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Development of a framework to compare the cost-effectiveness of traffic crash countermeasures

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Development of a framework to compare the cost-effectiveness of traffic crash countermeasures

by

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A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Civil Engineering (Transportation Engineering)

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Iowa State University

Ames, Iowa

2017

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NOMENCLATURE

AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
CalTrans	California Department of Transportation
CMF	Crash Modification Factor
DEV	Daily Entering Vehicles
DOT	Department of Transportation
EB	Empirical Bayes
FARS	Fatality Analysis Reporting System
FAST	Fixing America's Surface Transportation
FHWA	Federal Highway Administration
FI	Fatal/Injury
HSIP	Highway Safety Improvement Program
HSM	Highway Safety Manual
IHSDM	Interactive Highway Safety Design Model
MAP-21	Moving Ahead for Progress in the 21st Century
MDOT	Michigan Department of Transportation
MLD	Multilane Divided
MLU	Multilane Undivided
MnDOT	Minnesota Department of Transportation
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NSC	National Safety Council
ODOT	Ohio Department of Transportation
PDO	Property Damage Only
PSL	Posted Speed Limit
RTM	Regression-to-the-Mean
SDF	Severity Distribution Function
SPF	Safety Performance Function
TOR	Time of Return
TWLTL	Two-way Left-turn Lane
VMT	Vehicle Miles Traveled
2L	2 Lane
2U	2 Lane Undivided
3T	2 Lane Undivided with a TWLTL
4U	4 Lane Undivided
5T	4 Lane Undivided with a TWLTL
4D	4 Lane Divided
6D	6 Lane Divided
8D	8 Lane Divided
KABC	Fatal, Incapacitating, Minor, Possible Injury
O	Property Damage Only

ACKNOWLEDGMENTS

I would like to express my sincere gratitude to my major professor, Dr. Peter Savolainen, for all he has done to support me in my endeavors at Iowa State University. His vast knowledge in the field was a wellspring of inspiration as I moved forward with my research.

I would also like to thank my committee members, Dr. Shauna Hallmark, and Dr. Peng Wei for their guidance and input throughout the course of this research.

I would also like to acknowledge the Dwight D. Eisenhower Transportation Fellowship Program for their support of my research and my education at Iowa State University.

In addition, I would like to thank my parents and my siblings, especially my sister Linda, who was my biggest cheerleader, my support whenever I needed it, and my timekeeper. Without her unwavering assistance through the ups and the downs, this would not have been possible.

DISCLAIMER

The findings and conclusion of this study are those of the author and do not necessarily represent the views of the Michigan Department of Transportation, the Dwight D. Eisenhower Fellowship Program, or Iowa State University.

ABSTRACT

As the transportation industry moves towards an ultimate goal of zero deaths on roads in the United States, decisions are made every day regarding how to best utilize limited transportation funding for the implementation of crash countermeasures. At a time when many jurisdictions face difficulties in maintaining their existing infrastructure, additional tools are necessary to ensure that available funding is spent in the most productive manner. Determining whether or not a crash countermeasure is financially justified is one of the primary considerations in transportation agencies' planning and programming efforts. However, a myriad of analytical concerns limit the ability to effectively determine the cost-effectiveness of specific countermeasures. Using a series of locally-derived safety performance functions (SPFs) and severity distribution functions (SDFs), this study provides a set of tools that can be used to assess the feasibility of potential countermeasures for various location types (e.g., segments, intersections, etc.). Construction cost data for a series of countermeasures can be integrated with robust crash modification factors (CMFs), allowing for a flexible economic analysis framework in which competing or complementary countermeasures can be evaluated. The final product of this project provides decision-makers with a planning-level tool that will allow for direct consideration of the prospective economic impacts and related uncertainty that is inherent in such estimates.

CHAPTER 1: INTRODUCTION

1.1 Background

Every year in the United States, more than 30,000 people are killed due to roadway

related crashes (FARS, 2016). The total number of fatalities can fluctuate widely from year

to year but, as illustrated in Figure 1, general trends show that traffic fatalities have been

declining over the last 35 years. To control for variations in exposure (e.g., fluctuations in the

miles traveled each year), it is better to look at the rate of fatalities per 100 million vehicle

miles traveled (VMT), which have been decreasing steadily, excluding a small increase

around 1985, until 2010. Over the time period shown in Figure 1, the fatality rate started at a

high of 3.35 fatalities per 100 million VMT in 1980 and decreased to approximately 1.5

fatalities per 100 million VMT in 2005. At this point, as part of their Strategic Highway

Safety Plan, the American Association of State Highway and Transportation Officials

(AASHTO) set a goal to lower the fatality rate to 1.0 fatalities per 100 million VMT by 2008

(AASHTO, 2005). This goal was close to being realized by 2010, but few further

improvements have been made; the fatality rate has fluctuated around the 1.1 fatalities per

100 million VMT since 2010.
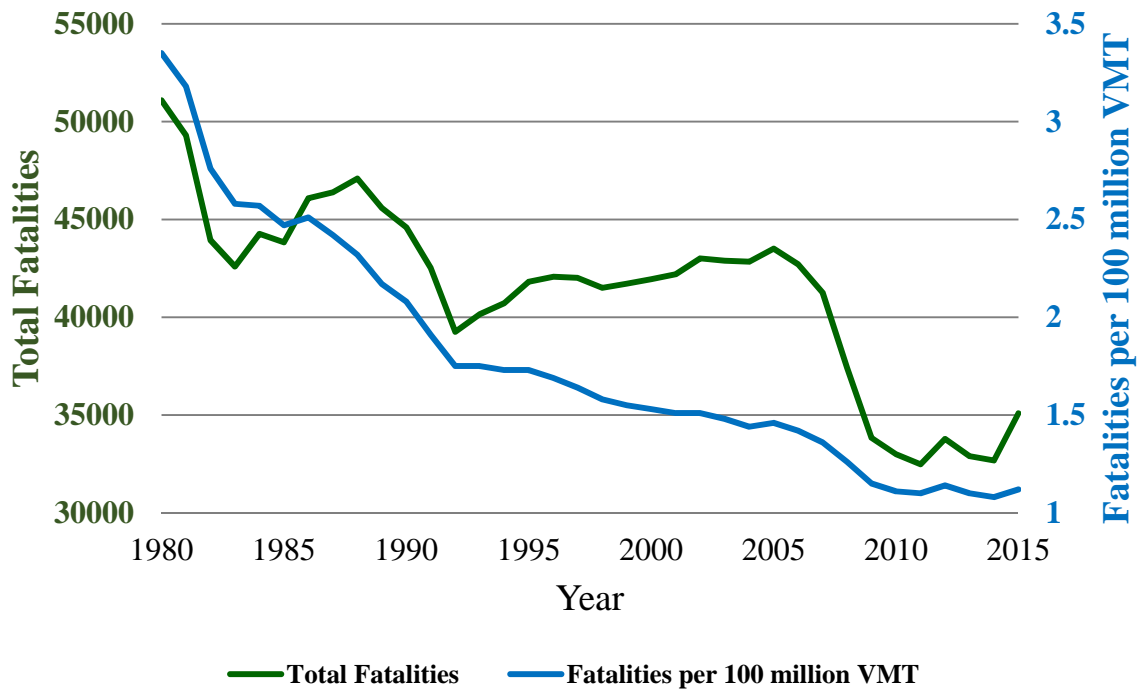
Figure 1. Traffic Related Fatalities in the US, 1980 to 2015, by Total and Rate

The decline can be attributed to several factors. Vehicle safety has improved dramatically over the years. For example, the invention of anti-lock brakes has allowed drivers to maintain better control of their vehicles when the brakes would have otherwise locked up and not allowed for steering to occur (Burton, 2004). In a 2012 study, it was determined that there was a 5 percent decrease in crash probability and a 3 percent increase in the probability of being uninjured if a crash did occur in a 2008 vehicle vs a 2000 vehicle (Glassbrenner 2012). Efforts have been also made to address unsafe driving behaviors. Public awareness campaigns about issues such as seat belt use and child restraints have had a positive impact on citizen compliance with the laws. Usage of a seat belt can reduce the risk of death for a front-seat occupant by 45 to 60 percent (NHTSA). Increased seat belt use in the US, particularly since the institution of the Click It or Ticket campaign, implemented in all states in 2004, can therefore be partially linked to a decrease in fatalities. Safety

countermeasures are also likely responsible for some of the decrease in fatalities. Cable median barrier has been shown to reduce the number of cross-median head-on fatal crashes by nearly 50 percent (Olson et al. 2013). The addition of a crash cushion at a roadside fixed object can reduce fatal and injury crashes by 69 percent (Elvik and Vaa, 2004). Turning a 4 lane undivided roadway into a 3 lane roadway with a two-way left-turn lane can reduce crashes by 15 to 25 percent (Pawlovich et al. 2006). Other safety treatments have had similar, if less drastic, results.

The way transportation agencies have evaluated traffic safety has likewise changed in recent years, including the ways in which road facilities have been classified in terms of their safety or risk potential. For many years, a roadway was considered "nominally" safe if it met all the relevant minimum design criteria in design manuals, such as AASHTO's A Policy on Geometric Design of Highways and Streets (also known as the "Green Book") (AASHTO, 2011). For example, so long as the minimum turning radius was sufficient for the functional class, the street was considered safe.

This way of approaching safety largely changed in 2010 with the introduction of the AASHTO Highway Safety Manual (HSM) (AASHTO 2010). Instead of focusing on nominal safety, the HSM outlines a variety of state-of-the-art methods to determine if a roadway is substantively, or quantitatively, safe through the use of data analytics. Crash rates and frequencies are compared across similar types of locations using various methods to determine if statistically significant differences exist and whether specific locations present higher risk. These methods include: before-and-after studies, which compare the frequency/rate of crashes between the periods before and after a specific treatment is applied;

cross-sectional studies, where similar locations are compared, some of which have the treatment while others do not; and combinations of these and others.

Safety performance functions (SPFs) and severity distribution functions (SDFs) are important facets of traffic safety data analysis using the methods outlined in the HSM. Due to the fact that crash countermeasures are rarely implemented on a system-wide basis due to budget constraints, sites tend to be selected based on the basis of disproportionately high crash frequencies or rates (calculated using the appropriate exposure variable, annual average daily traffic (AADT), VMT, or daily entering vehicles (DEV)). Given that crashes tend to be rare and random, a decrease in crashes at a specific location may simply be due to normal fluctuation, potentially leading to an overestimation of the effectiveness of a specific countermeasure. One method of addressing this regression-to-the-mean (RTM) bias is to calculate the expected number of crashes for that site. The most widely applied method for addressing RTM is known as the empirical Bayes (EB) method and is outlined in the HSM. The EB framework combines the long-term crash history at a given location with the predicted number of crashes as determined by a regression model developed using data from sites that are similar to where the treatment has been applied. SPFs and SDFs are generally used to calculate the predicted number of crashes.

The influence of analytics can also be seen when deciding what projects to fund. Cost effectiveness evaluation is a way of determining if the total benefit from the project is equal to the cost of implementing it. When dealing with limited funds for projects, it is important that the most cost effective solutions are selected, that is, the solutions that provide more benefits than costs. In terms of traffic safety countermeasures, if the total value of the crashes

prevented, translated into dollars, does not exceed the total cost of implementing the countermeasure, it is very likely that the money could better spent elsewhere.

One practical limitation of the HSM is that the processes and underlying statistical methods on which they are derived can be very complex. For even experienced practitioners, the safety planning process can be very time- and resource-intensive. Beginning with calibrating the HSM provided SPFs with local crash data, the practitioner must have historical data available from the roadways in the jurisdiction over time. If the SPFs have already been calibrated, then the practitioner must use the various SPFs (fatal/injury (FI) single vehicle, fatal/injury multi-vehicle non-driveway, property damage only (PDO) single vehicle, PDO multi-vehicle non-driveway) to calculate predicted crashes and then use an SDF to estimate how many crashes of each type would occur at each injury severity level.

Next, for project feasibility studies, the economic costs of those crashes over time must be forecasted and the present (or annual) value calculated. The installation and maintenance costs of the countermeasure must also be estimated for the service life of the countermeasure. Then, these crash cost savings and agency cost values may be used to calculate the benefit cost ratio or various other metrics. Therefore, determining a single number for one site can require a substantial investment in terms of time and data, making it particularly difficult when attempting to compare several projects across different candidate sites to determine the most cost-effective alternatives.

1.2 Research Objectives

The objective of this thesis was to develop an easy-to-use analysis tool to allow transportation professionals and decision makers to assess the economic feasibility of alternative crash countermeasures. Such a tool should be easily modified, which would allow

for its application across different jurisdictions. This is important as research suggests safety performance and the related predictive equations tend to vary across geographic areas due to unobserved factors beyond traffic characteristics and crash rates, necessitating calibration of generalized models, estimation of new ones, or other methods to account for local conditions (Chen 2012). The tool integrates a series of SPFs, which account for the effects of AADT and regional effects to predict the number of crashes occurring on urban and suburban road segments. The tool is presented using data drawn from the state of Michigan.

This tool is designed to be used for project-level planning, allowing for quick pre-feasibility tests on proposed countermeasures. Once the SPFs and SDFs are calibrated for the jurisdiction, a minimal amount of data (such as facility type, road length, and AADT) is required to calculate an estimate of the benefit/cost ratio that would result if the countermeasure were implemented for that particular roadway. This allows for rapid comparison of projects across a wide variety of sites and identifies suitable candidates for more in-depth evaluation.

1.3 Thesis Structure

This thesis is organized into six chapters, which detail the background of the research problem of interest, provide context with respect to the extant research literature, outline the development of the relevant models, discuss the creation of the spreadsheet tool, and present the methods of modifying the tool, prior to presenting uses and recommendations. A brief description of the remaining chapters follows:

Chapter 2: Literature Review – This chapter summarizes the extant literature on the subject of SPF and SDF development and economic analysis of safety countermeasures.

Chapter 3: SPF and SDF Development – This chapter provides a brief description of the data used for the development of the SPFs and SDFs used as the 'starter' equations, followed by the methods used to estimate the models. General formulation of the statistical methods is provided, including a discussion as to why these methods are appropriate for the nature of the data.

Chapter 4: Tool Development – The methods used for the development of the tool are presented in this chapter. The inputs and outputs of the spreadsheet are discussed in detail. The formulas and Visual Basic code included in the spreadsheet are also presented.

Chapter 5: Tool Modification – This chapter presents the methods used for modifying the tool for use in jurisdictions other than Michigan urban and suburban trunkline segments.

Chapter 6: Conclusion – This chapter discusses the uses of the spreadsheet tool, as well as future work that could be done to improve it.

CHAPTER 2: LITERATURE REVIEW

Data-driven approaches to safety analysis and safety planning have become a focal point in recent years. The Moving Ahead for Progress in the 21st Century Act (MAP-21) and the Fixing America's Surface Transportation (FAST) Act have both implemented requirements for analyses that provide support for the safety improvements that countermeasures are supposed to provide. Identifying locations that are suitable for safety improvements and treatments has become a priority all around the country. This is a crucial part of safety improvement programs, but identifying candidate locations can be very costly (Hauer, 2002). A variety of methods have been used in the past, with cost and time considerations favoring those that require the least amount of data.

The two methods most widely used historically by state departments of transportation (DOTs) in identifying high-risk locations are the crash frequency and crash rate methods (Alluri, 2008; Hauer, 1997). However, both of these methods are not without their flaws, due in part to their simplicity. The crash frequency method favors higher volume locations, ignoring the effects of traffic exposure. A location with a large amount of AADT is likely to have more crashes due simply to the increase in the number of vehicles present. However, on a per-vehicle basis, these sites may actually be safer than other lower volume locations. In contrast, using crash rates that account for such exposure variables tend to prioritize improvements at low-volume locations, due to a single crash having more weight (Persaud, 2001). It also fails to properly compare sites when crashes and traffic volume do not have a linear relationship (AASHTO).

Finally, both methods suffer from the flaw of using only observed crashes over a short period, typically three to five years, as the metric for site selection. As this doesn't take

into account short term fluctuations in crash trends, the conclusions from both methods can be misleading (Persaud, 2001). Predictive models can help address this issue by estimating the number of crashes that would occur based on data from similar locations where the treatment has not been applied. Part C of AASHTO's HSM provides general forms of a series of predictive models, known as SPFs, to calculate predicted crashes (AASHTO, 2010).

2.1 SPFs

SPFs are used to predict crash frequency using AADT, as well as other variables such as roadway geometric characteristics. The HSM contains a general statistical framework to predict crashes on roadway segments. This value, representing the predicted annual number of crashes per year for a segment with base (i.e., default) conditions, is denoted as N_{spf}.

$$N_{spf} = \exp(a + b \times ln(AADT) + ln(L))$$
2.1 (AASHTO, 2010)

where:

$AADT$ = annual average daily traffic volume (vehicles/day) on roadway segment;

L = length of roadway segment (mi); and

a, b = regression coefficients.

The HSM provides values for the coefficients a and b in a series of tables that are unique to specific facility types. These equations are then used to estimate the number of single and multi-vehicle crashes, disaggregated by injury severity into FI and PDO crashes. The basic equations from the HSM were estimated using data from a small subset of states. Given differences in roadway geometry, driver behavior, and weather, these base SPFs may provide limited accuracy when applied in other jurisdictions. Table 1 presents the number of sites used in the development of the SPFs for urban and suburban arterial segments in the

HSM. These equations were developed as part of a series of National Cooperative Highway

Research Program (NCHRP) reports (Harwood, 2007; Harwood, 2008).

Table 1. Number of Sites Used in the Development and Validation of SPFs for Urban and Suburban Arterial Segments in the Highway Safety Manual (Harwood et al. 2007; 2008)

Site Type	Sites by Type and State			Total
	MN	MI	WA	
2U	577	590	286	1453
3T	380	100	47	527
4U	741	440	106	1287
5T	198	549	371	1118
4D	540	140	54	734
Total	2436	1819	864	

While the general estimates can be useful, a more accurate estimate of the crash rates

can be obtained by either calibrating the HSM SPFs to local conditions or by developing new

SPFs for the jurisdiction in question using local data. Table 2 summarizes recent efforts by

states and countries to do just that.

Table 2. Summary of studies involving calibration or development of specific SPFs (Savolainen et al. 2016)

State/ Country	Study Year	Site Type(s)	No. of Sites	No. of Years	Calibrated HSM SPFs	Jurisdiction Specific SPFs
AL	2012	4D	4000	4	Yes	Yes
AL	2015	2U, 3T, 4U, 4D, 5T	2613, 479, 1054, 3153, 1598	3	Yes	Yes
FL	2011	2U, 3T, 4U, 4D, 5T	5076, 709, 1251, 7506, 2868	5	Yes	Yes
FL	2012	2L, MLU, MLD	2038, 245, 6923	4	No	Yes
IL	2010	One-way, 2L, MLU, MLD	1263, 10091, 4285, 9118	5	No	Yes
LA	2015	2U, 3T, 4U, 4D, 5T	50, 32, 50, 50, 50	3	Yes	No
MD	2014	2U, 3T, 4U, 4D, 5T	7215, 537, 741, 5338, 276	3	Yes	No
MI	2016	2U, 3T, 4U, 5T, 4D, 6D, 8D, One-way	489, 236, 373, 239, 439, 119, 166, 189	5	Yes	Yes
MO	2013	2U, 4D, 5T	73, 66, 59	3	Yes	No
NJ	2013	2U	372	3	Yes	No
NC	2011	2U, 3T, 4U, 4D, 5T	59.39, 7.57, 15.29, 15.5, 12.46 (miles)	3, 5	Yes	Yes
OH	2015	2U, 3T, 4U, 4D, 5T	150, 150, 150, 150, 150	3	Yes	No
OR	2012	2U, 3T, 4U, 4D, 5T	491, 205, 375, 86, 323	3	Yes	No
OR	2001	Urban non-freeways	2257	2	No	Yes
PA	2016	2U, 4U, 4D,	530, 179, 306	5	No	Yes
TX	2008	2U, 4U, 2D, 4D, 6D, 8D	72, 140, 12, 492, 217, 9	3	Yes	No
VA	2010	2-lane (urban)	57605	5	No	Yes
WA	2004	4U	121.95 (miles)	4	No	Yes
Edmonton, Alberta	2014	Urban residential collectors	406	4	No	Yes
India	2013	Single and dual urban roads	141, 115	-	No	Yes
Saudi Arabia	2015	4D	172	3	Yes	Yes

Six states did not calibrate the HSM models and just developed SPFs for their jurisdictions. Seven states only calibrated the HSM models. Five states did both. Most states that estimated models for their jurisdictions used the same classification method as the HSM for developing their SPF models, where the facility type is given by the number of lanes followed by a U for undivided roadways, a T for undivided roadways with a two-way left-turn lane (TWLTL), and D for a divided roadway. Some states, such as Washington and North Carolina, did not give a number of sites used for the estimation of the models, but instead used roadway length to describe the datasets. Some states used very few sites, most notably Louisiana and Missouri using fewer than 75 sites for their calibrations, with as few as 32 segments for 3T roadways in LA.

2.2 Economic Analysis

In order to provide guidance on whether a safety measure is cost effective, the Federal Highway Administration (FHWA) outlines in their Highway Safety Improvement Program (HSIP) manual two methods of benefit/cost analysis that focus on lifetime cost savings and lifetime expenses (FHWA 2011). Both methods convert future value to present value using standard economic principles.

The uniform annual benefits method treats the benefit value as an annuity. The total annual benefits are multiplied by a factor to convert it from future payouts to current value. The following equations are used:

$$PVB_v = Total\ Annual\ Monetary\ Benefits\ \times\ (P|A, i, n) \qquad 2.2$$

$$(P|A, i, n) = \frac{(1+i)^n - 1}{i*(1+i)^n} \qquad 2.3$$

where:

PVB_v = present value of benefits

$(P|A, i, n)$ = multiplier to determine total present value of monthly benefits

i = discount rate

n = service life in years

This method is used when the benefits are fixed for every year. The discount rate can be the inflation rate, or the interest rate at which the money could be invested if not used. The service life in years is the number of years that the particular safety countermeasure will be in the field.

The second method is for non-uniform annual benefits. The following equation is used:

$$PVB_v = Total\ Annual\ Monetary\ Benefits\ \times\ (P|F, i, n) \qquad\qquad 2.4$$

$$(P|F, i, n) = (1 + i)^{-n} \qquad\qquad 2.5$$

where:

i = discount rate

n = service life in years

The PVB_v for each year must be calculated and then summed. This method is best used when the benefits change over time, such as the retroreflectivity of lane markings, which degrade over time and so have less of an impact on crashes as they grow older.

To quantify the economic impact of crashes for the benefit/cost analysis, the HSM presents a table of comprehensive crash costs, seen in Table 3 (FHWA, 2011). In addition to estimating SPFs for their jurisdiction, an agency can also provide their own estimates of crash costs to obtain a better estimate of the benefits of safety countermeasures. Comprehensive crash costs include not only the property damage, but also cost of congestion, loss of productivity, court/legal costs, emergency responders, and more. The National Safety Council (NSC) estimates the cost of the crash on a per person basis, that is, there is a cost associated with each fatality, incapacitating injury, and so on (NSC, 2014). This makes it more difficult to apply these costs to a crash, as the SPFs only predict the number of crashes and, if SDFs are used, the maximum severity breakdown, not the number of people involved in the accident. As such, the average number of fatalities per crash, incapacitating injuries per crash, and so on would need to be calculated on a system level for the jurisdiction. The crash costs in Table 3 are per crash.

Table 3. Comprehensive Crash Costs by Severity Level (FHWA, 2016)

Injury Severity Level	Comprehensive Crash Cost
Fatality (K)	$4,008,900
Incapacitating Injury (A)	$216,000
Minor Injury (B)	$79,000
Possible Injury (C)	$44,900
Property Damage Only (O)	$7,400

2.3 Existing Tools/Guidance

AASHTO summarizes some of the tools available that can be used to implement the HSM. The Crash Modification Factors (CMFs) Clearinghouse website can be used to locate

CMFs for numerous countermeasures that have been published in reports, papers, and journal articles. There are also various programs that are available to supplement the HSM. SafetyAnalyst and the Interactive Highway Safety Design Model (IHSDM) both require large amounts of data in order to use effectively. SafetyAnalyst works with Part B of the HSM, which details the process to select locations based on metrics including crash rates and frequencies. The IHSDM works with the predictive methods found in Part C of the HSM. Included in the data needs for this program are roadway geometry in addition to traffic volume and crash data (AASHTO 2017).

The Michigan DOT utilizes a spreadsheet tool for conducting a time-of-return (TOR) analysis for candidate projects. This spreadsheet uses observed crash frequencies and AADT growth factors to calculate the time required for the savings from crashes prevented to meet or exceed the cost of implementation of the project. Three to five years of crash data are recommended for the TOR spreadsheet, as it uses only observed crash data at the location, which means it is also vulnerable to the short term fluctuations in crash rates. The spreadsheet assumes a linear relationship between crashes and AADT, which, as covered earlier, is not necessarily an appropriate assumption.

The Minnesota DOT has developed a guidance document on conducting benefit/cost analysis for transportation projects. In the document, there is discussion on the various uses of a benefit/cost analysis and its uses in project planning, as well as in the design phase and construction planning. It is suggested that different alternatives, whether they are projects, countermeasures, or sites, be considered to determine which have benefits that are worth the investment. Other states, such as Ohio, use benefit/cost ratios when considering projects, but do not have published methods for how they calculate them (ODOT, 2017). California DOT

uses a spreadsheet tool to do life-cycle benefit/cost analyses. Their spreadsheet is very generalized. Given that it is designed to estimate the benefit/cost ratio and life-cycle costs for any type of construction or improvement project, it has many of possible inputs and uses historical crash data (CalTrans, 2017).

Data driven analysis for safety countermeasures have driven the use of SPFs in calculating safety effectiveness and the available tools and documentation show that there is interest in using the benefit/cost ratio when determining which projects should move forward at the planning stage. However, the existing tools rely primarily on historical crash frequencies, with some integration of SPFs to conduct EB analyses. The amount of data required can be impractical for project-level planning efforts when a large amount of countermeasures are being considered. SPFs can provide a prediction for the number of crashes and, by calculating the effect of a safety countermeasure, can provide an estimate of the benefit/cost ratio with minimal data requirements, making this information accessible at the project planning stage. This project hopes to encourage the use of SPFs in the benefit/cost analysis at the planning stages by creating an easy to use tool that can calculate the benefit/cost ratio for prospective projects quickly and can be easily modified to with locally calibrated SPFs.

CHAPTER 3: SPF AND SDF DEVELOPMENT

The accuracy of an SPF depends heavily on the quality and quantity of the data used to estimate it. More complex models that include a large variety of inputs in an effort to account for the many differences in roadway and traffic characteristics to adequately predict crashes, necessarily require a great deal of information regarding the roadway and traffic stream. When examining projects at the pre-feasibility level, it is not generally convenient to gather all of this information. However, it is possible to produce a simplified (and generalized) SPF that might be less accurate for a particular road segment, but requires much less data to use for prediction. This technique is used for the models included in the spreadsheet tool developed for this project. These SPFs use just 3 variables, AADT, length, and a regional indicator variable to account for general differences in crash expectancy across geographic regions. To calculate the economic impact of the crashes, SDFs were used to predict the distribution of crash severity. The SDFs used in this spreadsheet tool require a total of 3 inputs, which are speed limit, terrain type, and roadway division type. Facility type is an additional input that is used to select the particular model to be used and also determines the roadway division type, allowing for only 2 manual inputs for use in the SDFs.

It would have been possible to utilize the general SPFs provided in the HSM. However, to demonstrate how this tool can be individualized for use in a particular jurisdiction, SPFs have been developed for Michigan state-maintained urban and suburban roadways (that is, segments that are within the city limits of communities with a population of 5000 people or more). By predicting the number of crashes occurring on a roadway using very few variables, they allow the user to use the tool to quickly examine the benefit/cost ratio for a variety of safety countermeasures at a variety of locations, identifying those

candidates most suitable for future study with a minimum of cost and effort while still using data-driven analysis. Much of the framework developed for the tool and detailed in Chapter 4 was built around the variables used in these particular SPFs.

3.1 SPF Development

SPFs take the form of generalized linear models, with the negative binomial model being the framework most widely utilized in practice. Due to the nature of crash data, which are comprised of non-negative integers, regression techniques such as ordinary least-squares are typically inappropriate. There are many factors that influence crashes, including AADT, lane width, and others, and these factors do not necessarily have a linear relationship with crashes. As a measure of exposure, AADT is the backbone of an SPF and therefore can have a linear effect on crashes, but many times the relationship between the two will appear to follow more of an exponential fit. A simple linear least-squares regression would not accurately capture these effects. Given the nature of crash counts as non-negative integers, a Poisson distribution provides a starting point for statistical analyses of crash data. However, a base assumption for a Poisson distribution is that the variance is equal to the mean. This is often not a valid assumption when looking at the frequency of crashes over a variety of road segments (such as all the roads in a state), as many segments will have few to no crashes while others will have an extremely high frequency of crashes. Because of this, the variance tends to be much higher than the mean, and the data are described as overdispersed as a result.

This violation of the Poisson assumption is controlled for by using a specific type of Poisson model, known as a negative binomial model (sometimes called a Poisson-gamma model). In this type of model, the single value Poisson parameter is replaced with a function.

The negative binomial model is recommended in the HSM for the development of SPFs and is used in the SPFs provided in that manual.

The SPFs used in the spreadsheet tool use the following equation:

$$N = Length * AADT^{\beta_{AADT}} * e^{(I + \beta_{Region} * I_{Region})} \qquad 3.1$$

where:

N = FI or PDO crashes per year

I = Intercept

I_{Region} = Regional indicator

β_{Region} = Coefficient for region

Both length and AADT were log-transformed during the estimation of the models and length was used as an offset variable, resulting in the equation in the form seen above. As an offset variable, the coefficient was fixed at 1.0. This introduces a practical constraint in that crashes are expected to change proportionately to segment length (i.e., if length doubles, crashes will double, as well). The regional indicators were included in these models because they can be used to capture regional differences without requiring the inclusion of a large number of variables. The regional differences can include weather (the amount of rain, snowfall, and plowing tendencies), roadway design (lane width, shoulder widths, and others), and driver behavior. This allows for improved model fit with a minimum number of inputs.

As crashes vary largely by facility type (the number of lanes and organization of those lanes), a separate SPF was estimated for each. Also, to facilitate later economic impact calculations, FI crashes and PDO crashes were estimated in separate models. This follows the

same procedure as the HSM. The intercept value in these models shifts the model up or down

the vertical axis, in this case, increasing or decreasing the number of crashes that would

'occur' by a scalar. Although the value of the intercept does not have very much practical

meaning in and of itself, it is important to include in the model as failure to do so may result

in biased parameter estimates. The remaining coefficients represent the impacts of specific

variables on the total number of crashes and must be remembered in the context of Equation

3.1. AADT coefficients are the power to which the AADT value is raised. If the coefficient is

equal to 1.0, then crashes will increase directly in proportion to AADT. If the coefficient is

less than one, as AADT increases, the rate at which crashes increase will slow. If the

coefficient is greater than one, as AADT increases, the rate at which crashes increase will

grow. Coefficients of 1.0 or greater are termed elastic with respect to AADT. AADT has also

been shown to be inelastic in some contexts where crashes increase at a lesser rate as AADT

increases (i.e., when the coefficient is less than 1.0). For the regional indicator coefficients,

the sign indicates whether that region experiences more or fewer crashes in general than the

Metro region (which was used as the base case to avoid over constraining the model). The

magnitude of the coefficient indicates relative differences in safety performance on segments

between that region and the Metro region.

A model was estimated for each individual facility type. Facility types are designated

based on the number of lanes on the roadway as well as the configuration of those lanes.

They are given in the form of a number followed by one of 3 letters. The number represents

the number of lanes. The 3 possible letters are 'U', 'T', and 'D'. 'U' stands for an undivided

roadway, with a yellow centerline. 'T' stands for a roadway with a TWLTL in place of a

yellow centerline. 'D' stands for a divided roadway, where some barrier is in place between

the lanes going in opposing directions. Images of the different facility types can be found in Figure 9 in section 4.1.1.

For 2U segments, the FI crashes tend to be more elastic with AADT than the PDO crashes, as can be seen by the coefficients in Table 4. The regional effects also differ between FI and PDO. Of particular note is the fact that the signs of several of the regional indicators change between FI and PDO crashes. For example, the coefficient for the North region is -0.233 for FI crashes (meaning there are fewer FI crashes with respect to AADT compared to the Metro region) and 0.132 for PDO crashes (meaning there are more PDO crashes with respect to AADT compared to the Metro region). This change can be seen in the graphs below. In Figure 2, the orange line that shows the crashes per mile in the North region is below the blue line that represents crashes per mile in the Metro region (base case). In Figure 3, the orange line for the North region is above the blue line that represents crashes per mile in the Metro region. This shows the differences that can appear between the two types of crashes and highlights the need to model them separately.

Table 4. SPF for Crashes on 2U Segments with AADT and Regional Indicators

Variable	Fatal and Injury Crashes			Property Damage Only Crashes		
	Value	Std. Error	t-statistic	Value	Std. Error	t-statistic
Intercept	-8.016	0.528	-15.177	-3.960	0.324	-12.241
AADT	0.856	0.056	15.224	0.566	0.034	16.462
Superior Region Effect	-0.416	0.131	-3.186	-0.108	0.082	-1.319
North Region Effect	-0.233	0.108	-2.157	0.132	0.076	1.745
Grand Region Effect	0.053	0.094	0.566	0.376	0.073	5.182
Bay Region Effect	0.001	0.091	0.015	-0.031	0.071	-0.430
Southwest Region Effect	-0.296	0.096	-3.082	0.066	0.067	0.993
University Region Effect	-0.061	0.083	-0.735	0.112	0.064	1.742
Inverse Dispersion Parameter	0.066	-		0.336	0.021	

*Note: Metro Region Effect serves as baseline reference category
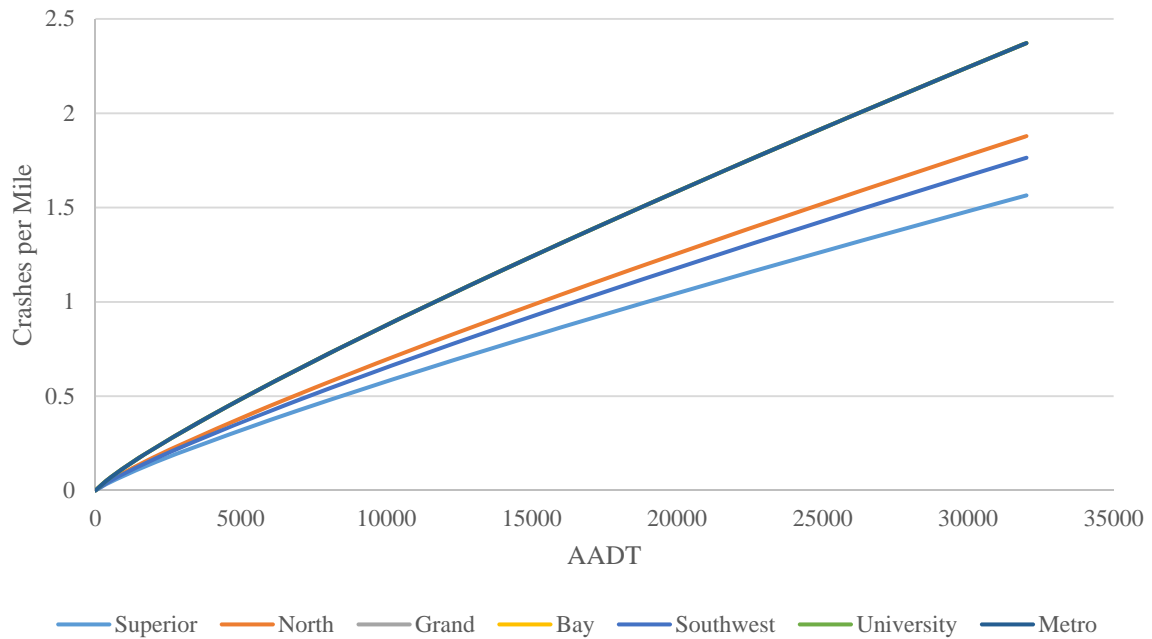
Figure 2. FI Crashes per Mile for 2U Segments with Regional Effects
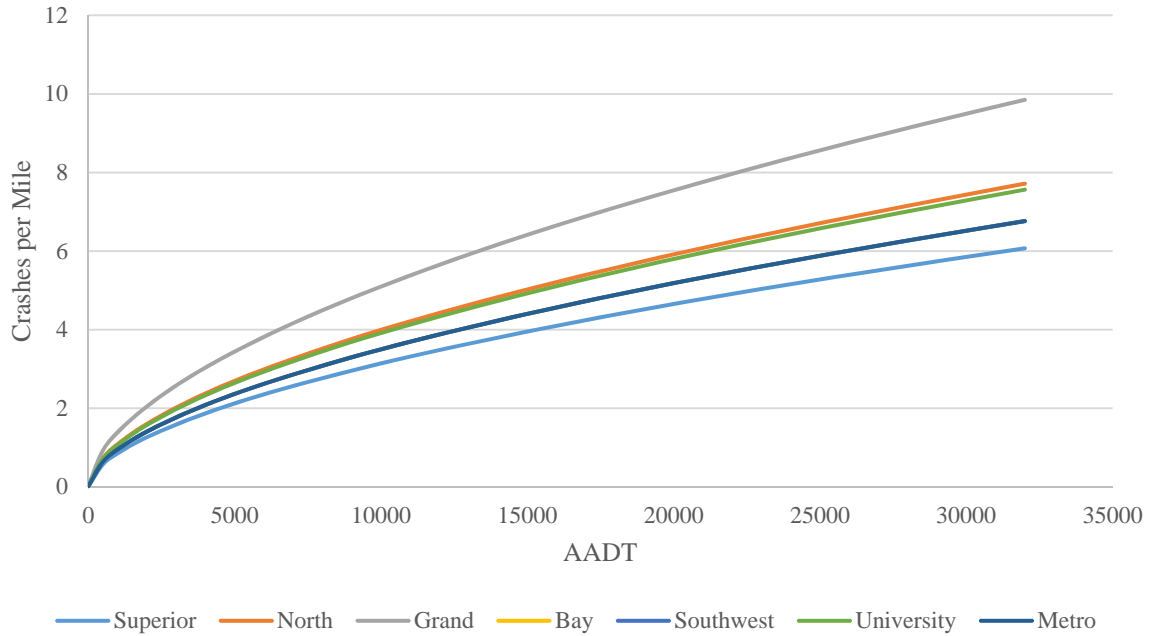
Figure 3. PDO Crashes per Mile for 2U Segments with Regional Effects

For the 4U segments, PDO crashes are fairly elastic with AADT, but as AADT increases, the rate of FI crashes also increases (coefficient is greater than 1). This can be seen in the slopes of the lines in Figure 4. While the PDO line reaches a higher number of crashes, its slope is mostly linear, with a slight tendency towards concave down. The FI line, on the other hand, has a distinct concave up shape. The regional effects for this facility type are more consistent, with no coefficients changing signs. The coefficients can be found in Table 5.

Table 5. SPF for Crashes on 4U Segments with AADT and Regional Indicators

Variable	Fatal and Injury Crashes			Property Damage Only Crashes		
	Value	Std. Error	t-statistic	Value	Std. Error	t-statistic
Intercept	-12.655	1.035	-12.231	-7.543	0.677	-11.143
AADT	1.330	0.104	12.788	0.941	0.069	13.717
Superior Region Effect	-0.478	0.207	-2.309	-0.273	0.131	-2.084
North Region Effect	-0.411	0.157	-2.625	-0.140	0.114	-1.228
Grand Region Effect	0.266	0.137	1.940	0.194	0.109	1.786
Bay Region Effect	-0.176	0.136	-1.291	-0.365	0.105	-3.470
Southwest Region Effect	-0.375	0.143	-2.619	-0.207	0.101	-2.045
University Region Effect	0.075	0.123	0.609	0.245	0.094	2.601
Inverse Dispersion Parameter	10.630	-		2.650	0.035	

*Note: Metro Region Effect serves as baseline reference category
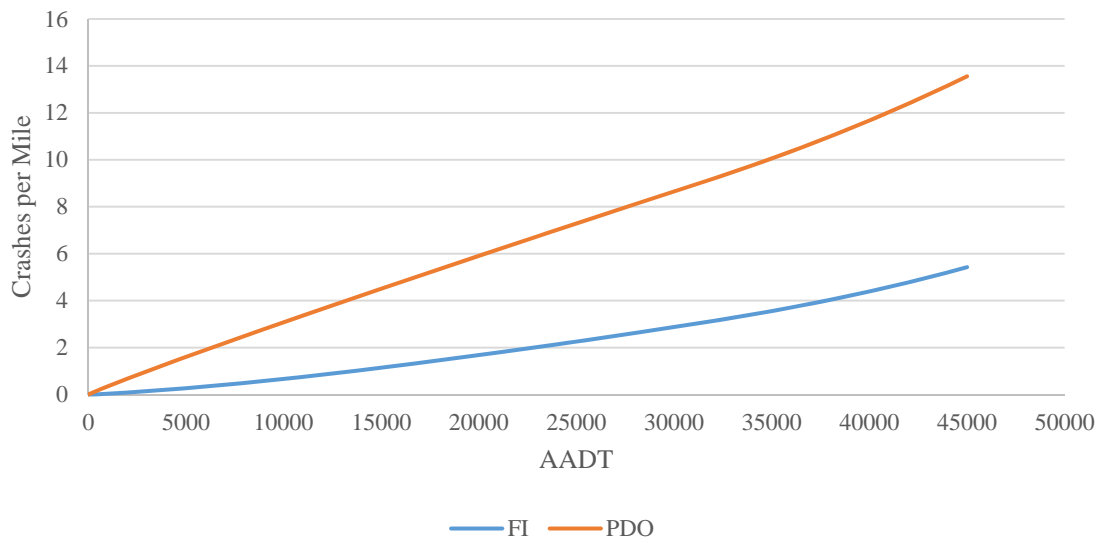
Figure 4. Annual Crashes per Mile for 4U Segments in Metro Region

The relationship between AADT and crashes is more uniform between FI and PDO crashes for the 3T facility type. Both crash types are very elastic with regards to AADT as well. The coefficients are in Table 6.

Table 6. SPF for Crashes on 3T Segments with AADT and Regional Indicators

Variable	Fatal and Injury Crashes			Property Damage Only Crashes		
	Value	Std. Error	t-statistic	Value	Std. Error	t-statistic
Intercept	-10.673	1.320	-8.084	-8.923	0.778	-11.463
AADT	1.100	0.138	7.988	1.085	0.080	13.529
Superior Region Effect	-	-	-	0.328	0.310	1.058
North Region Effect	0.061	0.291	0.210	-0.006	0.195	-0.031
Grand Region Effect	-0.006	0.299	-0.020	0.028	0.196	0.143
Bay Region Effect	-0.011	0.292	-0.038	-0.104	0.194	-0.536
Southwest Region Effect	-0.049	0.272	-0.180	-0.201	0.184	-1.091
University Region Effect	0.188	0.268	0.703	0.075	0.182	0.413
Inverse Dispersion Parameter	1.855	0.124		2.100	0.047	

*Note: Metro Region Effect serves as baseline reference category

For both FI and PDO crashes, the graph is concave up. All but the Superior region have positive coefficients for the regional indicators for the 5T facility type, as seen in Table 7.

Table 7. SPF for Crashes on 5T Segments with AADT and Regional Indicators

Variable	Fatal and Injury Crashes			Property Damage Only Crashes		
	Value	Std. Error	t-statistic	Value	Std. Error	t-statistic
Intercept	-13.760	0.718	-19.170	-10.117	0.517	-19.576
AADT	1.446	0.070	20.569	1.206	0.051	23.740
Superior Region Effect	-0.442	0.114	-3.867	-0.066	0.078	-0.849
North Region Effect	0.040	0.096	0.418	0.366	0.075	4.880
Grand Region Effect	0.292	0.071	4.124	0.304	0.062	4.903
Bay Region Effect	0.057	0.080	0.717	0.243	0.063	3.876
Southwest Region Effect	0.086	0.083	1.035	0.295	0.065	4.545
University Region Effect	0.189	0.070	2.688	0.283	0.057	4.939
Inverse Dispersion Parameter	2.910	0.032		2.202	0.022	

*Note: Metro Region Effect serves as baseline reference category

For the 4D segments, FI crashes are elastic with AADT, but PDO crashes are somewhat inelastic with that variable. The coefficients can be found in Table 8.

Table 8. SPF for Crashes on 4D Segments with AADT and Regional Indicators

Variable	Fatal and Injury Crashes			Property Damage Only Crashes		
	Value	Std. Error	t-statistic	Value	Std. Error	t-statistic
Intercept	-10.221	0.823	-12.413	-6.450	0.463	-13.937
AADT	1.041	0.085	12.261	0.814	0.048	16.853
Superior Region Effect	0.141	0.147	0.960	0.290	0.083	3.486
North Region Effect	-0.119	0.321	-0.371	-0.349	0.191	-1.830
Grand Region Effect	0.089	0.085	1.052	0.095	0.057	1.661
Bay Region Effect	0.152	0.189	0.806	-0.059	0.114	-0.516
Southwest Region Effect	-0.074	0.153	-0.485	-0.210	0.087	-2.408
University Region Effect	-0.232	0.150	-1.544	-0.032	0.081	-0.394
Inverse Dispersion Parameter	4.310	0.061		2.840	0.028	
*Note: Metro Region Effect serves as baseline reference category						

The effect of AADT on the crashes for 6D segments results in a concave up graph shape, as can be inferred from the coefficients in Table 9.

Table 9. SPF for Crashes on 6D Segments with AADT and Regional Indicators

Variable	Fatal and Injury Crashes			Property Damage Only Crashes		
	Value	Std. Error	t-statistic	Value	Std. Error	t-statistic
Intercept	-11.566	1.385	-8.354	-10.806	1.086	-9.951
AADT	1.189	0.136	8.743	1.255	0.107	11.707
Superior Region Effect	-	-	-	-	-	-
North Region Effect	-	-	-	-	-	-
Grand Region Effect	0.111	0.224	0.496	0.214	0.167	1.282
Bay Region Effect	-	-	-	-0.074	0.497	-0.149
Southwest Region Effect	0.036	0.744	0.048	-0.073	0.458	-0.159
University Region Effect	-0.518	0.272	-1.906	-0.339	0.162	-2.090
Inverse Dispersion Parameter	2.690	0.073		1.740	0.057	
*Note: Metro Region Effect serves as baseline reference category						

Due to a lack of 8D segments outside the Metro region, regional effects were not estimated for this facility type. The coefficients in Table 10 represent the AADT only model for 8D segments. The high coefficient for AADT shows a strong relationship between AADT and crashes.

Table 10. SPF for Crashes on 8D Segments with AADT

Variable	Fatal & Injury Crashes			Property Damage Only Crashes		
	Value	Std. Error	t-statistic	Value	Std. Error	t-statistic
Intercept	-14.194	1.188	-11.945	-12.527	0.817	-15.331
AADT	1.437	0.116	12.356	1.405	0.080	17.475
Inverse Dispersion Parameter	1.700	0.069		1.990	0.038	

3.2 SDF Development

The SDFs were developed generically for the two way urban and suburban trunkline system as part of a project for Michigan DOT (Savolainen et al. 2016). The SDFs can be used to estimate the proportion of crashes that result in specific injury severity levels based on the KABCO scale. For this scale, K represents a fatal crash where at least one person involved in the crash was killed, A represents an incapacitating injury, B represents a non-incapacitating injury, C represents possible injury, and O is a property-damage-only (or no-injury) crash. This determination is made by the police officer responding to the crash and is recorded in the crash reporting form. The SDFs use some geometric characteristics to individualize the estimated proportions to the site.

A multinomial logit (MNL) model was used to estimate the probabilities. The following equations were used:

$$P_K = \frac{e^{V_K}}{1 + e^{V_K} + e^{V_A} + e^{V_B}} \qquad 3.2$$

$$P_A = \frac{e^{V_A}}{1 + e^{V_K} + e^{V_A} + e^{V_B}} \qquad 3.3$$

$$P_B = \frac{e^{V_B}}{1 + e^{V_K} + e^{V_A} + e^{V_B}} \qquad 3.4$$

$$P_C = 1 - (P_K + P_A + P_B) \qquad 3.5$$

where:

P_j = probability of the occurrence of crash severity j;

V_j = systematic component of crash severity likelihood for severity j.

The following equations were used to calculate the components of the above

equations:

$$V_K = ASC_K + b_{ter,K} \times I_{ter} + b_{div,K} \times I_{div} + b_{psl,K} \times PSL \qquad 3.6$$

$$V_A = ASC_A + b_{ter,A} \times I_{ter} + b_{div,A} \times I_{div} + b_{psl,A} \times PSL \qquad 3.7$$

$$V_B = ASC_B + b_{ter,B} \times I_{ter} + b_{div,B} \times I_{div} + b_{psl,B} \times PSL \qquad 3.8$$

where:

I_{ter} = terrain indicator variable (=1.0 if level, 0.0 if it is rolling);

I_{div} = divided road indicator variable (=1.0 if divided, 0.0 otherwise);

PSL = posted speed limit on the segment, miles per hour;

ASC_j = alternative specific constant for crash severity j; and

$b_{k,j}$ = calibration coefficient for variable k and crash severity j.

The parameter estimates for the SDFs are severity specific. The variables included in

this model provided the best fit for the data while at the same time being logical. The

variables included for consideration were the variables that, considered when developing a

fully specified model, had an impact on crashes. The coefficients can be found in Table 11.

Table 11. Parameter estimation for SDFs (Savolainen et al. 2016)

Coefficient	Variable	Fatality (K)		Incapacitating injury (A)		Non-Incapacitating injury (B)	
		Value	t-statistic	Value	t-statistic	Value	t-statistic
ASC	Alternative specific constant	-4.930	-7.49	-2.631	-8.28	-1.427	-6.99
b_{ter}	Terrain (1=level; 0=rolling)	-0.656	-2.54	-0.256	-1.69	-0.130	-2.53
b_{div}	Divided road (1=divided; 0=others)	-0.355	-1.99	-0.354	-4.16	-0.130	-2.53
PSL	Posted speed limit, mph	0.042	3.49	0.018	3.28	0.013	3.74
Observations		10,021 crashes (K=173; A=809; B=2,340; C=6,699)					

CHAPTER 4: TOOL DEVELOPMENT

For a tool to be valuable, accessibility and ease of use are two of the main concerns that must be considered. Although SPFs and SDFs can provide a solid statistical basis for evaluating the effect of safety countermeasures – something that matters as transit agencies seek to use data to drive the decision making process – the complexity of the statistical equations can be a concern when it comes to usability. As described in Chapter 2, tools for using the methods in the HSM exist, but they require large amounts of data. Therefore, this tool was developed in order to leverage the advantages provided by using SPFs and SDFs at the pre-feasibility stage while reducing the complexity of running comparisons.

Rather than write a stand-alone program, the decision was made to use a common spreadsheet program as the tool framework. This software is widely prevalent and most users will already be familiar with basic operations, reducing the learning curve and achieving the goal of making the tool accessible and easy to use. This tool is intended for use as a project-level planning tool to do simple pre-feasibility analyses. It calculates a benefit/cost ratio based on the SPFs loaded into it. It does not calculate time of return, nor does it utilize observed crashes. The predictive models included in the model were developed using data from Michigan state-maintained urban and suburban non-interstate roadways. The underlying SPFs can be modified to allow other jurisdictions to utilize the framework for their own roadways.

The spreadsheet consists of multiple tabs, as seen in Figure 5. The Instructions tab (Figure 6) details the process of how to modify the predictive equations to suit the jurisdiction. The Inputs tab prompts for the inputs necessary to estimate the benefit/cost ratio of the countermeasure. Intermediate calculations are presented in the SDF Proportions,

Crashes, and Benefit/Cost tabs. Finally, the Summary and Saved Outputs tabs display the

results of the analysis. The Tables and Lists tab, normally hidden from the user (displayed

visibly in Figure 7), contains the coefficients for the predictive equations, various lists, and a

series of helper cells.
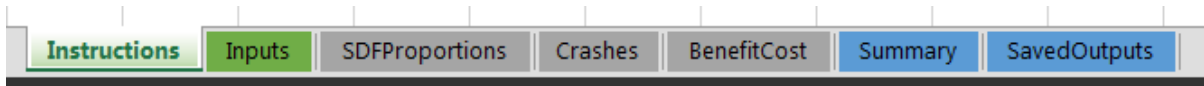
Figure 5. Software Tool Tabs

Figure 6. Instructions Tab
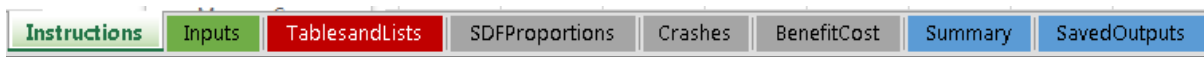
Figure 7. Software Tool Tabs with Tables and Lists

4.1 Inputs

The inputs tab (pictured in Figure 8) asks for three 3 different types of information

from the user: roadway and traffic characteristics, safety countermeasure/treatment

information, and analysis information.

Facility Type	4D
Region	Superior
AADT	17500
Terrain	Level
Speed Limit (mph)	40
Length (miles)	5
CMF Option	Preset
Presets	Cable Barrier (Severity Specific)
Capital Expense Cost per Mile	140000
Maintenance Cost per Mile	6000
Decimal Discount Rate	0.04
Service Life (years)	20
Treatment	Cable Median Barrier
Facility Name	Random Rd
Town, State	Paradise, MI
Date of Analysis	2/1/2017
Conducted by	Patty Thompson

Summary Sheet

Figure 8. Inputs Tab

4.1.1 Roadway/Traffic characteristics

The first input for the roadway and traffic characteristics is facility type. As discussed in Chapter 3, this refers to the number of lanes and configuration of those lanes. The models preset in the spreadsheet tool are for Michigan urban and suburban trunkline segments, which have facility types ranging from 2U to 8D. Figure 9 contains examples of each facility type.

2 Lane Undivided (2U)

3 Lane with a TWLTL (3T)

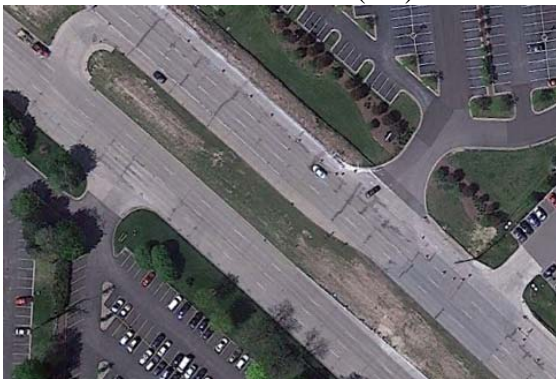

4 Lane Undivided (4U)

5 Lane with a TWLTL (5T)

4 Lane Divided (4D)

6 Lane Divided (6D)

8 Lane Divided (8D)

Figure 9. Facility Types

In the Inputs tab, facility type is selected using a dropdown list, as shown in Figure 10. Facility type is extremely important for the tool, as it dictates which SPF is used for calculating crashes and is used to set the divided roadway variable in the SDF. By using a dropdown list, the inputs are standardized, allowing the formulas embedded in the spreadsheet to reference other values based on facility type, which is particularly important for the SPFs as discussed in Chapter 3. The list of facility types for the dropdown menu can be changed if necessary and is pulled from the tables and lists tab.

Figure 10. Facility Type Dropdown Menu

The next input, Region, also utilizes a dropdown menu for consistency and for ease of use. By using the dropdown menu, the user will not have to remember which regional identifiers were used in order to select the appropriate regional coefficients. The input options can be seen in Figure 11. Like the facility type dropdown, this list is pulled from the tables and lists tab. As discussed in section 3.1, region was chosen as the 3rd variable in the SPF (after AADT and length) because it captures some of the differences in roadway design between areas of the state, such as lane and shoulder widths, weather, and driver behavior.
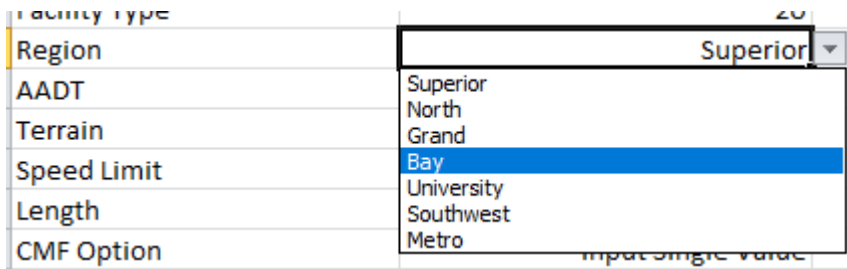
Figure 11. Region Dropdown Menu

AADT, the next input, is a numeric value from the analyst. Values for this cell have been restricted to integers greater than 0. If the AADT input is greater than 80,000, the cell will turn red to indicate that an AADT far outside the model ranges has been entered and the results should be treated with caution. Table 12 contains the model AADT ranges, rounded down to the nearest 100 for the minimums and up to the nearest 100 for the maximums.

Table 12. Model AADT Ranges

Facility Type	Min AADT	Max AADT
2U	200	30200
3T	2400	31100
4U	3700	43900
5T	4100	51300
4D	1800	35900
6D	3400	77600
8D	6000	77600

A dropdown menu with 2 choices is the input for Terrain type, used in the SDF calculations. The options for this are Level and Rolling. The spreadsheet tool menu can be seen in Figure 12. Examples of level and rolling terrain can be seen in Figure 13. Crashes on rolling terrain tend to be more severe, which matters when considering the economic impact of a safety countermeasure.

Figure 12. Terrain Dropdown Menu

Figure 13. Level (left) and Rolling (right) Terrain

The next input is the speed limit of the road. Like AADT, this is a numeric input from the analyst. The value input into this cell is restricted to integer values between 15 and 85 miles per hour. This range can be modified in the future if higher speed limits are introduced. Details on the modification process can be found in chapter 5.

The length of the road is the final input in the roadway and traffic characteristics. Road length here measures the segment length that the safety countermeasure is being considered on and is given in miles.

4.1.2 Safety countermeasure/treatment

The first input for the safety countermeasure/treatment characteristics is the CMF. There are 3 different ways to use CMFs with the spreadsheet tool. A dropdown menu allows the analyst to select one of these 3 options: Preset, Input Single Value, and Input Severity Specific. Figure 14 shows this menu. Depending on the input method selected, different rows

are visible. Selecting Preset displays a row with a 2nd dropdown menu that contains several

preset CMFs, taken from CMF Clearinghouse. The values included for cable median barrier

come from 2 different studies (Elvik, 2004; Olson et al. 2013). The 4U to 3T lane diet CMF

came from an EB study (Persaud et al., 2010). The rumble strips CMF comes from a NCHRP

report (Torbic et al., 2009). More CMFs can be added as they are developed. If the

jurisdiction develops CMFs for countermeasures in their area, these can be used in place of

values from the CMF Clearinghouse. This list can be seen in Figure 15. Modifying the values

available will be discussed in Chapter 5. Selecting Input Single Value provides a row labeled

'Single Value' for the input of the relevant CMF, as shown in Figure 16. Selecting Input

Severity Specific displays a series of rows where CMFs can be manually input for crashes on

the KABCO severity scale, as seen in Figure 17.

Figure 14. CMF Dropdown Menu

Figure 15. Presets Dropdown Menu

CMF Option	Input Single Value
Single Value	0.95
~~Capital Expense Cost per Mile~~	~~10000~~

Figure 16. Input Single Value

CMF Option	Input Severity Specific ▼
Severity Specific	
K	0.8
A	0.9
B	0.95
C	1
O	1.5

Figure 17. Input Severity Specific

The next inputs have to do with the cost of installing and maintaining the proposed countermeasure. During the development of the tool, incorporating the cost values into the presets with the CMFs was considered. However, due to vastly differing costs across the country, and the desire to have this tool be usable easily by any jurisdiction, it was determined that leaving the cost values as an input for the analyst would allow for the most flexibility for the tool. The first of these two inputs calls for the capital expense cost per mile, or the initial installation cost. The second of these two inputs calls for the yearly maintenance cost per mile. As with the capital expense cost, this is left as a numeric input by the analyst. The values for these two cells are restricted to values greater than 0 for the capital expense and greater than or equal to 0 for the maintenance cost. The values seen in the sample input in Figure 8 are for cable barrier installation in the Greater Minnesota area. As of December 2016, the Minnesota DOT estimated that cable barrier cost $140,000 to $150,000 per mile to install and $6000 per mile per year in maintenance (MnDOT 2016).

The decimal discount rate is another analyst input, which is used to allow for inflation to be taken into account when looking at the value of the benefits and costs in the future. Default values for this field can range from 0.025 to 0.04.

Service life is the final input used in calculations. The number of years that a countermeasure is in the field determines the total cost of the countermeasure (given the maintenance costs) as well as the total benefit (given the crashes prevented each year).

4.1.3 Analysis information

This group of inputs, seen in Figure 18, is used for identification of the site in question and the person who is running the analysis. The first input is the name of the treatment being considered. This allows easy identification of which countermeasure is being evaluated for a given benefit/cost ratio in the saved outputs tab for later comparison. The next field is for facility name. This can be however specific the analyst desires. The 3rd field is the town and state where the facility is located. This information can be used in conjunction with the previous input to determine the specific street. The 4th field is the date the analysis was conducted. The final input is the name of the analyst.

Treatment	Cable Median Barrier
Facility Name	Random Rd
Town, State	Paradise, MI
Date of Analysis	2/1/2017
Conducted by	Patty Thompson

Figure 18. Analysis Information on Inputs Tab

4.2 Calculation Tabs

This series of tabs is used for the intermediate calculations. The proportions of crashes for each severity level are determined on the SDF Proportions tab as seen in Figure 19. Values from the inputs are inserted into the SPF equations from chapter 3 to calculate the predicted crashes on the Crashes tab, Figure 20. The CMFs are also applied on that tab. The net change in crashes is then used to calculate the total comprehensive crash costs associated with the countermeasure on the BenefitCost tab (Figure 21) and present values of the benefits and costs are determined. The following sections will go into more detail on what the tabs contain.

4.2.1 SDF proportions

This tab (shown in Figure 19) calculates the proportions of FI crashes that fit into each severity type on the KABCO scale. Using the models presented in section 3.2, the values of the utility functions for K, A, and B crashes are calculated. Following that, the proportions of the K, A, and B crashes can be calculated. The proportion of C crashes is found by subtracting the proportions of the other 3 severities from 1.

Injury Type	Utility Function
K	-4.261
A	-2.521
B	-1.167
Proportion of FI Crashes	
K	0.010035794
A	0.057177366
B	0.221441428
C	0.711345411

Figure 19. SDF Proportions Tab

4.2.2 Crashes

This tab (displayed in Figure 20) contains the calculations for the SPFs. PDO crashes

and FI crashes are calculated based on the inputs outlined in section 4.1. Using these

numbers, the total crashes are calculated. Once the total crashes predicted are known, it

applies the CMFs. In the cases where a single CMF applies to all severity types, then the one

value is multiplied to each of the predicted crashes. In the cases where there are severity

specific CMFs, the appropriate CMF value is multiplied to each severity. After the predicted

crashes post countermeasure installation are calculated, the total crashes reduced are

determined by subtracting the post CMF crashes from the predicted totals.

PDO Crashes				FI Crashes		
Intercept	-6.45			Intercept		-10.221
AADT	0.814			AADT		1.041
Regional Effect	0.29			Regional Effect		0
SPF Calculated Crashes	30.0296			SPF Calculated Crashes		4.7539
	K	A	B	C		O
Total Crashes	0.9542	5.4363	21.0541	67.6331		600.5912
	K	A	B	C		O
PostCMF Crashes	0.7633	4.8927	20.0014	67.6331		900.8868
	K	A	B	C		O
Crashes Prevented	0.1908	0.5436	1.0527	0.0000		-300.2956

Figure 20. Crashes Tab

4.2.3 BenefitCost

The BenefitCost tab (pictured in Figure 21) shows the calculations for the benefit/cost

ratio. First, the monetary value of the crashes after the safety countermeasure is installed is

calculated. In cases where the treatment increases crashes for some severity levels, these

values will be negative. The total of the values is the present value of the crashes per year. To

compare all costs and benefits in the current year, a formula is used that calculates a

multiplier for the present value of an annuity given the number of years and an interest rate

(FHWA 2016). These values are taken from the inputs, as the service life of the

countermeasure and the discount rate. The formula used is as follows:

$$(P|A, I, n) = \frac{(1+I)^n - 1}{I*(1+I)^n}$$
4.1

where:

  I = discount rate

  n = service life

The result of this equation, $(P|A,I,n)$, is multiplied to the present value for 1 year to

calculate the total value over the service life. The same value is multiplied to the maintenance

cost, to determine the present value of the yearly maintenance. The present value of the

benefits and the present value of the costs are both summed. The benefit value is then divided

by the cost value to determine the benefit cost ratio.

If this value is greater than 1, then from an economic standpoint, the safety

countermeasure being examined would be a net benefit. The larger the number, the greater

the benefit is in comparison to the cost of implementation and maintenance. If this value is

less than one but is still positive, then the costs outweigh the benefit and the countermeasure

is not feasible from an economic standpoint. If the value is negative, then there is no

economic benefit at all and the countermeasure is not feasible.

Crash Type	Total	
K	$	765,042.70
A	$	117,423.93
B	$	83,163.87
C	$	-
O	$	(2,222,187.43)
Total, PV	$	(1,256,556.94)
(P|A,I,n)		13.59032634
PVB	$	(17,077,018.85)
Installation Costs	$	700,000.00
Yearly Maintenance	$	30,000.00
PVMaintenance	$	407,709.79
PVCosts	$	1,107,709.79
Benefit/Cost Ratio		-15.4

Figure 21. BenefitCost Tab

4.3 Tables and Lists

  The backbone of the spreadsheet is the Tables and Lists tab (excerpt in Figure 22),

which contains all the lists and cell references used to make the spreadsheet work. Changes

to this spreadsheet are unnecessary for normal use, except when modifying the tool to use

SPFs and SDFs calculated for the local area, and have the potential to break the tool if

changed accidentally. However, it is not possible to lock this spreadsheet to prevent

accidental editing (as is done for the calculations tabs) because the user does need the

capability to edit this spreadsheet in order to modify the tool for their jurisdiction. Therefore,

the tab is simply hidden from view during normal use.

This tab contains all the lists used for the dropdown menus in the Inputs tab. The

coefficients for the SPFs and SDFs are present in this tab as well. All the cell references

between sheets are done using named cell ranges, for reasons discussed in Chapter 5.

Facility Type	Terrain	Region	
2U	Level	Superior	Rumble S
3T	Rolling	North	Lane Diet
4U		Grand	Cable Bar
5T		Bay	
4D		University	
6D		Southwest	
8D		Metro	

Figure 22. Section of Tables and Lists Tab

4.4 Output Tables

The summary table presents the results of the calculations, as seen in Figure 23. The

analysis information (from section 4.1.3) is all listed in the summary table, as well as the

benefit/cost ratio, present value of both the benefits and the costs, the net changes in crashes,

and the AADT and length values, as well as the service life and discount rate used. Included

on the tab are 3 buttons. The first button, labeled 'Copy Data to Saved Outputs' does exactly

that. Pressing it copies the formatting and values of the summary table to the saved outputs

tab. The second button, labeled 'Go To Saved Outputs' makes the Saved Outputs tab the

active tab. The third button, 'Return to Inputs', makes the Inputs tab the active tab. These

buttons are used to make it easier to navigate between tabs, as well as save the data from the

summary table so that more iterations can be completed.

Location	Paradise, MI			Facility Name	Random Rd
Date	2/1/2017			Conducted by	Patty Thompson
Facility Type	4D				
				Proposed Treatment	Cable Median Barrier
Benefit/Cost Ratio	10.53				
				Service Life	20
Present Value of Benefits	$ 11,665,748.17			Discount Rate	4%
Present Value of Costs	$ 1,107,709.79				

Net Crash Changes due to Countermeasure				
K	A	B	C	O
-0.870	-5.812	-10.701	-34.375	847.548

| AADT | 30000 |
| Length | 5 |

Figure 23. Summary Table

The Saved Outputs tab provides the same information as the summary tab, the only difference being that the Saved Outputs tab contains only information saved using the button on the summary tab and will have each successive summary tables pasted 1 row down from the previous one. There are 3 buttons on this tab, pictured in Figure 24. The first clears all the data on the tab. Since this cannot be undone, as the deletion is done using Visual Basic code, a confirmation box pops up to make sure the analyst wants to delete the data. The other two buttons change the active sheet back to Inputs and Summary respectively.

| Clear Saved Outputs | Return to Inputs | Return to Summary |
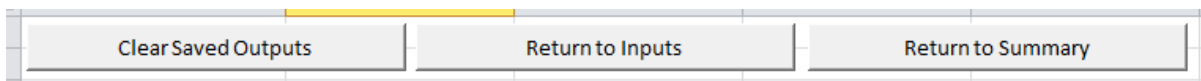
Figure 24. Saved Outputs Buttons

4.5 Visual Basic Code

For the most part, the Visual Basic code in the spreadsheet is limited. Its primary purpose is for ease of use and ease of accessibility. Modifications to the tool should not need to include modifications to the Visual Basic code. The buttons used to navigate between the Inputs, Summary, and Saved Outputs tabs were coded using Visual Basic by creating macros which were assigned to buttons. The button that saves the data selects the entirety of the

summary table, copies it, and pastes it into the Saved Outputs tab. The code 'remembers'

where the last tables was placed and puts each subsequent table 1 row further down the tab so

that previously saved tables are not overwritten by the new ones. A specific paste command

is used, so that only the values and number formats are copied, not the formulas, so that the

numbers on the Saved Outputs tab do not change when new inputs are added.

All the tabs in the spreadsheet, bar one, are locked through Visual Basic code as well.

Any time anything changes on the tab, the sheet will re-lock. This is the reason that the

TablesandLists tab is hidden and not locked, as it would be much more difficult to modify

the tables if the tab had to be unlocked after every single change.

The Inputs tab uses Visual Basic for more than just buttons. Depending on the option

selected in cell B8 (CMF option: Preset, Input Single Value, Input Severity Specific),

different rows are visible. This is done using Visual Basic code to only display the rows that

match with the option selected from the dropdown menu. Also, though the analyst is allowed

to modify values in cells B1 through B25, all other cells on the tab cannot be edited without

unlocking the spreadsheet first.

CHAPTER 5: TOOL MODIFICATION

This tool was developed to show how simple it is to use SPFs to provide fast and simple project-planning level analyses. The ability to modify the tool for use in other jurisdictions is an important part of its development. By integrating SPFs and SDFs that have been estimated for their own area, an agency can adapt the framework to allow for the same ease of use demonstrated using the Michigan equations. The predictive equations, the SPFs and the SDFs, are the obvious portions of the required information. Other lists that must be compiled include the types of facilities for which SPFs and SDFs are available, any locally derived CMFs to be added to the preset list, and local comprehensive crash costs, if values different from HSM provided are desired to be used. The methods for integrating the equations and lists are described in this chapter.

There are a few steps that must be undertaken by an agency to modify the tool for use in their area. The TablesandLists tab is hidden in the spreadsheet, to prevent accidental changes to the values. Therefore, in order to change the coefficients for the predictive equations, the lists (such as regions or facility types), the preset CMFs, and the comprehensive crash costs, the tab must be made visible. Step by step instructions with screenshots are in the Instructions tab in the spreadsheet. To unhide the TableandLists tab, the analyst must right click on any tab, select 'Unhide', and click OK with TablesandLists selected. This shows the tab.

The use of named cell ranges allows for the modification of the size of the various ranges used without having to modify every reference to the range in the spreadsheet. This is the reason that the named ranges were used. For example, rather than having to go to every cell where the SPF coefficients are referenced to change the cell references, the cells the

name refers to can be changed instead. Table 13 presents the list type and name of the range

for the values most likely to be modified. To modify the dropdown lists, the values present

can be simply overwritten. If the new list is smaller or larger than the previous, then the cell

ranges should be changed.

Table 13. Named Cell Ranges

List	Named Range
Facility Type	FacilityType
Terrain	Terrain
Region	Region
SDF Coefficients	SDFTable
SPF Coefficients	SPFTable
CMF Presets	PresetList

5.1 SPFs and SDFs Modification

To modify the SPFs or the SDFs, the values must be formatted in the manner that the

current tables are formatted. The required naming convention for the SPF coefficients to

function properly consists of <Facility Type><Coefficient Type>. For example, the intercept

term for a 4U segment would be listed as 4UIntercept. The AADT coefficient for an 8D

segment would be listed as 8DAADT. If the jurisdiction facility types match those used for

Michigan, the values in column A may be used for the intercept and AADT terms without

modification if care is taken to make sure the correct model values are assigned to the labels..

These values can be seen in Figure 25. Regional indicator names (or other single additional

variable) can be created using the concatenate function to combine the names to follow the

convention <Facility Type><Variable Name>. If regions are used, it is important that the

name value in column A for the regional indicators, such as 2USuperior, matches the value in

cell P2. The value in cell P2 is automatically generated based on the inputs selected on the

Inputs tab and is used to select the 3rd variable coefficient from the SPF coefficients table.

For this reason, all the possible combinations of facility type and variable should be represented in the table. This can be seen in Figure 26.

	A	B	C
14		FI	PDO
15	2UIntercept	-8.016	-3.96
16	3TIntercept	-10.673	-8.923
17	4UIntercept	-12.655	-7.543
18	5TIntercept	-13.76	-10.117
19	4DIntercept	-10.221	-6.45
20	6DIntercept	-11.566	-10.806
21	8DIntercept	-14.194	-12.527
22	2UAADT	0.856	0.566
23	3TAADT	1.1	1.085
24	4UAADT	1.33	0.941
25	5TAADT	1.446	1.206
26	4DAADT	1.041	0.814
27	6DAADT	1.189	1.255
28	8DAADT	1.437	1.405
29	2USuperior	-0.416	-0.108
30	2UNorth	-0.233	0.132
31	2UGrand	0	0.376

Figure 25. SPF Coefficient Table

	N	O	P	
1		Inputs to Usable		
2		Type&Region	2USuperior	
3		TerrainIndicator	1	
4		LNAADT	10.30895	
5		FacilityIntercept	2UIntercept	
6		FacilityAADT	2UAADT	
7		Divided	0	
8				

Figure 26. Input Conversion Cells

5.2 CMF Preset Modification

CMF presets were used to allow for frequently used values to be included for easy access. The dropdown list on the inputs tab displays the values in column D in Figure 27. The default range for the list is from row 1 to row 6. If more values are added, the range can be changed in the name manager. This interface can be found in the Formulas tab, as seen in Figure 28. The name for the list cell range is PresetList, as seen in Table 13. The numbers in column E are used for selecting the column in the CMF array for the selected CMF values. The CMF array, as seen in Figure 29, contains the name of the preset as well as the CMF values for each severity. CMFs that have a single value applied to all severity levels have the same number repeated for each row, while the severity specific CMFs change. The CMF values in cells G26 through G30 (Figure 29) are selected based on the option selected in the dropdown on the inputs tab. Cell G25 selects the column from the array below to mirror the values from. By using an intermediate column, the cell names that reference the CMFs for use on the Crashes tab do not have to change with different presets.

D	E
	1
Rumble Strips (0.99)	2
Lane Diet (4U to 3T) (0.53)	3
Cable Barrier (Severity Specific)	4
	5
	6
	7
	8
	9
	10
	11

Figure 27. CMF Dropdown List Options

Figure 28. Name Manager Location

Figure 29. CMF Presets

The cell ranges for the array and the numbers in column E (Figure 27) are set to handle 11 preset CMF values. However, as mentioned previously, the default number of presets available in the dropdown is only 6. This was done to reduce the amount of white space to scroll through in the dropdown list. Modifying PresetList will adjust the values seen in the dropdown. If more than 11 preset options are desired, the numbers in column E must be extended down to match the CMF descriptions in column D, the formula in cell Q32 should be copied over to the right for as many presets that are being added, the new end column should be noted, and the range PresetCMFArray should be extended to the new end column.

CHAPTER 6: CONCLUSION

6.1 Summary

The software tool created as part of this project is a proof-of-concept for the development of an easy to use method for determining a rough benefit/cost ratio for proposed safety countermeasures. The use of the SPFs allows for quick predictions of how many crashes will occur on the roadway, without having to look up historical crash rates and frequencies. This allows for simple estimates of the benefit/cost ratio, which can be used to determine which safety countermeasures should be explored more in depth. By using this method to sort the proposed treatments, the total number of full feasibility studies can be reduced by excluding those that are either obviously not cost effective or the least cost effective.

The current literature and software tools rely on historical crash frequencies and information about roadway characteristics. This tool fills a gap by relying on predicted crash frequencies to allow for faster calculations and higher efficiency. It can also be used as an educational tool, permitting students to understand how different roadway aspects, such as speed limit and AADT, can affect the cost efficiency of a safety countermeasure. However, its main purpose is to assist agencies in selecting projects to pursue full feasibility studies for.

6.2 Software Tool Uses

This software tool is intended to be used as a project-level planning tool. In order to facilitate the decision-making process, historical crash data is not needed to estimate the effectiveness of safety countermeasures using this method. The only information needed by decision makers includes: facility type; AADT, which is measured by municipalities and DOTs and is most likely available in a map format on the appropriate website; speed limit,

which should be known if a countermeasure is being proposed; length of the section; type of

terrain; and information about the various countermeasures under consideration.

This differs from some software tools available that utilize time-of-return (TOR)

calculations. For example, examining one such spreadsheet from the Michigan DOT shows

that it relies on historical crash data for the previous five years and estimates the number of

crashes that will occur in the future based on an AADT growth factor. This may work

reasonably well for the facility types where crashes are elastic with respect to AADT, but

will over or underestimate the crashes when the coefficient for AADT in the facility's SPF is

not near 1.0. This type of analysis also requires the historical crash data, which must be

pulled from the crash database.

The intended use of this spreadsheet tool is to get a yes or no answer to the question

of whether or not a safety countermeasure should be evaluated further for implementation at

a specific location. This question is answered using the magnitude of the benefit/cost ratio,

whether it is greater than or less than 1.0. However, it can also be used to get an estimate on

the relative 'potential success' of the proposed countermeasures by comparing the

benefit/cost ratios. Likewise, it allows an estimate of how the benefit/cost ratio would change

if there was a future change in facility type, increase or decrease in AADT, or changes in the

speed limit as well, allowing it to explore and evaluate all kinds of possibilities while

remaining rooted in solid statistical analysis. This can help identify areas where further study

will offer the most 'bang for the buck,' both now and in the future.

6.3 Tool Limitations

As with any software tool, there are limitations. The software tool can only predict

crashes based on the SPF coefficients. It does not account for high observed crash rates.

Given this, it does not replace the need for an Empirical Bayes (EB) type analysis for a full

feasibility study on a specific safety countermeasure, which will take into account the historical crash data for a particular site as well as the SPF predictions. Therefore, the estimates given by the tool are intended to be guidance for a project-planning level only.

Additionally, this tool does not address one-way road segments because of the small data set available for one-way segments. Although it is possible to produce an SPF for these segments, there is not sufficient data to calculate an SDF (specifically because higher severity crashes are too rare in the small sample size to produce a statistically meaningful estimate). Rather than use the SDFs calculated for a two-way segment, which would introduce their own inaccuracies in the calculations, the decision was made to exclude one-way segments from the analysis, since it is not possible to calculate the benefit/cost ratio without the SDF. It would be possible to easily modify the tool to include the one-way segments, but the challenge of which SDFs to use for the calculations remains. If the two-way segment SDFs are used, caution should be employed when evaluating the benefit/cost ratios produced by the model, as the SDFs were not developed for that specific road type. However, this limitation should have a minor impact on the usage of the tool, as one-way segments are rarer and experience lower severity crashes.

6.4 Future work

Like the TOR spreadsheet mention in section 6.1, this software tool could be improved by adding ability to include a growth factor for AADT in the future years. Currently calculations are done assuming a static AADT across the timespan evaluated, which does not account for the potential for changes in AADT affecting the benefit/cost ratio in later years. The simplest approach would be to add space for a single growth factor, but a more robust implementation would allow the user to input a function for growth. Another

improvement could come from adding in the capability of using historical crash data to conduct an EB type analysis. This could improve the benefit/cost ratios calculated by combining observed crashes with the predicted values, but would require more data from the user and thus should only be implemented as an optional approach, in order to maintain the usability of the tool in situations where the data available is limited.

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