety performance measure for safety analysis because it is easy to calculate and understand. Two other common safety performance measures are annual economic cost and severe crash proportion. They provide information about the severity of the crashes. Another safety performance measure is crash rate which includes information about traffic volumes. Each safety performance measure has strengths and weaknesses in conveying safety conditions. Consider the following example:

Suppose an intersection is experiencing many severe crashes, and the proposed solution is to lower the speed limit of each leg. If the intersection experiences no change in crash frequency, but the severity of crashes is reduced, this would be considered an improvement at the site, which would not have been recognized had crash frequency been the only considered metric.

Annual economic cost and severe crash proportion provide more information than crash frequency, but like crash frequency, these performance measures do not consider the traffic volume, or vehicular exposure, at the studied site. On the other hand, crash rate includes vehicular exposure. Without considering vehicular exposure, larger intersections are more likely to appear unsafe, which can be problematic for processes such as project prioritization. Consequently, these performance measures should be examined comprehensively for more robust insight into safety effectiveness. This chapter introduces a new safety performance measure that combines aspects of these different safety performance measures.

Method

Calculation

We call the new safety performance measure “Expected Cost”. It combines concepts of annual economic cost and crash rate. The calculation is based on economists' concept of “expected utility” for risk appraisal (Schoemaker, 1982). Suppose there are a set of possible outcomes $\{1, 2, \ldots, i\}$, such as the possible outcomes for investing in the stock market or the possible outcomes from playing a multi-award lottery. Each outcome has a payout or penalty, which economists call “utility”. The utility, U_i, for an outcome can be positive or negative. Furthermore, each outcome has a probability of occurrence, P_i. Thus, the expected utility is the probability-weighted sum of the utility for each outcome:

$$E(U) = U_1 * P_1 + U_2 * P_2 + \cdots + U_n * P_n \tag{6}$$

or

$$E(U) = \sum U_i * P_i \tag{7}$$

When expected utility is applied in the context of stock market investments, each “outcome” is the return from an investment. If the expected utility exceeds the investment cost, then the investment is deemed worthy. In the context of traffic safety, each “outcome” is the economic cost, C_s, associated with crash severity s (listed in Table 2.1), including the outcome of not being involved in a crash (\$0). The probability of each outcome is equal to the number of vehicles involved in crash severity s divided by the total volume ($\frac{V_s}{V}$). Thus, the expected cost is:

$$Expected\ Cost = E(C) = \sum C_s * \frac{V_s}{V} \tag{8}$$

where V_s is the number of unit crashes in year n for severity s, C_s is the economic cost equivalent for severity s, and V is the vehicle volumes (VMT for segments, TEV for intersections) for year n. The units of expected cost are dollars per vehicle-miles for segments or dollars per vehicle for intersections. An example of this calculation for an intersection is shown in Table 5.1.

Table 5.1 Example Calculation of Expected Cost for an Intersection

Severity	**Cost Per Crash Event**	**Crashes**	**Events x Cost**	**Severe Crashes**	**Vehicles**	**Probability**	**Probability x Cost**
s	**Cs**	**X**	**X * Cs**	**K or A**	**Vs**	**P = Vs/V**	**Cs * P**
Fatal Accident	$11,800,000	1	$11,800,000	1	2	0.000005%	$0.65
A Injury Accident	$564,335	2	$1,128,670	2	5	0.000014%	$0.08
B Injury Accident	$153,707	7	$1,075,949	0	16	0.000044%	$0.07
C Injury Accident	$78,488	13	$1,020,344	0	24	0.000066%	$0.05
Property Dmg Report	$3,976	21	$83,496	0	48	0.000132%	$0.01
No Crash	$0			0	36,499,905	99.99974%	$0.00
Safety Performance Measure							
5 Year Total		44	$15,108,459	2	36,500,000	100%	$0.85
Crash Frequency		8.8					
Annual Economic Cost			$3,021,692				
Proportion Severe				4.5%			
Crash Rate					1.21		
Expected Cost							$0.85

In this example, the probability of a fatal crash is considerably low (1 out of 36.5 million entering vehicles), but the cost of a fatal crash occurring is exceptionally high – so much so that the expected cost of fatal crashes is greater than all other severities. The total expected cost of driving through the intersection is about 85 cents per vehicle. If a person were to drive through the intersection to and from work, they would generate about 520 trips through the intersection a year (~260 workdays per year). This is a risk exposure of $441 a year.

Similar calculations have been used in other studies; however, they were not proposed as a new safety performance measure. Li and Al-Mahamda (2020) created a collective risk (CR) score that weighed crash rates by crash severity costs to identify crash-prone locations. This metric is considerably more complex than expected cost as it was based on the Getis-Ord statistic, which verifies whether a site is part of a larger cluster of crash-prone locations. Miaou and Song (2005) used a generalized linear mixed model within a Bayesian framework to rank sites by crash cost per vehicle-mile traveled. They referred to this performance measure as a “crash cost rate”.

Demonstration

We developed a Python program to calculate the expected cost for every road segment and intersection in Idaho. We used the program to demonstrate the usefulness of the new safety performance measure with three example applications.

Application 1: Network Screening

One way this new metric can be used is for Network Screening, which is the first step of the Safety Management Process (see Chapter 2). The goal of Network Screening is to determine which segments or intersections are most in need of improvement. The HSM recommends using a 5-year analysis period for Network Screening. For the demonstration, we used expected cost to rank ten segments and ten intersections with crash data from 2016 to 2020. The segments and intersections are located in Moscow, Idaho. The results were compared to the four standard safety performance measures to examine correlation.

Application 2: Safety Effectiveness Evaluation

The new metric can also be used for Safety Effectiveness Evaluation, the sixth step of the Safety Management Process (see Chapter 2) and the intent of the new GIS tool (see Chapters 3 and 4). The HSM recommends using a 3-year before period and a 3-year after period for Safety Effectiveness Evaluation. For the demonstration, before and after expected costs were calculated for two segment projects and two intersection projects in Idaho:

- Key No. 13488: Homedale Rd. in Caldwell (segment)
- Key No. 13995: US 93 to Kimberly in Twin Falls (segment)
- Key No. 12046: Karcher Rd. and Middleton Rd. in Caldwell (intersection)
- Key No. 13502: Middleton Rd. and Flamingo Ave. in Caldwell (intersection)

Project 13488 attached beacons to multiple stop signs. Project 13995 involved adding speed limit signs and stop bars as well as enlarging stop signs. Project 12046 added thru and turn lanes to a signalized intersection. Project 13502 converted a two-way stop-controlled (TWSC) intersection to a signalized intersection.

Application 3: Route Choice Navigation

The new metric can also be used for route choice navigation. Many people use navigation systems, such as Google Maps, Garmin Navigation, and Mapquest, to calculate routes to their destinations. Typically, these systems offer route options based on the shortest travel time. Researchers have developed similar algorithms based on minimizing fuel consumption (Ericsson et. al., 2006). We demonstrate how routes can be identified based on minimizing expected costs. For this application, we used 5 years of crash data to compare six routes in the Treasure Valley of Idaho. Three shorter routes (~1.5 miles each) in Boise were first tested, each traveling from North Junior High School to the North River St. entrance to Julia Davis Park. Three longer routes (~25-30 miles each) stretching across the treasure valley from Caldwell to Boise were tested next: a major arterial route, a minor arterial route, and a backroads route. The major arterial route primarily travels along Interstate 84, and the minor arterial route primarily travels along Highway 20/26 (also known as Chinden Blvd. in Boise). The backroads route primarily travels along a variety of collectors and local roads on the northern half of the valley, strategically avoiding segments and intersections with high expected costs.

Results

Network Screening Results

As seen in Table 5.2, of the ten observed intersections in Moscow, the expected costs ranged from \$0.01/vehicle to \$0.42/vehicle, with an average of about \$0.10/vehicle and a median of \$0.05/vehicle. The intersection at Baker St. and A St. is highest and significantly higher than the others, suggesting it would be the most critical intersection to improve. This location had a relatively high crash rate and annual economic cost; the severe crash proportion was exceptionally high at 29%. The crash frequency was relatively low, so the high severe crash proportion is likely a result of a few severe crashes out of a relatively low number of total crashes. With a low crash frequency and a high crash rate, it can be assumed that the intersection has a low vehicle volume. A low volume would explain why only a few severe crashes could create a high expected cost.

Table 5.2 Ten Intersections Ranked by Expected Cost

Location	Expected Cost (per vehicle)	Crash Frequency (per year)	Crash Rate (per volume)	Severe Proportion (percent)	Annual Economic Cost (per year)
Baker St. & A St.	$0.42	1.4	1.05	29%	$289,000
Farm Rd. & Hwy 8	$0.15	6.4	1.73	0%	$354,000
Washington St. & 6th St.	$0.13	3.2	0.49	13%	$312,000
US 95 & Lauder Ave.	$0.07	2.2	0.65	0%	$113,000
Peterson Dr. & Hwy 8	$0.05	4.6	0.97	0%	$287,000
Washington St. & 3rd St.	$0.04	3.0	0.60	0%	$146,000
US 95 & D St.	$0.04	2.0	0.33	0%	$113,000
Mtn View Rd. & D St.	$0.03	0.2	0.09	0%	$31,000
Mtn View Rd. & Hwy 8	$0.02	1.4	0.41	0%	$65,000
US 95 & Hwy 8	$0.01	4.8	0.82	0%	$49,000

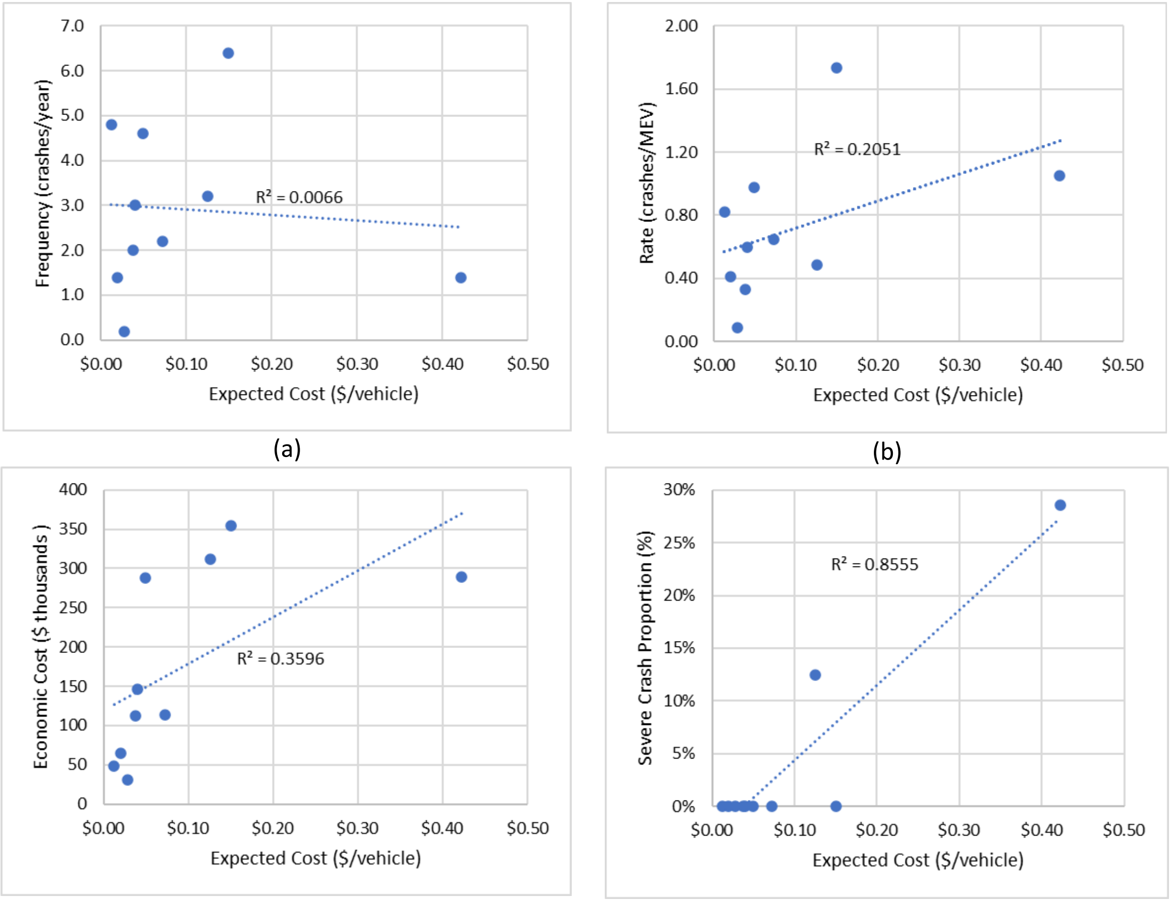
Table 5.3 shows the results of ten segments observed in Moscow. The expected costs ranged from $0.03/vehicle-mile to $1.58/vehicle-mile with an average of about $0.51/vehicle-mile and a median of $0.42/vehicle-mile. 3rd St. has the greatest expected cost, more than double the second-highest expected cost. The severe crash proportion for this location is relatively low, but the economic cost, crash rate, and crash frequency are all high. A low severe crash proportion and high economic cost could indicate that a fatal crash occurred in the analysis period. However, the economic cost of 3rd St. is too low for this indication. It is possible that a large number of B-injury or C-injury crashes occurred here. Combined with a moderate traffic volume and a few A-injury crashes, a high expected cost like that of 3rd St. can result.

Table 5.3 Ten Segments Ranked by Expected Cost

Location	Expected Cost (per vehicle-mile)	Crash Frequency (per year)	Crash Rate (per volume)	Severe Proportion (percent)	Annual Economic Cost (per year)
3rd St.	$1.58	29.6	12.19	2%	$1,290,000
Hwy 8	$0.63	39.0	5.09	2%	$2,277,000
A St.	$0.63	11.8	6.00	3%	$615,000
6th St.	$0.57	15.2	4.12	7%	$1,009,000
Washington St.	$0.45	16.8	8.56	5%	$858,000
Mountain View Rd.	$0.39	4.6	1.78	4%	$280,000
D St.	$0.33	6.8	3.34	3%	$363,000
US 95	$0.27	12.2	5.72	2%	$489,000
Jackson St.	$0.19	16.0	6.17	1%	$564,000
Main St.	$0.03	5.6	26.03	0%	$22,000

Figures 5.1 and 5.2 show the correlations between expected cost and the four safety performance measures introduced in Chapter 2. When testing these correlations, the economic cost was the most correlative with the expected cost overall. The correlation between crash frequency and expected cost for segments was comparably strong, but this was not the case for intersections. The crash rate was least the correlative with the expected cost overall. The correlation between severe crash proportion and expected cost for intersections was quite strong ($R^2 = 0.856$). This was likely due to the large number of intersections having no severe crashes and low expected costs.

It seems that expected cost is more largely impacted by the severity of crashes than volume, which is understandable considering the comparably high cost of severe crashes. The correlations are low enough to conclude that the expected cost is different enough from the other safety performance measures to provide a new perspective.



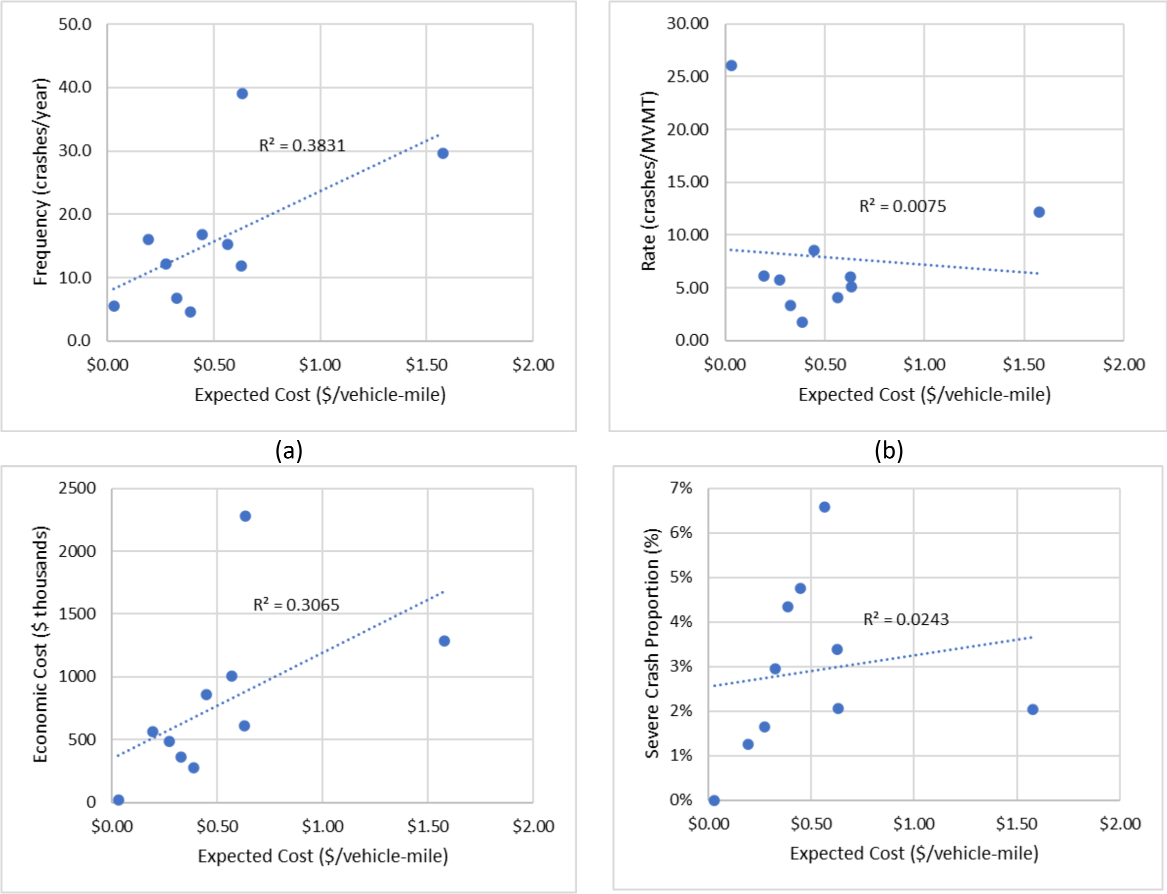
(a)

(b)

(c)

(d)

Figure 5.1 Intersection Expected Cost vs (a) Crash Frequency (b) Crash Rate (c) Annual Economic Cost and (d) Severe Crash Proportion.



(a)

(b)

(c)

(d)

Figure 5.2 Segment Expected Cost vs (a) Crash Frequency (b) Crash Rate (c) Annual Economic Cost and (d) Severe Crash Proportion.

Safety Effectiveness Evaluation Results

As seen in Table 5.4, of the two intersection improvement projects, only project 13502 resulted in a reduced expected cost. Figure 5.3 shows the intersection in 2011 as a TWSC intersection and in 2019 after signal installation. The expected cost of project 12046 increased significantly after project installation from $0.04/vehicle to $0.32/vehicle. The volume at this location did increase after construction, resulting in a lower crash rate. However, because of a fatal crash after construction, the cost of crashes significantly increased, as did the expected cost. Meanwhile, the expected cost of project 13502 decreased from $0.22/vehicle to $0.06/vehicle. While the crash frequency and rate did increase after construction at this site, the severity of crashes was noticeably lower.

Only one of the segment projects showed a decrease in expected cost after construction, which was the addition of stop beacons along Homedale Rd. (13488). The other performance measures, except for annual economic cost, did not show improvement. This is attributable to a fatal crash that occurred within the three years before construction. The other segment project (13995) dramatically increased in expected cost, going from $0.71/vehicle-mile to $8.42/vehicle-mile. The other performance measures showed no improvement, especially economic cost, which increased by 680% after construction.

Table 5.4 Before and After Evaluation Results

Key No.	**Crash Frequency (per year)**		**Crash Rate (per volume)**		**Severe Proportion (percent)**		**Annual Economic Cost (per year, $thousands)**		**Expected Cost (per vehicle or vehicle-mile)**	
	Before	**After**	**Before**	**After**	**Before**	**After**	**Before**	**After**	**Before**	**After**
13488	27.3	35.7	13.29	17.27	2.4%	4.7%	5,370	2,870	$5.53	$2.52
13995	26.0	32.3	1.87	2.13	5.1%	10.3%	1,350	10,530	$0.71	$8.42
12046	7.3	8.0	0.62	0.57	9.1%	8.3%	602	4,450	$0.04	$0.32
13502	3.7	5.0	0.96	1.10	9.1%	0.0%	426	119	$0.22	$0.06

(a)

(b)

Figure 5.3 Middleton and Flamingo intersection (a) before and (b) after the safety improvement.

Route Choice Navigation Results

As shown in Table 5.5, when testing the three shorter routes with the script, the fastest route was the most expensive route in terms of the expected cost. However, the slowest route of the three was only a minute longer than the fastest route and cost almost 25% less (approximately $0.38). While 38 cents may not seem to be a significant amount saved, if this route were taken daily like as a commute to work or school, the savings would greatly increase.

Figure 5.4 Short Distance Routing Example

Table 5.5 Expected Cost of Route Options

Route	ID	Miles	Estimated Travel Time	Expected Cost
Fast Route (9th St.)	1	1.59	5 min	$1.55
Intermediate Route (13th St.)	2	1.54	6 min	$1.32
Slow Route (3rd St.)	3	1.49	6 min	$1.17

When testing the three longer routes, the fastest route (major arterial route) was not the most expensive. In fact, using the freeway in Boise is quite inexpensive compared to traveling along other arterials in the valley. The minor arterial route produced an expected cost 6 dollars greater than the major arterial route (a 161% increase). This discrepancy is mainly due to the avoidance of intersections along an interstate. The expected costs produced by segment crashes were most expensive for the major arterial route, but the expected cost from intersection crashes was significantly lower than those produced by the other routes.

The backroads route produced the lowest overall expected cost of the three longer routes, saving about 54 cents in expected cost (~14%). However, the travel time for this route is about 38 minutes longer than the major arterial travel time (a 141% increase). In this case, the safest route is likely not the preferred route.

Figure 5.5 Commuter Routing Example

Table 5.6 Expected Cost of Commuter Routing Example

Route	ID	Miles	Estimated Travel Time	Expected Cost
Interstate Route	1	26.1	27 min	$3.73
Arterial Route	2	24.5	43 min	$9.75
Backroads Route	3	32.6	65 min	$3.19

Discussion

In the network screening application, the expected cost offered a new perspective for determining the safety of major intersections and segments in Moscow. The safety performance measure can also be used to analyze more minor intersections and segments, though it might be most effective to compare sites with similar characteristics like roadway classification or traffic volume. Grouping sites based on whether severe crashes were present may be another efficient way to improve the application of this metric since locations with severe crashes tended to possess significantly greater expected costs. None of the observed locations had notably low traffic volumes, but if a location were to have a handful of non-severe crashes and a considerably low volume, it may possess a high expected cost which would not be reflected in other performance measures except crash rate. While it is convenient to have a single measurement to determine the safety of sites, a comprehensive examination of multiple simple metrics might be more beneficial to see precisely *how* a location is unsafe. Maybe the best way to use this metric would be to perform an initial screening of sites based on the expected cost and then perform subsequent screenings using a comprehensive analysis of other safety performance measures.

In the safety effectiveness evaluation application, analysis periods with severe crashes had significantly greater expected costs than those without. Because of this, the changes in expected cost before and after construction resembled the changes in annual economic cost more than in crash rate. It is possible that using expected cost is not much of an improvement from using annual economic cost as a performance measure in this application. Perhaps the expected cost would be more useful in this application for locations with significant changes in volume after construction.

The script developed for the route choice navigation application calculates the expected cost of a given route, but perhaps it would be more useful for a tool to *generate* routes between two points based on the expected cost. Usually, when tools like Google Maps generate a route, they find the shortest path from the origin to the destination in terms of travel time, sometimes adjusting the route to minimize fuel consumption. As seen in the results, a tool that can calculate routes with the lowest expected costs might be helpful for short routes, but for long-distance routes, the “safest” route can also add significant travel time. Maybe expected cost would be most helpful in this application if used in conjunction with travel time calculations to determine the most overall cost-efficient route. This would be like the fuel consumption adjustments that exist in current tools.

The benefits from a tool such as this could be especially desirable for companies that heavily prioritize the safety of their drivers and passengers over optimal travel times. These companies could be taxiing businesses, ride-share companies such as Uber or Lyft, or logistics companies transporting large quantities of valuable cargo.

Other businesses, like insurance companies, could utilize expected costs through discount programs. Recently, auto insurance companies like State Farm and Progressive have offered discounts to drivers that demonstrate safe driving through a downloadable app on their smartphones. These apps can track where and how far one travels, vehicle speed, braking patterns (sudden acceleration or hard braking), and phone usage while driving, among other things. Insurance companies could further improve this program by rewarding drivers who choose to travel along roads with low expected costs.

Chapter 6: Conclusion

Three main objectives were accomplished in this thesis to provide transportation agencies like ITD with the information and tools for HSIP project evaluation. These three objectives were to create a GIS tool for safety effectiveness evaluation, to perform a case study evaluation of Idaho HSIP projects, and to invent a new performance measure and demonstrate its potential applications for improving transportation safety.

We developed a methodological framework and GIS tool to determine the effectiveness of projects. The tool and method were demonstrated for a case study that included ten segment projects and nine intersection projects that began between 2013 and 2015 and were completed by 2016. Ten of the projects experienced reductions in crash frequency; eleven experienced reductions in crash rate; eight experienced reductions in annual economic cost; and ten experienced reductions in severe crash proportion. Four projects experienced reductions in all four safety measures. The tool created a report that serves as a starting point for identifying HSIP projects that should be analyzed further using additional data and other methods.

Additionally, this thesis sought to improve the evaluation methods with the development of a new safety performance measure called expected cost. The new performance measure was calculable using the AADT and crash datasets from the evaluation tool. Expected cost was then demonstrated in three applications: network screening, safety effectiveness evaluation, and routing determination. For network screening, ten intersections and ten segments were ranked according to their expected costs. The rankings were different from those based on the four standard performance measures, showing that the new measure offers a new perspective into safety analysis. Two intersections and two segments were analyzed with the new measure to test its performance in safety effectiveness evaluation. The expected costs in this application were similar to the annual economic costs, but still offered a new perspective for projects with notable changes in volume after construction. Lastly, the expected cost demonstrated its benefits in route choice navigation, creating routes that optimized safety rather than travel time.

Appendix A: Empirical Bayes Method

An important safety performance measure is *crash frequency*, the average number of crashes over an analysis period. For Safety Effectiveness Evaluation it is common to use a three-year analysis period before and after the construction of a safety improvement project. However, the natural fluctuation of crashes can misconstrue the interpretation of the evaluation. This phenomenon is called Regression to the Mean (RTM) bias and is illustrated with a figure in Chapter 2.

One approach to mitigate RTM bias is to combine the observed crash frequency with a predicted crash frequency obtained from a Safety Performance Function (SPF). For demonstration, consider the SPF to predict crash frequency for a rural multilane divided highway segment. This equation was shown in Chapter 2 and is provided again here:

$$\overline{N}_{predicted} = e^{-9.03+1.05*\ln(AADT)+\ln(L)} \tag{A1}$$

where $\overline{N}_{predicted}$ is the predicted crash frequency (crashes/year), *AADT* is the segment vehicle volume, and *L* is the length of the segment (AASHTO, 2010).

SPFs are created using a statistical technique called negative binomial regression and crash data from dozens of sites that have similar characteristics (number of lanes, vehicle volumes, speed limits, etc.). The model will be reliable since it is based on data from so many similar sites. However, we don’t know what is more reliable: the observed frequency (which might be suffering from RTM bias) or the predicted frequency (which is inherently imperfect because it is only a model). The famous statistician Thomas Bayes developed a whole branch of statistics that combines observed information (which has flaws) with model predictions (which also have flaws) to produce a result that is more reliable than the observation or prediction alone.

The Empirical Bayes (EB) Method combines observed crash frequency with predicted crash frequency using a formula to produce the “expected crash frequency”. Figure A.1 illustrates the EB method. Suppose at location there is an observed crash frequency, $\overline{N}_{observed}$. The SPF model predicts a lower crash frequency for that location, $\overline{N}_{predicted}$. (By the way, the curve in the figure shows that as traffic volume increases the predicted crash frequency increases along the curve). In this example, the observed crash frequency is much greater than predicted. We don’t know if that is because the location is indeed worse than the dozens of locations that were used to create the model or if it is because there is RTM bias causing the observed crash frequency to appear higher than the comparison group. The EB method identifies a compromising value, that is, statistically speaking, more reliable than the observed and predicted values. This is the expected crash frequency, $\overline{N}_{expected}$.

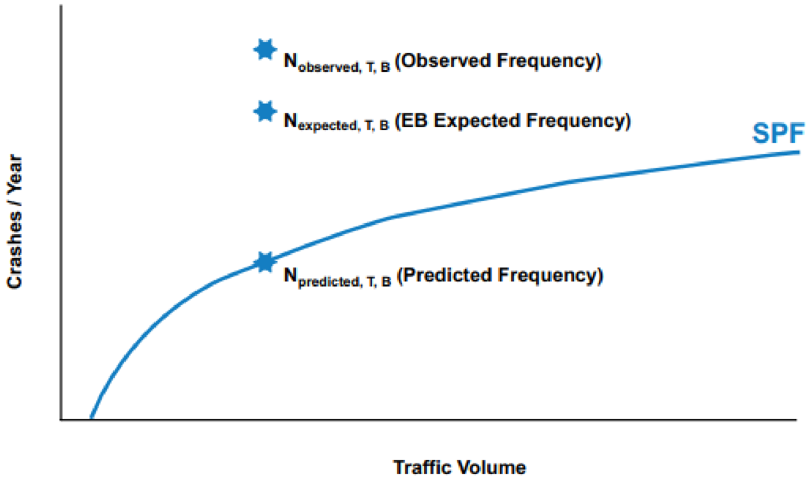


Figure A.1 Estimated crash frequency using EB method. (AASHTO, 2010)

Key to the EB method is deciding how much weight to give to the observed value and how much weight to give to the predicted model to determine the right compromise value. The answer comes from a statistic that indicates the reliability of the SPF called the overdispersion parameter, k. For example, the HSM provides the SPF shown above and equation A2 to calculate the overdispersion parameter:

$$k = \frac{1}{e^{1.55*\ln(L)}} \tag{A2}$$

The overdispersion parameter is than used to calculate the weight that should be given to the model, as follows:

$$w = \frac{1}{1 + k * N_{predicted}} \tag{A3}$$

The weight, w, is a number between 0 and 1. This weight and its complement $(1 - w)$ are used to combine predicted and observed as follows:

$$\overline{N}_{expected} = w * \overline{N}_{predicted} + (1 - w) * \overline{N}_{observed} \tag{A4}$$

Figure A.2 shows an example calculation for a roadway with *AADT* = 30,000 *vpd*, and length = 1.4 miles. The location has an observed crash frequency of 10.0 crashes/year. The predicted crash frequency, 8.4 crashes/year, is lower than observed. The EB Method produces an expected crash frequency of 9.7 crashes/year. This example is like Figure A.1 has an observed crash frequency greater than predicted. The opposite can also occur, i.e. observed crash frequency lower than predicted. Either way the EB method is a statistical adjustment that finds a compromise value to help overcome RTM bias.

$$\bar{N}_{observed} = 10.0$$

$$\bar{N}_{predicted} = e^{-9.03+1.05*\ln(30{,}000)+\ln(1.4)} = 8.4$$

$$k = \frac{1}{e^{1.55*\ln(1.4)}} = 0.59$$

$$w = \frac{1}{1+(0.59)(8.4)} = 0.17$$

$$\bar{N}_{expected} = 0.17 * 8.4 + (1-0.17) * 10.0 = \boldsymbol{9.7\ crashes/year}$$

Figure A.2 Example EB Method Calculation

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