Development of Safety Benefit Factors for New Location and Widening Projects for Use in the STI Scoring Process

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16. Abstract

Safety is a key component of the project scoring process conducted by NCDOT as part of the 2013 Strategic Transportation Investments (STI) law. For most improvement types in the STI process, Safety Benefit Factors (SBFs) are used to quantify the benefits expected from a reduction in crashes stemming from a given project. This study fills a gap that currently exists in the safety component of the STI process and enhancing the current state of knowledge on how new location projects (e.g. bypass, road extensions, etc.) and widening projects (e.g. rural and urban areas, widening to multi-lane divided facility, etc.) can impact safety. Taking into account the limited amount of data available at the time projects are scored, the research team developed SBFs and guidance that can be easily integrated into the current scoring process. Consistent with NCDOT's method of selecting SBFs, the research team focused on incorporating practices from the Highway Safety Manual (HSM) as well as existing crash modification factors (CMF) knowledge from research studies. In total, this study resulted in the generation of 10 new SBFs for NCDOT and the confirmation of 2 SBFs already utilized by NCDOT, as outlined in the following table. Additionally, approaches for developing SBFs using North Carolina project and crash data were also developed through this research. These findings and approaches can be used by NCDOT into the future to develop more reliable estimations of safety benefits for proposed projects, and ultimately improve the quality of North Carolina transportation projects developed in the future

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Executive Summary

Safety is a key component of the project scoring process conducted by NCDOT as part of the Strategic Transportation Investments (STI) law. For all highway improvement types in the STI process, Safety Benefit Factors (SBFs) are used to quantify the benefits expected from a reduction in crashes stemming from a given project. SBFs are designed to estimate the safety benefits that can be expected with the implementation of a specific project type with particular characteristics. While NCDOT utilizes evidence-based SBFs for numerous project types, the agency lacks SBFs for some types of projects because data needed to make reliable estimates of crash reductions is not always readily available at the time projects are being scored. Additionally, safety research on certain types of projects can be limited or unavailable.

This study fills a gap that currently exists in the safety component of the STI process and enhancing the current state of knowledge on how new location projects (e.g. bypass, road extensions, etc.) and widening projects (e.g. rural and urban areas, widening to multi-lane divided facility, etc.) can impact safety. Evidence-based safety research for new location and widening projects is limited, which makes evaluating the impact of such projects difficult. Consequently, this research focuses on developing evidence-based SBFs for these types of projects to enhance and increase the accuracy of safety estimates in the STI process.

Taking into account the limited amount of data available at the time projects are scored, the research team developed SBFs and guidance that can be easily integrated into the current scoring process. Consistent with NCDOT's method of selecting SBFs, the research team focused on incorporating practices from the Highway Safety Manual (HSM) as well as existing crash modification factors (CMF) knowledge from research studies.

For new location projects involving the introduction of a bypass roadway, the research team applied a naïve empirical Bayesian (EB) before-after method to develop SBFs. This approach considers the before period to comprise only the original roadway, whereas the after period to comprise of both the original roadway and the bypass. SBFs for relevant widening project types were developed use of Safety Performance Functions from the 1st edition of the HSM that were calibrated using North Carolina data. Additionally, other SBFs were recommendations based on an analysis of relevant studies in the FHWA Crash Modification Factors Clearinghouse that provided SBFs with a quality rating of 4 (out of 5) stars or higher.

In total, this study resulted in the generation of 10 new SBFs for NCDOT and the confirmation of 2 SBFs already utilized by NCDOT, as outlined in the following table. Additionally, approaches for developing SBFs using North Carolina project and crash data were also developed through this research. These findings and approaches can be used by NCDOT into the future to develop more reliable estimations of safety benefits for proposed projects, and ultimately improve the quality of North Carolina transportation projects developed in the future.

Specific Improvement Type (SIT) Group	Project Type	Area Type	Current NCDOT SBF	Recommended SBF	Source of Recommendation
5 - Construct Roadway on New Location	Freeway Bypass	Urban/ Rural	10	20	Developed through this study
	Superstreet Bypass	Urban/ Rural	5	30	Developed through this study
	All other projects	Urban/ Rural	-	30	Developed through this study
1 - Widen Existing Roadway	Widen 2 lane roadway to 4 lane divided roadway	Rural	55	60	Developed through this study
	Widen 2 lane roadway to 4 lane divided roadway (w/o controlled access)	Urban	-	0*	CMF Clearinghouse
	Install two-way left turn lane on a two lane roadway	Urban/ Rural	20	20	CMF Clearinghouse
	Install two-way left turn lane on a two lane roadway	Urban	-	0	Developed through this study, matches CMF Clearinghouse
	Install two-way left turn lane on a two lane roadway	Rural	-	30	Developed through this study
	Widen 4 lane undivided roadway to 4 lane divided roadway	Urban	-	20**	Developed through this study
	Widen 4 lane undivided roadway to 5 lane roadway	Urban	-	30	Developed through this study, matches CMF Clearinghouse
	Widen 4 lane divided roadway to 5 lane roadway	Urban	-	0	Developed through this study
	Widen 4 lane divided roadway to 6 lane divided roadway	Urban	15	15	CMF Clearinghouse

*Use with caution: SBF developed through this study shows no change in crashes, while CMF Clearinghouse SBF shows 65% crash reduction based on multiple sections of the same roadway

**Use with caution due to limited sample available for calculations

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1. Introduction

In 2013, North Carolina established the Strategic Transportation Investments (STI) law, which is focused on efficiently and effectively allocating transportation funding. The law also established the Strategic Mobility Formula, which allocates available revenues based on data-driven scoring and input from regional and local governments. The North Carolina Department of Transportation Strategic Prioritization Office (SPOT) guides the implementation of this law. Through the SPOT process, projects are compared using quantitative data to identify the projects that are most likely to enhance infrastructure while supporting economic growth, job creation, and a higher quality of life.

Safety is a key component of the STI scoring process. For all highway improvement types in the STI process, Safety Benefit Factors (SBFs) are used to quantify the benefits expected from a reduction in crashes stemming from a given project. SBFs are designed to estimate the safety benefits that can be expected with the implementation of a specific project type with particular characteristics. While NCDOT utilizes evidence-based SBFs for numerous project types, the agency lacks SBFs for some types of projects because data needed to make reliable estimates of crash reductions is not always readily available at the time projects are being scored. Additionally, safety research on certain types of projects can be limited or unavailable.

This study fills a gap that currently exists in the safety component of the STI process and enhancing the current state of knowledge on how new location projects (e.g. bypass, road extensions, etc.) and widening projects (e.g. rural and urban areas, widening to multi-lane divided facility, etc.) can impact safety. Evidence-based safety research for new location and widening projects is sparse, which makes evaluating the impact of such projects difficult. Consequently, this research focuses on developing evidence-based SBFs for these types of projects to enhance and increase the accuracy of safety estimates in the STI process.

The research team worked closely with NCDOT to identify and interpret required data as well as prioritize approaches based on their needs and preferences. Consistent with NCDOT's method of selecting SBFs, the research team focused on incorporating practices from the Highway Safety Manual (HSM) as well as existing crash modification factors (CMF) knowledge from research studies. The result of this research are evidence-based SBFs and guidance that can be easily integrated into the current STI process.

2. Study Objective

The impetus for this research is a critical need to improve and extend the Safety Benefit Factors used within the STI process for various types of new location projects (bypass, loop, road extensions, etc.) and widening projects (urban widening, widening to a multi-lane divided facility, widening to a superstreet facility, etc.). NCDOT lacks evidence-based SBF data and evaluation methods for these types of projects, which presents challenges when forecasting how such transportation investments will impact the safety of the proposed infrastructure investment. To address this problem, this study focused on refining SBFs and associated methods for specific types of new location projects and widening projects in the STI process.

The primary objectives of this research are:

- Develop an explanation of how new location and widening projects are considered in the STI process.
- Review current SBFs, including how they are used currently in the STI process, and present those results to NCDOT.
- Develop and discuss new location and road widening SBFs and evaluation methods based on the literature and best practices used in other states with the NCDOT Strategic Prioritization Office.
- Evaluate new measures through use cases and, where appropriate, discuss how prioritization of new location and widening projects might change in STI.
- Provide guidance for integrating revised SBFs and associated methods into the STI process.
- Develop a final report that summarizes these results.

This research will result in an expanded set of defensible SBFs and methods for evaluating the safety impacts of these specific types of improvement projects, with the goal of producing more accurate safety benefit estimates as part of the NCDOT project prioritization process.

3. Literature Review

The literature review is organized into several sections. First, this literature review provides basic definitions of widening and new location projects, as well as commonly used crash modification factor terms. Next, this review discusses safety methods used in other states. Key findings from the case studies reviewed are also discussed. The appendix of this report provides detailed information for each case study.

3.1 Safety Benefit Factors

Safety Benefit Factors (SBFs), which are related to Crash Modification Factors (CMFs), are a key method used across the world to evaluate the change in the number and type of roadway crashes that may occur due to a new geometric configuration, treatment, or the addition of another strategy. A number of national studies focus on the development of quality CMFs (Gross, Persaud, and Lyon, 2010). For example, in recent years, studies have estimated CMFs for signal installation, roadway lighting, and the safety effects of shoulder widths, among many other treatments (Aul and Davis, 2006; Shahdah, Saccomanno and Persaud 2014; Gross and Donnell, 2011). While these types of studies examine the safety benefits attributed to such transportation projects, the application of each resulting CMF in the planning phase is limited by variables such as the location of a project (urban vs. rural), volume, and the research study sample sizes.

This study will build upon existing literature to identify and recommend new SBFs for new location and widening projects in the STI scoring process. The impact of past projects conducted by the research team helped provide additional clarity on the use of SBFs in its project planning and operations practices. In particular, efforts were made to draw inferences between transportation investments and safety outcomes at the project level based on the proposed changes recommended by this research team.

3.2 Crash Modification Factors

Crash Modification Factors (CMFs) are a multiplicative factor used to compute the expected number of crashes after implementing a given countermeasure at a specific site. The CMF is multiplied by the expected crash frequency without treatment. A CMF greater than 1.0 indicates an expected increase in crashes, while a value less than 1.0 indicates an expected reduction in crashes after implementation of a given transportation countermeasure. For example, a CMF of 0.8 indicates a 20% expected reduction in crashes, while a CMF of 1.2 indicates a 20% expected increase in crashes (USDOT, 2010).

Although implementing several countermeasures is likely more effective than implementing a single countermeasure, it is unlikely that the full effect of each countermeasure would be realized when implemented concurrently. This is particularly true if the countermeasures target the same crash type (e.g., installing lighting and enhancing pavement markings to address nighttime crashes). Therefore, unless the countermeasures act completely independently and target unique crash types, multiplying several CMFs is likely to overestimate the combined effect. The likelihood of overestimation increases with the number of CMFs that are multiplied. Therefore, caution and engineering judgment should be exercised when estimating the combined effect of multiple countermeasures at a given location. Ideally, a CMF for a combination treatment should be derived directly from a rigorous before-after evaluation of sites where the combination treatment was applied.

3.3 Assessing the Safety Impacts of Widening and New Location Projects

Reducing the number of injuries and fatalities on North Carolina roads can be achieved through comprehensive consideration of safety in transportation planning, design, management, and operations. To accomplish this goal, knowledge of the safety factors and countermeasures which may be applied to improve safety are needed, as well as tools for facilitating application of that knowledge (AASHTO, 2010). Accurately predicting the safety effects of engineering countermeasures by determining the most optimal safety factors can improve the transportation decision-making process from the safety perspective (Herbel et al., 2010). However, the approaches used to assess these safety impacts and the level of safety improvements realized can vary depending on the type of new location or widening project.

Developing safety factors for new location projects, like the addition of bypass roads, can be especially challenging due to the complexity of network-level changes involved in these types of projects. Such challenges observed in the literature include those associated with impacts from vehicle volume changes, differences in the number and types of controlled intersections for the original routes versus the bypasses, the length of time many of these projects take to construct (and construction phasing), and changes in traffic conditions over these time periods.

The case of the Indiana Department of Transportation highlights the complexities involved in assessing the safety impacts of new location projects. The Indiana Department of Transportation identified a need to update Indiana Crash Reduction Factors (CRFs), which reflect the percentage crash reduction that might be expected after implementing a given countermeasure at a specific site, and increasing the size of the CRF database by adopting applicable CRFs for other regions similar to Indiana. As part of this effort, Tarko, Dey, and Romero (2015) conducted a safety study for Indiana in 2015 that included the development of CRFs for geometric safety improvements on rural and urban road segments. For these safety improvements, other regions with similar driving cultures and weather to Indiana have conducted recent CRF studies. Following this comprehensive analysis, INDOT revisited scoping road improvement and design projects and advancing their development with a new emphasis on using a systemic approach and cost-effectiveness. A new design paradigm based on ‘‘practical design,’’ with a focus on safer design solutions that are budget-conscious, was formulated and is now being implemented in Indiana (Park et al., 2015).

Regarding CMFs for new location and widening projects, Park, Abdel-Aty, Wang, and Lee (2015) assessed the safety effects for widening urban roadways in developing CMFs, finding that widening urban roadways can be effective in reducing crashes, however, safety benefits can vary depending on the roadway characteristics (Park et al., 2015). Lee, Abdel-Aty, and Wang (2015) developed CMFs for changing lane widths for roadway segments based on non-linear relationships between lane width and crash rates. Finally, Fitzpatrick, Lord, and Park (2008) developed new factors for median characteristics on urban and rural freeways and on rural multilane highways. For this research, equations were developed for urban and rural medians with rigid barriers, urban medians without barriers, and rural medians without barriers (Fitzpatrick et al., 2008).

3.4 Relevant Crash Modification Factors Identified

In an effort to build upon existing literature related to the safety benefits of new location and widening projects, the research team conducted a thorough review of safety studies both from the United States and internationally. The following table presents the results of a comprehensive analysis of the literature associated with project types NCDOT relevant to this research study.

Exhibit 1 and Exhibit 2 outline the findings from a scan of available Crash Modification Factors for new location and widening projects respectively. These studies primarily utilize data from the United States and some incorporate North Carolina data specifically. As shown, there are several well-rated CMFs available for several widening project types. However, the research team was not able to identify any reliable CMFs for the new location types of interest, likely due to many of the limitations outlined in the previous section.

Due to the limited number of CMFs identified, the research team sought out additional literature, including studies from outside of the United States. The results of this effort are presented for new location projects in Exhibit 3, Exhibit 4, and Exhibit 5, which summarize the results from the ten relevant studies identified, all of which are from Europe. In some cases, English translations of these studies were not available.

Of those available in English, Elvik et al. (2001), which produced a CMF of .81, was the most applicable and relevant. This research is more recent than many of the other European studies explored, applied a comprehensive approach to a reasonable sample size, and utilized methods to measure of safety impacts of bypass roads in a manner that most closely aligns with the approaches used in this NCDOT project.

Exhibit 1. Crash Modification Factors: Findings from US Literature – Widening Projects

Improvement Type	Current NCDOT Safety Benefit Factor (% Reduction)	Segment/ Point Location	CMF Clearinghouse			
			No. of CMFs	CMF Range	Includes NC Data?	Max. Star Rating
1A - Widen Existing Roadway - Add lane to Freeway	10	Segment	3	0.74-0.76		3
1B - Widen Existing Roadway - Widen 2 lane roadway to 4 lane divided - Rural	55	Segment	5	0.55-0.79		4
1C - Widen Existing Roadway - Install two-way left turn lane on a two lane roadway - Urban/Rural	20	Segment	15	0.47-1.02	✓	5
1D - Widen Existing Roadway - Widen 2 lane roadway to 4 lane divided Superstreet with Partial Control of Access - Urban	15	Segment				
1E - Widen Existing Roadway - Widen 2 lane roadway to 4 lane divided with Partial Control of Access - Urban	10	Segment				
1F - Widen Existing Roadway - Widen 4 lane divided roadway to 6 lane divided - Urban	15	Segment	24	0.66-1.25		4
1G- Widen Existing Roadway - All other projects	N/A	Segment				
1G.1 - Widen Existing Roadway - Widen 2 lane roadway to 4 lane divided roadway - Urban (without controlled access)			*5*	*0.24-0.47*		*4*
1G.2 - Widen Existing Roadway - Widen 4 lane roadway to 5 lane roadway - Urban			*18*	*0.18-1.11*		*4*
1G.3 - Widen Existing Roadway - Widen 2 lane roadway to 4 lane divided roadway - Urban/Rural			*3*	*0.25-1.05*		*4*
1G.4 - Widen Existing Roadway - Install two-way left turn lane on a two lane roadway - Urban			*4*	*0.91-1.05*	✓	*4*
1G.5 - Widen Existing Roadway - Install two-way left turn lane on a two lane roadway - Rural			*7*	*0.49-0.83*	✓	*5*
1G.6 - Widen Existing Roadway - Widen 6 lane divided roadway to 8 lane divided roadway - Urban			*1*	*1.4*		*2*

Exhibit 2. Crash Modification Factors: Findings from Literature – New Location Projects

Improvement Type	Current NCDOT Safety Benefit Factor (% Reduction)	Segment/ Point Location	CMF Clearinghouse				Alternate Resource (If CMF not available in CMF Clearinghouse)
			No. of CMFs	CMF Range	Includes NC Data?	Max. Star Rating	
5 - Construct Roadway on New Location							
5A - Construct Roadway on New Location - Freeway Bypass	10	Segment	No CMFs Available				1. Cena *et al.* (2011) looked at the effect of highway bypasses on crashes and crash rates in Iowa. 2. Elias *et al.* (2006 and 2011) looked at the influence of a bypass road on urban development and safety in Israel. 3. Elvik *et al.* (2001) looked at the effects on injury crashes of bypass road projects in Norway. 4. Egan et al. *(2003) summarizes the injury effects of new roads (urban roads, bypasses, major connecting roads) in various European countries.*
5B - Construct Roadway on New Location - Superstreet Bypass	5	Segment	No CMFs Available				
5C - Construct Roadway on New Location - All other projects	N/A	Segment	No CMFs Available				
6 - Widen Existing Roadway and Construct Part on New Location							
6A - Construct Roadway on New Location - Freeway Bypass	10	Segment	No CMFs Available				See references above.
6B - Construct Roadway on New Location - Superstreet Bypass	5	Segment	No CMFs Available				
6C - Construct Roadway on New Location - All other projects	N/A	Segment	No CMFs Available				

Exhibit 3. Crash Modification Factors: Findings from European Literature – New Location Projects

Study Details	Country	Methodology	Sample Size	CMF		
				Total Crashes	Fatal Crashes	Injury Crashes
5 - Construct Roadway on New Location - Bypass Construction						
Andersson PK, Lund BLC, Greibe P. Omfartsveje: den trafiksikkerhedsmæssige effekt. Copenhagen, Denmark: Danmarks TransportForskning; 2002.	Denmark	Not in available English	11	-	0.96	0.94
Elvik R, Amundsen FH, Hofset F. Road safety effects of bypasses. Transportation Res Rec. 2001;1758:13–20.	Norway	a) Studied the effects of 20 bypass road projects on injury crashes in Norway. b) Used the empiral Bayes method to control for RTM and general trends - shows 19% reduction in injury crashes (a simple before-after analysis using the same data and not controlling for RTM and trends showed a 7% reduction in injury crashes) c) Compared the old road in the before period to combined old road and bypass in the after period. d) Also conducted a Meta-Analysis using results from 9 studies that studied the impact of bypass roads. These studies were conducted between 1962 and 2000 and use data from Great Britain (1), Norway (5), Germany (1), and Sweden (2). 5 of these studies were simple before-after, while 4 used comparison groups. the combined effect of all studies was calculated as (1) using fixed-effects model, 25% reduction in injury crashes and 20% reduction in PDO crashes, and (2) using random effects model, 26% reduction in injury crashes and 29% reduction in PDO crashes.	20	-	-	0.81
Jørgensen NO. The safety effects of a major infrastructure project. In: Euro Traffic '91: Congress Report. Aalborghallen, Denmark: Pan-European Traffic Congress; 1991:247–255.	Denmark	Not in available English	1	-	0.97	1

Exhibit 4. Crash Modification Factors: Findings from European Literature - New Location Projects (continued)

Study Details	Country	Methodology	Sample Size	CMF		
				Total Crashes	Fatal Crashes	Injury Crashes
Leeming JJ. Road Accidents: Prevent or Punish? London, England: Cassell; 1969.	United Kingdom	a) Studied the effects of 19 bypass road projects on injury crashes in Great Britain and Ireland. b) Before-after analysis with control group. Short study period, two years before and only one year after. c) Compared the old road in the before period to the combined old road and bypass in the after period. d) Also calculated 6% reduction in fatal crashes and 12% reduction in fatal and serious injury crashes, both not significant.	19	-	-	0.67
Cena L, Keren N, Li W, Carruquiry AL, Pawlovich MD, Freeman, SA. A Bayesian assessment of the effect of highway bypasses in Iowa on crashes and crash rate. Journal of Safety Research. 2011;42:241-252.	United States	a) Studied the effects of 19 bypass road projects on total crashes in Iowa. b) Used generalized Poisson model to estimate posterior distribution of the expected annual crash frequencies. c) For expected crashes on old alignment only - computed posterior means and sets of expected crash frequencies for main road before and after the construction of bypass - 44% reduction in total crashes. d) For overall expected crashes - computed posterior means and sets of expected crash frequencies for main road before the construction of bypass and sum of expected crash frequencies of main road and the bypass after the construction of the bypass - 66% reduction in crashes.	19	0.56 (old align) 0.34 (new align)	-	-
Newland VJ, Newby RF. Changes in crash frequency after the provision of by-passes. Traffic Eng Control. 1962;3:614–616.	United Kingdom	a) Studied the effects of 7 bypass road projects on injury crashes in Great Britain. b) Before-after analysis with control group. Before period varied between 12 - 30 months After period varied between 12 - 36 months. c) Compared the old road in the before period to the combined old road and bypass in the after period. d) Also calculated a 16% reduction in fatal and serious injury crashes, which was not significant.	7	-	-	0.75

Exhibit 5. Crash Modification Factors: Findings from European Literature – New Location Projects (continued)

Study Details	Country	Methodology	Sample Size	CMF		
				Total Crashes	Fatal Crashes	Injury Crashes
6 - Widen Existing Roadway and Construct Part on New Location - Major Urban Roads						
Jadaan KS, Nicholson AJ. Effect of a new urban arterial on road safety. Aust Road Res. 1988;18:213–223.	New Zealand	a) Investigates the effect of a two-lane undivided arterial road in New Zealand on crashes in the region of the arterial. b) Before-after study comparing crashes on a network of 54 links and 34 intersections around the new arterial road in the Christchurch metropolitan area. c) Used 4 years of before and 4 years of after data.	1	-	-	0.934
Sæverås OJ. Vestre innfartsåre: sammenligning av ulykkessituasjonen før og etter åpning av ny innfartsåre fra vest (ytre del). Bergen, Norway: Statens Vegvesen Hordaland, Trafikksikkerhetsseksjonen; 1998.	Norway	Not in available in English	1	-	-	0.915
Levine DW, Golob TF, Recker WW. Accident migration associated with lane-addition projects on urban freeways. Traffic Eng Control. 1988;29:624-629	United States	a) Investigates the effect of adding freeway lane using 2 case studies in California. b) Before-after analysis with control group - sites selected using criteria to minimize potential regression to the mean effects.	2	-	-	0.99
Amundsen and Elvik, Unpublished Data - 2001	Norway	Unpublished	4	-	-	0.96 0.81 (incl Sec Roads)

3.5 Practices of Other States

To further assess the state of the practice related to safety factors for new location and widening projects, total of five interviews were conducted with transportation officials in other states. The research team focused on acquiring data from state agencies and interactions with state personnel through professional organizations. Additional efforts to gain interview subjects included circulating a request for information through the state safety engineer listserv managed by Iowa State University and transportation planning networks. In all, the research team interviewed key staff members from the following states regarding their processes for incorporating SBFs or similar approaches into project prioritization: Virginia, Colorado, Kentucky, Ohio, and the North Central Texas Council of Governments. Through these interviews, the researchers gained a reasonable sample of experiences and data from different states/agencies facing challenges that were both similar and unique to that experienced by NCDOT. A summary of the key lessons learned for each case study are provided in the following sections, with further context from files and data shared by the subjects provided in the appendices.

3.5.1. Virginia

Virginia House Bill 2, signed by Governor Terry McAuliffe on April 6, 2014 and effective as of July 1, 2014, (as defined in § 33.2-214.1) required the development of a prioritization process that the Commonwealth Transportation Board (CTB) was to use for project selection by July 2016. The prioritization process evaluates projects using following factor areas: congestion mitigation, economic development, accessibility, safety, environmental quality and land use coordination (in areas with over 200,000 population). Factor areas are weighted differently across the commonwealth based on certain characteristics and may be weighted differently within each district. Candidate projects are screened to determine if they meet an identified need in VTrans, the Commonwealth’s long-range transportation plan, and to determine if they meet eligibility requirements.

Projects are scored based on an objective analysis applied statewide. SMART SCALE also requires that project benefits be analyzed relative to project cost. CTB policy requires the project benefits be analyzed relative to the amount of SMART SCALE funds requested, so the final SMART SCALE score is based on the project cost to the state. In 2017, the General Assembly adopted HB2241/SB1331 (as defined in § 33.2- 214.2) updating several items related to SMART SCALE. These bills provide the responsibility for the implementation of the SMART SCALE process to the Office of Intermodal Planning and Investment, which reports to the Secretary of Transportation in their role as the Chairman of the CTB. It also requires that the scores be released at least 150 days prior to the CTB action to include SMART SCALE projects in the Six-Year Improvement Program, or January of odd-numbered years. This will ensure there is always 5 months for public discussion of the results of the project evaluations. Additional information for this case study is provided in Appendix 1.

3.5.2. Colorado

Within the Colorado Department of Transportation (CDOT), the Safety and Analysis Programs group is responsible for leading and supporting ongoing statewide efforts to improve safety and quantify the benefits of safety improvements throughout the state. In 2020, CDOT embarked upon the development of the 2020-2023 Colorado Strategic Transportation Safety Plan (CDOT, 2020). The goal for this plan is to establish a collaborative and shared vision and mission for transportation safety in the state. One of the key components of this plan is an effort to address both severe crash types (e.g., infrastructure, crash reduction locations, intersections, and roadway departures) as well as programmatic elements (e.g., data, safety program coordination and cooperation, law enforcement, legislation, etc.) As part of this effort, CDOT has begun a new sub-initiative to better quantify the safety benefits of specific transportation improvements using a ranked approach. This approach, which is similar to VDOT, will identify and implement the most effective wide-scale systemic safety mitigation strategies in conjunction with implementing hotspot improvement projects. Examples of these strategies, which will be quantified through the development of crash modification factors, include rumble strips, median barriers, and fully protected left-turn phasing. CDOT will lead implementation with support from local city and county transportation departments as well as CDOT Region Traffic Engineers. While there's no specific guidance for widening and new location projects, the 2020-2023 Colorado Strategic Safety Plan establishes a framework by which these types of projects might be evaluated and prioritized as those measures are developed.

In addition to the 2020-2023 Colorado Strategic Transportation Safety Plan, as part of the Highway Safety Impact Program, CDOT uses two key methods for identifying locations with a potential for crash reduction: Level of Service of Safety (LOSS) and Diagnostic Analysis. Additional information on the calculation process is provided in Appendix 2. LOSS is based on the concept of Safety Performance Functions (SPF), while Diagnostic Analysis is developed around the idea of statistical pattern recognition. LOSS reflects how the roadway segment is performing in regard to its expected crash frequency and severity at a specific level of annual average daily traffic. It provides a comparison of crash frequency and severity with what is expected for that type of highway facility. While crash rates are commonly used to measure safety, they are often misleading since rates can change with Annual Average Daily Traffic (AADT).

Using the Crash Data System, CDOT has calibrated and deployed SPFs for all public roadways in Colorado, which were stratified by the number of lanes, terrain, environment, and functional classification for all roadway and intersection types. By using these three data sets, CDOT is able to gain a better picture of the roadway facilities and identify with better precision the locations with potential for crash reduction. CDOT ST&E Branch develops a statewide summary of locations with high potential for crash mitigation (LOSS III and IV) and locations with identified crash patterns. The summary is stratified by region. The regional summaries are distributed to the CDOT Regions for consideration in project identification (CDOT, 2016).

3.5.3. Kentucky

The Kentucky Transportation Cabinet (KYTC) applied the Systemic Safety Project Selection Tool (Tool) to a local road system. Through the Federal Highway Administration Focus State Initiative, KYTC staff had previously conducted systemic planning focused on roadway departure crashes on State highways. Based on crash issues identified in previous statewide data analyses, KYTC decided to move forward with roadway departure crashes on horizontal curves in an effort to test this key aspect of safety improvements on current highway characteristics. Through the use of crash data for the 2007-2011 timeframe and roadway attribute information from photo logs, a total of 92 segments along 217 miles of roadways in five counties were analyzed. Five key risk factors representing different roadway attributes were selected from the initial study:

- Horizontal curve density (number of curves per mile with a radius between 500 and 1,200 feet);
- Lane width;
- Shoulder type;
- Shoulder width; and
- Posted speed limit.

Next, each factor was associated with a threshold value based on the following pre-determined criteria:

- Horizontal curve density that's greater than the median density;
- Lane width less than 10.5 feet;
- Unpaved shoulders;
- Shoulder width less than 10 feet; and
- Posted speed limit greater than 30 mph

For each of these factors, each road segment received a "1" if it contained the attributes beyond each threshold value or a score of "0" otherwise

It is worth noting that this planning effort, however, did not analyze or suggest any improvements for rural county roads. KYTC has a separate initiative that focuses on five or six counties each year (selected based on crash data) to assist the county agency staffs with reviewing corridors and identifying specific safety-related improvements. For their 2012 effort, KYTC used the Tool to analyze county roadway corridors on behalf of local agency staff in five counties—Boyle, Bourbon, Franklin, Mercer, and Montgomery (USDOT, 2013). Additional information regarding a comparison of risk ratings and crash rates with annual average daily traffic less than or equal to 400 is provided in Appendix 3.

3.5.4. Ohio

The Ohio Department of Transportation (ODOT) uses a data-driven approach to identify, screen, and prioritize potential highway safety improvement projects. ODOT analyzes crash, roadway, and traffic data to identify sites with potential for safety improvement. Typically, ODOT studies up to 300 locations annually across the State. ODOT District offices and local agencies diagnose safety issues at these locations and develop targeted countermeasures to address the underlying crash contributing factors. The District offices develop funding applications for safety projects and submit the applications to the Central Office for further consideration. Multidisciplinary committees review and evaluate the project applications based on factors such as crash analysis; statewide, regional or local priority; matching funds; and benefit-cost analysis. To support the highway safety project prioritization process, ODOT developed the Economic Crash Analysis Tool (ECAT).

ECAT supports analysts in estimating the safety performance of a given facility (existing or proposed), conducting alternatives analyses, and completing a benefit-cost analysis. Using ECAT for benefit-cost analysis, the user can select which type and can enter basic information such as the expected project costs and the associated safety benefits. Analysts can use other supporting modules in ECAT that can best estimate the project safety benefits in terms of predicted and expected crashes. Specifically, the tool requires users to enter in expected annual crash rates, such as the number of fatal and incapacitating injury crashes, number of injury crashes, and total crashes. This tool automates much of the analysis, simplifying the process and allowing people with various skill levels to use the tool and make better safety investments (USDOT, 2017). Additional information about this tool can be found in Appendix 4.

3.5.5. North Central Texas Council of Governments

While the North Central Texas Council of Governments (NCTCOG) is still in the process of developing its own safety benefit factors for scoring and evaluating its transportation projects based on crash rates data as part of its Regional Safety Plan, based on interviews with officials there is ongoing work related to better quantifying the safety impacts attributed to widening and new capacity projects. Currently, NCTCOG uses the number of vehicle crashes and weights those crashes based on the total vehicle miles traveled. From there, NCTCOG then prioritizes projects to receive funding from its safety program based on this weighting formula. Points are assigned and adjusted based on how each project ranks within the NCTCOG region in terms of expected number of reduction in crashes and the types of treatments.

In addition, the North Central Texas Council of Governments (NCTCOG) Safety Program annually calculates county level crash rates on limited access facilities for the NCTCOG 12-County Metropolitan Planning Area (MPA). County Level Crash Rate Maps display crash rates by county in comparison to the regional crash rate for that year. As shown in Appendix 5, Counties that have a higher crash rate than the regional rate are shown in red, while counties with a rate below the regional crash rate are shown in green (NCTCOG, 2020). Additional information regarding the crash rates and the top 10 contributing factors for crashes is in Appendix 5.

3.5.6. Summary of Results

Two key lessons were learned as a result of these case studies. First, nearly every state that was reviewed does extensive planning related to determining the safety impacts of transportation projects, and second, that some states are actively considering quantifying the safety impacts associated with new location and widening projects. Many states even do some form of qualitative sketch planning for widening and new location projects. For example, Virginia assesses factor areas that are weighted differently across the commonwealth based on certain characteristics and may be weighted differently within each district. Candidate projects are screened to determine if they meet an identified need in the long-range transportation plan, and to determine if they meet eligibility requirements.

In 2020, CDOT embarked upon the development of the 2020-2023 Colorado Strategic Transportation Safety Plan. The goal for this plan is to establish a collaborative and shared vision and mission for transportation safety in the state. Examples of these strategies, which will be quantified through the development of crash modification factors, include rumble strips, median barriers, and fully protected left-turn phasing. CDOT will lead implementation with support from local city and county transportation departments as well as CDOT Region Traffic Engineers. While there's no specific guidance for widening and new location projects, the 2020-2023 Colorado Strategic Safety Plan establishes a framework by which these types of projects might be evaluated and prioritized as those measures are developed.

3.6 Literature Summary

Accurately predicting the safety effects of engineering countermeasures by determining the most optimal safety factors can improve the safety component of the transportation decision-making process (Herbel et al., 2010). However, there are a limited number of studies that assess the safety impacts and the level of safety improvements realized from new location or widening projects, which are the focus of this effort. Developing safety factors for new location projects, like the addition of bypass roads, can be especially challenging due to the complexity of network-level changes, such as changes in traffic volumes and intersection control types, involved in these types of projects. Exhibit 1, Exhibit 2, and Exhibit 3 outline the findings from a scan of available Crash Modification Factors with several well-rated CMFs for multiple widening project types. However, the research team was not able to identify any reliable CMFs for the new location types of interest. Well-rated CMFs for some widening project types were also unavailable. Due to the limited number of CMFs identified, the research team sought out additional literature, including studies from outside of the United States. The results of this effort are presented in Exhibit 3, which summarizes the results from the ten relevant studies identified, all of which are from Europe. In some cases, English translations of these studies were not available.

4. Methodology and Results – New Location Projects

This section presents the evaluation approach used to determine the SBFs for new location projects and the results of the analysis. The research team focused efforts on NCDOT Specific Improvement Type (SIT) 5 - Construct Roadway on New Location, hereafter called "bypass" projects.

The following subsections present an overview of the evaluation methods, summary of data used for the analysis, and a discussion of the results.

4.1. Evaluation Approach

The safety evaluation method for this type of assessment typically fall into one of two broad categories: before-after and cross-sectional studies. Before-after studies include all techniques by which one may study the safety effect of some treatment that has been implemented on a group of sites. On the other hand, cross-sectional studies include those with a focus on comparing the safety of one group of sites having some common feature (treatment of interest) to the safety of a different group of sites not having that feature to assess the safety effect of the treatment (Carter et al., 2012). The research team investigated both of these options to determine which approach offered more reliable results given NCDOT's preferences and available data.

There is a general consensus in the safety evaluation community that well-designed before-after studies provide more reliable estimates of safety effects compared to cross-sectional studies. This is because before-after studies are less prone to confounding (aka other influences) since the study evaluates the same roadway (or roadway network) used by probably the same or similar users in the before and after period (Elvik, 2011). Confounding, on the other hand, is an issue in cross-sectional studies and can confuse the association between an exposure and an outcome.

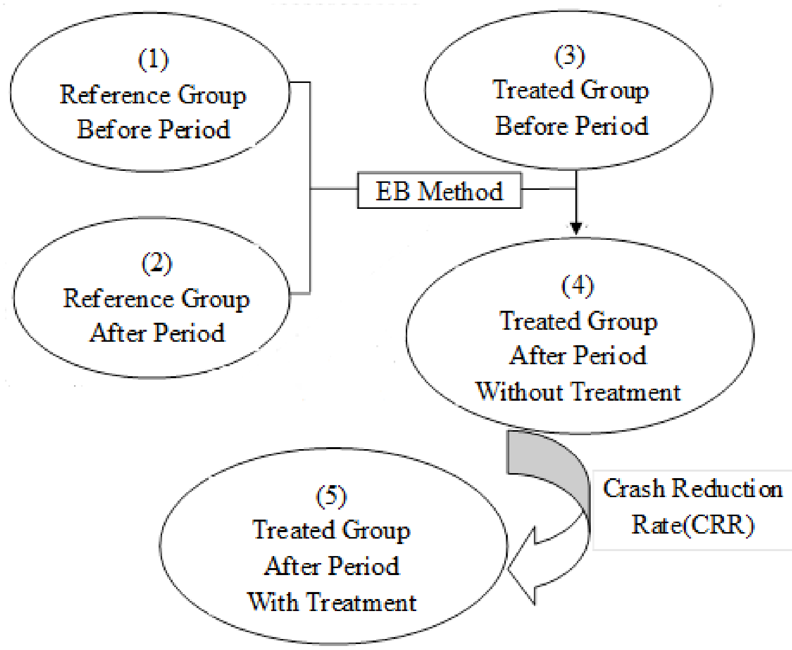
The research team investigated the use of both cross-sectional and before-after studies for this evaluation. Following is a discussion of the pros and cons of each method with respect to this specific evaluation.

4.1.1. Before-After Study

Safety effects derived from before-after studies are based on the change in safety due to the implementation of a treatment. The most practically established approach for before-after evaluations is the empirical Bayesian method (EB). The EB approach associates a reference group (refers to sites without the treatment) which is similar to treated sites (treated group) and is introduced to capture trends in the absence of the treatment, as illustrated in Exhibit 6 (Chen, 2013).

The five groups as identified in Exhibit 6 form a grid with the dimension of reference and treated groups crossed by the dimension of before and after periods. The goal here is to seek a CMF (or crash reduction rate, CRR from Exhibit 6, i.e., SBF) through a safety comparison between groups 4 and 5. The EB approach estimates the expected safety improvement of the treatment that is being evaluated (Chen, 2013).

Exhibit 6. Logical Framework of Before-After Evaluations



The objective of the EB before-after study is to estimate the number of crashes that would have occurred at an individual treated site in the after period had the treatment not been implemented. The advantage of the EB approach is that it accounts for changes in crash frequencies before and after a treatment that may be due to the regression to the mean (RTM) phenomenon.

Often, agencies select high crash locations for implementing treatments (which can be a rational approach for implementing safety countermeasures), and if the possible bias due to RTM is not properly accounted for, the evaluation may overestimate the safety effect of the treatment. In accounting for RTM, the number of crashes expected in the before period without the treatment is estimated as a weighted average of the number of crashes observed in the before period at treated sites and the number of crashes predicted at treated sites based on data from untreated reference sites with similar characteristics. The 1st edition of the Highway Safety Manual (AASHTO, 2010) considers the EB approach as an effective approach for conducting reliable before-after studies.

Based on the limitations and resources, conducting an EB before-after evaluation for the bypass improvement type was outside the scope of this project. However, a naïve EB before-after method (modifying the EB approach to exclude the reference group) is feasible and can account for changes in traffic volumes and other trends.

The naïve EB before-after method would consider the before period to comprise only the original roadway, whereas the after period would comprise of both the original roadway and the bypass.

4.1.2. Cross-Sectional Study

Safety effects from cross-sectional studies are based on the comparison of the safety of the "treated" sites to the safety of a different group (with similar features) of "untreated" sites. The following two cross-sectional approaches could be used in this evaluation:

- Cross-Sectional Method Comparing Original Route to Bypass Route
- Cross-Sectional Method Comparing Bypass Route and Original Route with Similar Routes

Both of these cross-sectional approaches would make use of data after the building of the bypass and involve comparing the crash rates of the "treated" groups and "untreated" groups. The definition of the treated and untreated groups is different in the two cross-sectional methods.

Alternatively, instead of comparing crash rates, a crash prediction model can be used to compare the propensity of crashes in the treated and untreated groups. Unlike crash rates, the crash prediction model accounts for the non-linear relationship between crashes and exposure.

Cross-Sectional Method Comparing Original Route to Bypass Route

This approach compares the propensity of crashes on the bypass road with the associated original route. In this case, the bypass road is the "treated" group, and the original route is the "untreated" group. With this approach, the SBF would be based on the percentage difference between the crash rate[1] of the bypass roads compared to the crash rate of the original routes.

Using this approach, a SBF can be developed for the project type considering the crash propensity of the original roadway to the type that exists after a bypass project is constructed, with considerations for variation in characteristics, e.g., application of weights to adjust for roadway characteristics like AADT and length to stratify these factors based on the safety outcomes.

Cross-Sectional Method Comparing Bypass Route and Original Route with Similar Routes

This approach considers the bypass along with the associated original route as the "treated" group, and a route similar to the original route as the "untreated" group. The SBF would then be based on the percentage difference between the crash rate of the treated group with the crash rate of the untreated group. As in the case of the first cross-sectional method discussed above, the percentage difference can be computed by weighting the rates by VMT, AADT, or crash counts.

Unlike the first cross-sectional method, this method would require the identification of a route similar to the original route, and compiling data from this untreated group. Doing so would include identifying a stratified sample of similar routes for which the necessary data is available. If the comparison data is collected, it would make more sense to conduct an EB before-after analysis instead of a cross sectional analysis.

4.2. Evaluation Methodology

Based on input from NCDOT, the naïve EB methodology for before-after studies was used for the new location evaluation in this study. As mentioned previously, this includes modifying the EB

[1] Crash rate is the ratio of the number of crashes to vehicle miles traveled.

approach to exclude the reference group. This would mean excluding Groups 1 and 2 from the framework presented earlier in Exhibit 6.

The naïve EB before-after method considers the before period to comprise only the original roadway, whereas the after period to comprise of both the original roadway and the bypass. The following steps are needed to conduct a naïve EB before-after evaluation:

1. Estimate safety performance functions (SPFs) using the before and after period data for the original roadway and the after period data from the bypass relating crashes to the characteristics of the facility.
2. Calculate the statewide annual crash rates to account for the temporal effects (e.g., variation in weather, demography, vehicle population, and crash reporting) on safety performance. These crash rates should then be calibrated to a base year.
3. Use the SPFs, annual calibrated crash rates, and site characteristics for each year in the before period for the original roadway to estimate the number of crashes that would be predicted for the before period.
4. Calculate the EB estimate of the expected crashes in the before period at each original site as the weighted sum of the actual crashes in the before period and predicted crashes from step 3.
5. For each original roadway / bypass combination, estimate the product of the EB estimate of the expected crashes in the before period and the SPF predictions for the after period divided by the SPF predictions for the before period. This is the EB expected number of crashes in the after period that would have occurred had no bypass been built (i.e., no treatment). The variance of this expected number of crashes is also estimated in this step. The expected number of crashes without the treatment along with the variance of this parameter and the number of reported crashes after the treatment is used to calculate the safety effect of the treatment (θ) along with the standard error, which is an estimate of the precision of the estimate of the safety effect. It is important to note that θ is the same as a CMF.

Based on the safety effect (θ), the percent change in crashes (i.e., the SBF) is calculated as 100(1-θ). Therefore, a value of θ=0.9 with a standard of error of 0.05 indicates a 10% reduction in crashes with a standard error of 5%. Conversely, a value of θ=1.2 with a standard of error of 0.1 indicates a 20% increase in crashes with a standard error of 10%. Further details about the equations involved in estimating θ and its standard error are available in Appendix 6.

4.3. Data Compilation

Data were collected for the following 16 bypass locations:

1. Jacksonville Bypass
2. Washington / Chocowinity Bypass
3. Williamston Bypass
4. Windsor Bypass
5. Goldsboro Bypass
6. Knightdale Bypass
7. Pittsboro Bypass

8. Elizabeth City Bypass
9. Wake Forest Bypass
10. Jacksonville Parkway
11. Wilmington Bypass (selected section between US 421 and US 74)
12. Vass / Cameron Bypass
13. Rolesville Bypass
14. Clayton Bypass
15. Manns Harbor – Manteo Bypass
16. Ellerbe Bypass

Data were collected for five years before and after the construction of the bypass (excluding the construction years).

Exhibit 7 and Exhibit 8 provide summary statistics for the original roadway (before and after periods) and the bypass (after period) used in the analysis. The analysis sample included 16 bypass routes. Note that from some roadways and bypasses, more than one segment was used in the analysis.

Exhibit 7. Roadway Summary Statistics

Site Type	Analysis Period	Number of Segments	Length (mi)	Average AADT
Original Roadway	Before Period	26	132.18	23692.35
Original Roadway	After Period	26	132.18	16256.97
Bypass	After Period	20	118.78	15725.58

Exhibit 8. Crash Summary Statistics (Total Crashes)

Site Type	Analysis Period	Minimum (/segment/ year)	Maximum (/segment/ year)	Average (/segment/ year)	Total Crashes
Original Roadway	Before Period	1	471	81.79	10,633
Original Roadway	After Period	0	334	60.27	6,690
Bypass	After Period	0	121	24.24	2,206

4.4. Results

As described previously, the first step in the evaluation is to estimate a safety performance function (SPF). Generalized linear modeling was used to estimate model coefficients assuming a negative binomial error distribution, which is consistent with the state of research in developing these models.

The total crash SPF is as follows:

$$Total\ Crashes = \ exp^{-8.6618} \times AADT^{1.1313} \times Length \times Years$$

Where,
$AADT$ = Average annual daily traffic,
$Length$ = Length of segment in miles, and
$Years$ = number of years of data being used.

Next, the annual crash rates calibrated to a base year were calculated. The construction periods of the bypasses meant that the data used was spread between 1996 and 2019. As such, when calibrating the annual crashes rates, 1996 was used as the base year.

Exhibit 9 provides the crash rates and the annual calibration factor (using 1996 as the base year and crash rates for all North Carolina primary routes[2]).

The estimated crash safety effects for bypass construction on a new location are shown in Exhibit 10. The EB expected crashes in the after period had the bypass not been constructed are shown along with the actual number of crashes observed in the after period (original roadway + bypass), the CMF, the standard error of the CMF, and 95% significant range of the CMFs. The expected crashes in the after period without treatment is provided with a decimal, because it is an estimated quantity, unlike the crashes in the after period that are observed.

Exhibit 9. Crash Rates and Calibration Factors for All North Carolina Routes (1996 – 2019)

Year	Crash Rates (per 100 MVMT)	Annual Calibration Factors
1996	178.42	***1***
1997	183.60	1.03
1998	183.67	1.03
1999	181.83[#]	1.02
2000	180.00[#]	1.01
2001	178.16	0.99
2002	178.43	1.00
2003	183.09	1.03
2004	183.87[#]	1.03
2005	184.64	1.03
2006	174.45	0.98
2007	168.03	0.94
2008	156.19	0.88
2009	143.46	0.80
2010	143.37	0.80
2011	154.77	0.87
2012	144.18	0.81
2013	148.85	0.83
2014	152.41	0.85
2015	163.45	0.92
2016	166.19	0.93
2017	175.73	0.98
2018[a]	175.85	0.99
2019[a]	182.78	1.02

[a] Crash rates were based on a 3-year average, however, for 2018 and 2019 they were based on a 5-year average.

[#] Crash rates for 1999, 2000, and 2004 were not available. These were interpolated based on the available crash rates.

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[2] The crash rates were extracted from the "Crash Data and Maps" page on Connect NCDOT website - https://connect.ncdot.gov/resources/safety/Pages/Crash-Data.aspx

Exhibit 10. Estimated Total Crash Safety Effects

Total Crashes	
Crashes in the after Period	8,896
Expected Crashes in the After Period without Treatment	10,571.21
CMF	0.669
Standard Error of CMF	0.0099
Range of CMFs (95% Significance)	0.688 - 0.649

The results indicate that bypass construction on a new location led to a statistically significant 33.1% reduction in crashes (CMF of 0.669).

To further understand the impact of facility types on safety, disaggregate analysis was conducted for different facility type combinations of the original roadway and bypass. The most prevalent facility type was identified and assigned to each of the 16 original roadway and bypass pairs (i.e., the facility type with most mileage was assigned).

Exhibit 11 summarizes these facility type pairs and their counts, while Exhibit 12 presents the estimated crash safety effects for disaggregated facility type pairs.

Exhibit 11. Facility Type Pairs (Original Roadway – Bypass)

Facility Types		No. of Sites
Original Roadway	**Bypass**	
Traditional Multi-Lane	Freeway	11
Traditional Multi-Lane	Traditional Multi-Lane	3
Freeway	Freeway	1
Traditional Multi-Lane	Superstreet - RCI	1
Traditional Multi-Lane	*Superstreet – RCI**	*3*

*This pair includes the bypass being assigned as a Superstreet – RCI irrespective of the prevalent facility type. If prevalence of RCI is instead considered then there is one site in the sample that would be categorized as an RCI.

Exhibit 12. Estimated Total Crash Safety Effects for Disaggregated Facility Type Pairs

Facility Type Pair (Original Roadway / Bypass)	Crashes in the After Period	Expected Crashes in the After Period without Treatment	CMF	Standard Error of CMF
Traditional ML / Freeway	6,937	8,689.57	0.680	0.0112
Traditional ML / Traditional ML	1,389	801.32	0.648	0.0277
Freeway / Freeway	362	821.78	0.798	0.0497
Traditional ML / Superstreet-RCI	208	259.19	0.567	0.0520
*Traditional ML / Superstreet-RCI**	757	1,009.79	0.629	0.0380

* This pair includes the bypass being assigned as a Superstreet – RCI irrespective of the prevalent facility type. If prevalence of RCI is instead considered then there is one site in the sample that would be categorized as an RCI.

The results of the disaggregate analysis indicate statistically significant crash reductions of between 20.2% to 43.3%. Sample sizes were as low as 1 site per disaggregate facility type pair. The only facility type pair with a large sample was *Traditional Multi-Lane / Freeway* with 11 sites.

The crash reduction for this pair was 32%, which is consistent with the 33.1% crash reduction for the aggregate sample.

4.5. SBF Recommendation

Based on the analysis presented in Section 4.4, the total crashes decreased by a statistically significant amount, resulting in a crash reduction of 33.1% with the construction of a bypass on a new location. The disaggregate analysis based on facility type pairs showed varying results with crash reductions ranging from 20.2% to 43.3% (each statistically significant), however some of these were based on samples as low as one pair.

The research team recommends a SBF of **20** for construction of a freeway bypass on a new location and **30** for the construction of a super street and all other bypasses on a new location. This is a conservative recommendation based on rounding down the crash reduction rates. The following exhibits outline the recommendations for each Specific Improvement Type (SIT) 5 - Construct Roadway on New Location (bypass) project type subgroup.

Exhibit 13. SBF Recommendations for NCDOT New Location Projects - SIT 5 (Bypass Projects)

Specific Improvement Type (SIT)	Sub SITs	Area Type	Current NCDOT SBF	Study Developed SBF	Study Recommended SBF	Recommendation Considerations
5 - Construct Roadway on New Location	5A - Construct Roadway on New Location - Freeway Bypass	Urban/ Rural	10	30	**20**	Conservative SBF recommended due to the small number of sites of this type in the sample used to develop the SBF paired with the research team's expertise related to safety outcomes.
	5B - Construct Roadway on New Location - Superstreet Bypass	Urban/ Rural	5	30	**30**	Same SBF is recommended for SIT 5B and 5C project types due to amount of data available and similar SBF results for different types
	5C - Construct Roadway on New Location - All other projects	Urban/ Rural	-	30	**30**	Same SBF is recommended for SIT 5B and 5C project types due to amount of data available and similar SBF results for different types

Recommendations for another new location project group, SIT 6 - Widen Existing Roadway and Construct Part on New Location, were not developed because the available data was inadequate to estimate SBFs for this group and NCDOT prioritized the development of SBFs for bypass projects. Due to the nature of SIT 6 projects, the research team recommends that NCDOT either maintain the Current NCDOT SBF for this type or utilize a value within the range recommended/used for SIT 5 projects (30) and SIT 1A (10).

4.6. Sensitivity Analysis

Using NCDOT data from the P5.0 prioritization cycle, the research team examined how the SBF recommendations for these project types impacted key measures in the process.

The number of bypass projects in the SIT 5A type examined from the P5.0 data as well as the previous SBF range and the SBF recommended through this study are outlined in Exhibit 14. Exhibit 15 show summaries of statistics representing the impact of the recommended SBF on the process measures. Overall, the integration of the recommended SBF resulted in higher scores and monetized benefits, which is to be expected given the increase in the value of the recommended SBF. Negative score values are likely associated to the project scaling applied in the prioritization process.

Exhibit 14. Sensitivity Analysis Sample Characteristics: SIT 5A (Bypass Projects)

Number of Projects	30
Previous SBF Range	10%
New SBF	20%

Exhibit 15. Sensitivity Analysis Results: SIT 5A (Bypass Projects)

Change in Results with Recommended SBF	Average Change	Minimum Change	Maximum Change
SBF Value	10%	10%	10%
Statewide Mobility Quantitative Score (Out of 100)	1.70	0.12	3.05
Regional Impact Quantitative Score (Out of 70)	1.45	0.12	2.50
Division Needs Quantitative Score (Out of 50)	1.02	0.20	2.15
Criteria: Benefit/Cost (Statewide Mobility, Regional Impact)	1.00	0.00	16.14
Criteria: Benefit/Cost (Division Needs)	4.39	-0.08	9.89
Criteria: Safety	3.04	1.20	4.68
Measure: Benefit/Cost Raw (SW, REG)	4.00	0.00	0.27
Measure: Benefit/Cost Scaled (SW, REG)	5.93	0.00	16.14
Measure: Benefit/Cost Raw (Division Needs)	0.08	0.01	0.26
Measure: Benefit/Cost Scaled (Division Needs)	4.45	-0.08	9.89
Measure: Safety Benefits - Raw	$16,210,040	$1,433,400	$38,682,200
Measure: Safety Benefits - Scaled	7.59	2.99	11.71
Data: Annual Safety Benefits ($)	$1,621,004	$143,340	$3,868,220
Data: Safety Benefits over 10 years ($)	$16,210,040	$1,433,400	$38,682,200

The sensitivity analysis for SIT 5B/C bypass project types are showing in the following exhibits. Exhibit 16 shows the number of bypass projects in the SIT type included in the sample the P5.0 data as well as the previous SBF range and the SBF recommended through this study. The summary of the statistics resulting from the sensitivity analysis are presented in Exhibit 17. As anticipated the higher recommended SBF resulted in higher scores and monetized benefits. Negative score values are likely associated to the project scaling applied in the prioritization process.

Exhibit 16. Sensitivity Analysis Sample Characteristics: SITs 5B and 5C (Bypass Projects)

Number of Projects	102
Previous SBF Range	0-5%
New SBF	30%

Exhibit 17. Sensitivity Analysis Results: SITs 5B and 5C (Bypass Projects)

Change in Results with Recommended SBF	Average Change	Minimum Change	Maximum Change
SBF Value	30%	25%	30%
Statewide Mobility Quantitative Score (Out of 100)	12.87	15.57	15.57
Regional Impact Quantitative Score (Out of 70)	6.97	0.94	13.79
Division Needs Quantitative Score (Out of 50)	5.07	-0.35	16.30
Criteria: Benefit/Cost (Statewide Mobility, Regional Impact)	1.00	-0.37	54.81
Criteria: Benefit/Cost (Division Needs)	19.51	-3.99	88.17
Criteria: Safety	18.93	0.00	39.87
Measure: Benefit/Cost Raw (SW, REG)	4.00	0.01	1.29
Measure: Benefit/Cost Scaled (SW, REG)	2.76	-0.37	54.81
Measure: Benefit/Cost Raw (Division Needs)	0.38	0.00	3.81
Measure: Benefit/Cost Scaled (Division Needs)	19.57	-3.99	89.45
Measure: Safety Benefits - Raw	$8,920,350	$-	$112,107,000
Measure: Safety Benefits - Scaled	47.34	0.00	99.67
Data: Annual Safety Benefits ($)	$892,035	$-	$11,210,700
Data: Safety Benefits over 10 years ($)	$8,920,350	$-	$112,107,000

5. Methodology and Results – Widening Projects

This section presents the evaluation approach used to determine the SBFs for widening projects and the results of the analysis. The following subsections present an overview of the evaluation method, summary of data used for the analysis, and a discussion of the results.

5.1. Evaluation Method

The method used to derive SBFs for widening projects makes use of SPFs from the 1st edition of the HSM that have been calibrated using data from North Carolina. The latest report from the calibration effort is "*Updated and Regional Calibration Factors for Highway Safety Manual Crash Prediction Models (2016 – 2019)*" (Report FHWA/NC/2020-27). NCDOT makes use of the calibrated SPFs for analysis on various projects and efforts. The research team used the same calibrated SPFs for deriving the SBFs for widening rural and urban roads. Existing NCDOT guidance related to CMFs/CRFs was also reviewed when conducting this analysis.

In some cases, NCDOT previously used the same SBF for both urban and rural projects of a given type due to a lack of sound individual SBFs for specific location types. Therefore, the research team develop SBFs specifically for urban and rural locations when possible.

5.1.1. Sample SPF from the 1st edition of the HSM

Based on the 1st edition of the HSM, the general form of the SPF is the following:

$$N_{spf} = N_{spf\_b} \times C \times (CMF_1 \times CMF_2 \times \ldots . \times CMF_n)$$

Where,
N_{spf_b} = SPF for base conditions,
C = calibration factor, and
CMF_1 through CMF_n = CMFs to adjust for conditions different from the base condition.

For <u>rural two-lane roads</u>, the SPF for base conditions for total crashes is the following:

$$N_{spf\_b} = AADT \times L \times 365 \times 10^{-6} \times e^{-0.312}$$

The base conditions are the following:

- Lane width = 12 feet
- Shoulder width = 6 feet
- Shoulder type = paved
- Roadside hazard rating = 3
- Driveway density = 5 driveways per mile
- Horizontal curvature = none
- Vertical curvature = none
- Centerline rumble strips = none
- Passing lanes = none
- Two-way left-turn lanes = none
- Lighting = none

- Automated speed enforcement = none
- Grade = 0%

SPFs for other roadway types are available in the 1st edition of the HSM.

5.1.2. Approach

This approach involves estimating the predicted number of crashes for each facility in their before and after conditions using the HSM predictive models that were calibrated using NC data from 2016 – 2019. To predict the number of crashes, assumptions need to be made regarding the characteristics of the facilities before and after the widening. Depending on the facility type, assumptions need to be made regarding AADT and other characteristics such as the number of driveways by type, roadside objects, and parking.

AADT Assumptions

As discussed earlier, a SBF is synonymous with a CRF or a CMF. Properly designed before-after studies are recommended for estimating CMFs. Typically, such before-after studies estimate the expected number of crashes in the after period had the treatment not been implemented and compares that with the actual crashes in the after period, and estimates the CMF based on these two parameters. Typically, the expected number of crashes in the after period is estimated after accounting for the change in traffic volume from the before to the after period. For example, if the AADT was 8,000 in the before period, and 10,000 in the after period, the expected number of crashes in the after period are estimated corresponding to the AADT of 10,000. Following the same approach, while estimating the predicted number of crashes in both the before and after conditions, the AADT used should be reasonable for the facility type after widening. This approach was applied in this study. The research team estimated AADTs for the after period based on project data from the P5.0 prioritization cycle.

Other Site Characteristics Assumptions

For the project types analyzed, NCDOT did not have information on site characteristics such as driveway density, roadside objects, and parking for facilities that have been widened. Therefore, the research team decided to use the data from sites that were used for calibrating the HSM predictive models. For this purpose, the latest data from 2016 - 2019 were used. In using the data for these sites, some sensitivity analysis was conducted by modifying the driveway density while estimating the crashes in the before period to match with the driveway density in the after period.

5.1.3. Application Illustration

If N_{spf} for four-lane divided roads and rural two-lane roads are available, then the SBF associated with the widening of a rural two-lane road to a four-lane divided road, can be written as follows:

SBF for widening = $100 \times \left(1 - \frac{N_{spf}\ for\ rural\ four{-}lane\ divided}{N_{spf}\ for\ rural\ two{-}lane\ undivided}\right)$

Applying this equation will require the calibration factors and assumptions on AADT and the CMFs. Report FHWA/NC/2020-27 estimated the following calibration factors for these two facility types based on data from 2016 to 2019:

Calibration factor for rural two-lane undivided roads = 1.29

Calibration factor for rural four-lane divided roads = 1.39

For a simple illustration, all the CMFs are assumed to be 1.0 for both SPFs. This assumes that the rural two-lane road is flat and has no horizontal curves. In addition, it is important to note that the base condition for shoulder width is 6 feet for rural two-lane roads and 8 feet for rural four-lane divided roads.

If the CMFs are assumed to be 1.0, N_{spf} is essentially the product of N_{spf_b} and the calibration factor. The SBF is a function of AADT. For this illustration, three values of AADT are used: 10000, 15000, and 20000.

For AADT = 10000, estimated SBF = 23.8

For AADT = 15000, estimated SBF = 22.2

For AADT = 20000, estimated SBF = 21.1

Since SBFs are planning level estimates and multiples of 5, based on these estimates, an SBF of 20 is recommended.

5.2. Data Summary

The data used for this analysis was collected as part of NCDOT Research Project 2020-27 "*Updated and Regional Calibration Factors for Highway Safety Manual Crash Prediction Models (2016 – 2019)*". Exhibit 18 presents a summary of this data for various roadway types.

Exhibit 18. Summary of Data from NCDOT Research Project 2020-27

Roadway Type	Sum of Length (miles)	Sum of Total Crashes (2016 - 2019)
Rural 2-Lane Undivided	732.74	2,923
Rural 4-Lane Divided	197.27	2,911
Urban 2-Lane Undivided	42.01	681
Urban 2-Lanes with TWLTL	19.16	621
Urban 4-Lane Divided	7.51	227
Urban 4-Lane Undivided	4.17	757
Urban 4-Lane with TWLTL	15.71	929

*Additional data for urban 6-lane divided roads, urban 6-lane undivided roads, and urban 8-lane divided roads from North Carolina were also collected as part of NCHRP Project 17-72 "*Update of Crash Modification Factors for the Highway Safety Manual*" to calibrate the crash prediction models in the upcoming 2nd edition of the HSM to a single state. However, since the work in still under review by the NCHRP panel, the data and the calibration factors could not be used to derive SBFs in this project.

5.3 Results

The following sections present the calculations for the various widening scenarios of interest to NCDOT. In cases where an SBF value of less than 0 was calculated, a SBF of 0 was recommended, as NCDOT currently utilizes SBFs to identify potential safety benefits of a project and does not calculate potential safety costs.

5.3.1. Widen Two-Lane roadway (2U) to Four-Lane divided (4D) Roadway - Rural

AADT for the estimation assumed to be <u>15,000</u>.

Number of crashes per mile for 2U = 9.91

Number of crashes per mile for 4D = 4.04

SBF = $\left(1 - \frac{4.04}{9.91}\right) \times 100 = \ 59.18 \sim \mathbf{60}$

The SPF for rural four-lane divided roadways in the 1st edition of the HSM does not account for driveway density. Hence in this calculation, the AADT was assumed to be 15000 for both the rural two-lane undivided roads and rural four-lane divided roads (to be reasonable for the widened facility type, i.e., rural four-lane divided roads), while the driveway density for rural two-lane undivided roads was not modified.

The SBF for this widening is estimated to be 60.

5.3.2. Install Two-Way Left Turn Lane on a Two-Lane Roadway (2U to 3T) – Urban

AADT for the estimation assumed to be 12,000.

Scenario 1: Driveway density was based on the calibration samples for 2U and 3T roads
Number of crashes per mile for 2U = 6.68

Number of crashes per mile for 3T= 9.01

SBF = $\left(1 - \frac{9.01}{6.68}\right) \times 100 = \ -34.91 \sim \mathbf{0}$

It is important to note NCDOT has made a decision not to have negative SBFs. So, negative SBFs default to zero.

Scenario 2: Driveway density for 2U was modified to be the same as 3T for all driveway types
Number of crashes per mile for 2U = 9.14

SBF = $\left(1 - \frac{9.01}{9.14}\right) \times 100 = \ 1.36 \sim \mathbf{0}$

In this calculation, the AADT was assumed to be 12,000 for both the urban two-lane undivided roads and urban two-lane roads with a two-way left-turn lane (to be reasonable for the widened facility type, i.e., urban two-lane roads with a two-way left-turn lane). For the driveway density, two separate scenarios were analyzed. The first scenario assumed the driveway density to be the same as in the calibration sample, while the scenario assumed the driveway density for the widened facility type, i.e., urban two-lane roads with two-way left-turn lane.

The SBF for this widening is estimated to be 0 as identified in scenario 2.

5.3.3. Widen Two-Lane Roadway (2U) to Four-Lane Divided (4D) Roadway - Urban (without controlled access)

AADT for the estimation assumed to be 20,000.

Scenario 1: Driveway density was based on the calibration samples for 2U and 4D roads
Number of crashes per mile for 2U = 13.16

Number of crashes per mile for 4D = 13.18

SBF = $\left(1 - \frac{13.18}{13.16}\right) \times 100 = \ -0.19 \sim \mathbf{0}$

Scenario 2: Driveway density for 2U was modified to be the same as 4D for all driveway types
Number of crashes per mile for 2U = 12.07

SBF = $\left(1-\frac{13.18}{12.07}\right)\times 100 = -9.29 \sim \mathbf{0}$

In this calculation, the AADT was assumed to be 20,000 for both the urban two-lane undivided roads and urban four-lane divided roads (to be reasonable for the widened facility type, i.e., urban four-lane divided roads). For the driveway density, two separate scenarios were analyzed. The first scenario assumed the driveway density to be the same as in the calibration sample, while the second scenario assumed the driveway density for the widened facility type, i.e., urban four-lane divided roads.

The SBF for this widening is estimated to be 0 as identified in scenario 2.

5.3.4. Install Two-Way Left Turn Lane on a Four-Lane Roadway (4U to 5T) – Urban

AADT for the estimation assumed to be 20,000.

Scenario 1: Driveway density was based on the calibration samples for 4U and 5T roads
Number of crashes per mile for 4U = 24.23

Number of crashes per mile for 5T = 16.40

SBF = $\left(1-\frac{16.40}{24.23}\right)\times 100 = 32.32 \sim 3\mathbf{0}$

Scenario 2: Driveway density for 4U was modified to be the same as 5T for all driveway types
Number of crashes per mile for 4U = 23.17

SBF = $\left(1-\frac{16.40}{23.17}\right)\times 100 = 29.21 \sim 3\mathbf{0}$

In this calculation, the AADT was assumed to be 20,000 for both the urban four-lane undivided roads and urban four-lane roads with two-way left-turn lane (to be reasonable for the widened facility type, i.e., urban four-lane roads with two-way left-turn lane). For the driveway density, two separate scenarios were analyzed. The first scenario assumed the driveway density to be the same as in the calibration sample, while the second scenario assumed the driveway density for the widened facility type, i.e., urban four-lane roads with two-way left-turn lane.

The SBF for this widening is estimated to be 30 as identified in scenario 2.

5.3.5. Install Two-Way Left Turn Lane on a Four-Lane Divided Roadway (4D to 5T) – Urban

AADT for the estimation assumed to be 20,000.

Scenario 1: Driveway density was based on the calibration samples for 4D and 5T roads
Number of crashes per mile for 4D = 13.18

Number of crashes per mile for 5T = 16.40

SBF = $\left(1-\frac{16.40}{13.18}\right)\times 100 = -24.34 \sim \mathbf{0}$

Scenario 2: Driveway density for 4D was modified to be the same as 5T for all driveway types
Number of crashes per mile for 4D = 14.74

SBF = $\left(1 - \frac{16.40}{14.74}\right) \times 100 = -11.25 \sim \mathbf{0}$

In this calculation, the AADT was assumed to be 20,000 for both the urban four-lane divided roads and urban four-lane roads with two-way left-turn lane (to be reasonable for the widened facility type, i.e., urban four-lane roads with two-way left-turn lane). For the driveway density, two separate scenarios were analyzed. The first scenario assumed the driveway density to be the same as in the calibration sample, while the second scenario assumed the driveway density for the widened facility type, i.e., urban four-lane roads with two-way left-turn lane.

The SBF for this widening is estimated to be 0 as identified in scenario 2.

5.3.6. Convert Four-Lane Undivided Roadway (4U) to Four-Lane Divided Roadway (4D) – Urban (NCDOT Special Request)

AADT for the estimation assumed to be 20,000.

Scenario 1: Driveway density was based on the calibration samples for 4U and 4D roads
Number of crashes per mile for 4U = 24.23

Number of crashes per mile for 4D = 13.18

SBF = $\left(1 - \frac{13.18}{24.23}\right) \times 100 = 45.57 \sim \mathbf{45}$

Scenario 2: Driveway density for 4U was modified to be the same as 4D for all driveway types
Number of crashes per mile for 4U = 16.46

SBF = $\left(1 - \frac{13.18}{16.56}\right) \times 100 = 19.89 \sim \mathbf{20}$

In this calculation, the AADT was assumed to be 20,000 for both the urban four-lane undivided roads and urban four-lane divided roads (to be reasonable for the widened facility type, i.e., urban four-lane divided roads). For the driveway density, two separate scenarios were analyzed. The first scenario assumed the driveway density to be the same as in the calibration sample, while the second scenario assumed the driveway density for the widened facility type, i.e., urban four-lane divided roads.

The SBF for this conversion is estimated to be 20 as identified in scenario 2.

5.4. SBF Recommendations

The SBF recommendation by the research team for the various for the widening project types are presented as follows:

- Exhibit 19 shows recommendations for Widen Existing Roadway SITs 1A through 1F
- Exhibit 20 shows recommendations for SIT 1G - Widen Existing Roadway - All Other Projects
- Exhibit 21 shows recommendations related to additional widening SBFs requested by NCDOT

Each of these exhibits provide a comparison between various SBFs including:

- Current NCDOT SBF
- SBFs developed in this study
- SBFs identified from CMF Clearinghouse

It should be noted that SBFs identified from CMF Clearinghouse were based on CMF Clearinghouse CMFs with a star rating of 4-Star or higher. Additionally, the research team did not recommend SBFs for some widening project types. As detailed in the tables, this was the case because for some project types because the research team was unable to develop a recommendation until the panel for NCHRP Project 17-72 (which involves a revised method for this approach) approves that research. In other cases, it is recommended that the SBF currently used by NCDOT SBF should continue to be utilized because there are no CMFs in the CMF Clearinghouse that are 4-stars or higher and available data was inadequate for the research team to estimate an SBF.

Based on this comparison, a recommended SBF for each widening/conversion scenario is presented along with a brief description of why a certain SBF is being recommended.

Following is a brief summary of CMF Clearinghouse CMFs that were considered when making SBF recommendations:

- 1C - Widen Existing Roadway – Install two-way left turn lane on a two-lane roadway – Urban/Rural
    - A SBF of 20 (derived from a 4-Star CMF in the CMF Clearinghouse – CMF ID 2341) is recommended for this widening scenario. The CMF in the CMF Clearinghouse was based on data from North Carolina (plus other states) and was derived from a robust empirical Bayes before-after study.
- 1F - Widen Existing Roadway – Widen 4 lane divided roadway to 6 lane divided – Urban
    - A SBF of 15 (derived from a 5-Star CMF in the CMF Clearinghouse – CMF ID 7924) is recommended for this widening scenario. The CMF in the CMF Clearinghouse was based on data from Florida and was derived from a robust empirical Bayes before-after study.
    - An SBF for this scenario was not developed in this study due to data limitations, however, this recommended SBF of 15 is consistent with the current NCDOT SBF.
- 1G.1 - Widen Existing Roadway – Widen 2 lane roadway to 4 lane divided roadway – Urban (without controlled access)
    - A SBF of 65 (derived from a 4-Star CMF in the CMF Clearinghouse – CMF ID 7566) was considered for this widening scenario. The CMF in the CMF Clearinghouse was based on data from Florida and was derived from a robust empirical Bayes before-after study. However, this CMF may be overestimating the safety effect due to the small sample used for its estimation.

    - The SBF developed in this study for this scenario was 0, and NCDOT does not have a current SBF for this.
    - SBF of 0 was recommended for this scenario as it was based on NC data and avoids any reliability issues with the CMF Clearinghouse CMF developed using Florida data.
- 1G.5 - Widen Existing Roadway – Install two-way left turn lane on a two-lane roadway – Rural
    - A SBF of 20 (derived from a 4-Star CMF in the CMF Clearinghouse – CMF ID 2358) is recommended for this widening scenario. The CMF in the CMF Clearinghouse was based on data from North Carolina and was derived from a robust empirical Bayes before-after study.
    - An SBF for this scenario was not developed in this study due to data limitations, and NCDOT does not have a current SBF for this.

Exhibit 19. SBF Recommendations for NCDOT Widening SITs 1A-1F

Specific Improvement Type (SIT)	Area Type	Current NCDOT SBF	Study Developed SBF	CMF Clearinghouse Findings (*4-Star or Higher*)		Study Recommended SBF	Recommendation Considerations
				SBF	Details		
1A - Widen Existing Roadway - Add lane to Freeway	Urban/ Rural	10				**TBD***	*Research team is unable to develop a recommendation for this SBF until the panel for NCHRP Project17-72 (which involves a revised method for this approach), approves that research
1B - Widen Existing Roadway - Widen 2 lane roadway to 4 lane divided - Rural	Rural	55	60	30	*Uses FL data, Derived from EB B/A analysis*	**60**	Developed SBF is consistent with Current NCDOT SBF
1C - Widen Existing Roadway - Install two-way left turn lane on a two lane roadway - Urban/Rural	Urban/ Rural	20	-	20	*Uses NC data*	**20**	CMF Clearinghouse SBF is consistent with Current NCDOT SBF
1D - Widen Existing Roadway - Widen 2 lane roadway to 4 lane divided Superstreet with Partial Control of Access - Urban	Urban	15				**N/A**	Recommended that the current NCDOT SBF is maintained because there are no Clearinghouse CMFs that are 4-stars or higher and available data was inadequate to estimate SBF
1E - Widen Existing Roadway - Widen 2 lane roadway to 4 lane divided with Partial Control of Access - Urban	Urban	10				**N/A**	Recommended that the current NCDOT SBF is maintained because there are no Clearinghouse CMFs that are 4-stars or higher and available data was inadequate to estimate SBF
1F - Widen Existing Roadway - Widen 4 lane divided roadway to 6 lane divided - Urban	Urban	15	-	15	*Uses FL data, Derived from EB B/A Analysis*	**15**	CMF Clearinghouse SBF is consistent with Current NCDOT SBF

Exhibit 20. SBF Recommendations for Subtypes of SIT 1G - Widen Existing Roadway - All Other Projects

SIT 1G- Widen Existing Roadway - All other projects Subtype	Area Type	Current NCDOT SBF	Study Developed SBF	CMF Clearinghouse Findings (*4-Star or Higher*)		Study Recommended SBF	Recommendation Considerations
				SBF	Details		
1G.1 - Widen Existing Roadway - Widen 2 lane roadway to 4 lane divided roadway - Urban (without controlled access)	Urban (w/o controlled access)	-	0	65	*Uses FL data, Derived from EB B/A analysis*	**0****	** Use with caution: SBF developed through this study shows no change in crashes, while CMF Clearinghouse SBF shows 65% crash reduction based on multiple sections of the same roadway
1G.2 - Widen Existing Roadway - Widen 4 lane roadway to 5 lane roadway - Urban	Urban (4-lane undivided)	-	30	30	*Use LA data, Derived from EB B/A analysis*	**30**	Developed SBF is consistent with CMF Clearinghouse SBF
1G.2 - Widen Existing Roadway - Widen 4 lane roadway to 5 lane roadway - Urban	Urban (4-lane divided)	-	0	-	-	**0**	
1G.3 - Widen Existing Roadway - Widen 2 lane roadway to 4 lane divided roadway - Urban/Rural	Urban/ Rural	-				**N/A**	Recommendation is informed by the separate SBF analyses for rural (60) and urban (0) projects of this type; Due to the wide spread between the two values, the research team is unable to recommend a an SBF that would apply to combined rural and urban locations
1G.4 - Widen Existing Roadway - Install two-way left turn lane on a two lane roadway - Urban	Urban	-	0	0	*Uses NC data*	**0**	Developed SBF is consistent with CMF Clearinghouse SBF; NCDOT currently using the SBF for 1C (SBF = 20) for this project type due to a lack of area-specific SBF
1G.5 - Widen Existing Roadway - Install two-way left turn lane on a two lane roadway - Rural	Rural	-	-	30	*Uses NC data*	**30**	CMF Clearinghouse SBF uses NC data; NCDOT currently using the SBF for 1C (SBF = 20) for this project type due to a lack of area-specific SBF
1G.6 - Widen Existing Roadway - Widen 6 lane divided roadway to 8 lane divided roadway - Urban	Urban	-				**TBD***	*Research team is unable to develop a recommendation for this SBF until the panel for NCHRP Project17-72 (which involves a revised method for this approach), approves that research

Exhibit 21. SBF Recommendations for Additional Project Types Requested by NCDOT

NCDOT Special Request Project Type	Area Type	Current NCDOT SBF	Study Developed SBF	CMF Clearinghouse Findings (*4-Star or Higher*)		Study Recommended SBF	Recommendation Considerations
				SBF	Details		
4D to 6U Conversion	Urban/ Rural	-	-	-	-	**TBD***	*Research team is unable to develop a recommendation for this SBF until the panel for NCHRP Project17-72 (which involves a revised method for this approach), approves that research
4U to 4D Conversion	Urban	-	20	-	-	**20*****	***Use with caution due to limited sample available for calculations

5.5. Sensitivity Analysis

Using NCDOT data from the P5.0 prioritization cycle, the research team examined how the SBF recommendations for relevant widening projects impacted key measures in the process. These results are detailed in the following sections. Sensitivity analyses were not conducted for all widening project types. A sensitivity analysis was conducted for project types that met the following criteria:

1. An SBF was recommended through this study for the given type
2. The recommended SBF is different than the SBF currently applied by NCDOT
3. The P5.0 cycle dataset included a sample size of at least 5 projects of the given type

For each relevant widening type, the first table outlines the number of projects examined from the P5.0 data as well as the previous SBF range and the SBF recommended through this study, while another shows a summary of statistics representing the impact of the recommended SBF on the process measures. For most project types, the integration of the recommended SBFs resulted in higher scores (which was expected because SBF values of 0 were replaced with non-zero values), monetized benefits, and proportion of total benefits, which can be attributed to the safety benefits applied in these analyses.

5.5.1. Widen Two-Lane roadway (2U) to Four-Lane divided (4D) Roadway - Rural

As shown in Exhibit 22 and Exhibit 23, this sample included 102 projects from P5.0 and overall, the integration of the recommended SBF resulted in only slightly higher scores. Monetized benefits also increased. Negative score values are likely associated to the project scaling applied in the prioritization process.

Exhibit 22. Sensitivity Analysis Sample Characteristics: Widen Two-Lane roadway (2U) to Four-Lane divided (4D) Roadway – Rural

Number of Projects	102
Previous SBF	55%
New SBF	60%

Exhibit 23. Sensitivity Analysis Results: Widen Two-Lane roadway (2U) to Four-Lane divided (4D) Roadway – Rural

Change in Results with Recommended SBF	Average Change	Minimum Change	Maximum Change
SBF Value	5%	5%	5%
Statewide Mobility Quantitative Score (Out of 100)	0.43	0.01	0.77
Regional Impact Quantitative Score (Out of 70)	0.36	0.01	0.74
Division Needs Quantitative Score (Out of 50)	0.23	0.00	0.58
Criteria: Benefit/Cost (Statewide Mobility, Regional Impact)	1.00	-0.13	3.45
Criteria: Benefit/Cost (Division Needs)	1.37	-0.09	2.74
Criteria: Safety	0.32	0.00	0.83
Measure: Benefit/Cost Raw (SW, REG)	4.00	0.00	0.12
Measure: Benefit/Cost Scaled (SW, REG)	1.54	-0.13	3.45
Measure: Benefit/Cost Raw (Division Needs)	0.04	0.00	0.12
Measure: Benefit/Cost Scaled (Division Needs)	1.37	-0.09	2.74
Measure: Safety Benefits - Raw	$2,364,646	$700	$11,055,900
Measure: Safety Benefits - Scaled	0.81	0.00	2.08
Data: Annual Safety Benefits ($)	$236,465	$70	$1,105,590
Data: Safety Benefits over 10 years ($)	$2,364,646	$700	$11,055,900

5.5.2. Install Two-Way Left Turn Lane on a Two-Lane Roadway (2U to 3T) – Urban

As shown in Exhibit 24 and, this sample included 38 projects from P5.0 and overall, the integration of the recommended SBF resulted in lower scores and a reduction in monetized benefits, which is to be expected given the recommended SBF of 0.

Exhibit 24. Sensitivity Analysis Sample Characteristics: Install Two-Way Left Turn Lane on a Two-Lane Roadway (2U to 3T) – Urban

Number of Projects	38
Previous SBF	N/A, although NCDOT is currently using the SBF for 1C (SBF = 20) for this project type due to a lack of area-specific SBF
New SBF	0%

Exhibit 25. Sensitivity Analysis Results: Install Two-Way Left Turn Lane on a Two-Lane Roadway (2U to 3T) – Urban

Change in Results with Recommended SBF	Average Change	Minimum Change	Maximum Change
SBF Value	-20%	-20%	-20%
Statewide Mobility Quantitative Score (Out of 100)	-19.32	-19.32	-19.32
Regional Impact Quantitative Score (Out of 70)	-8.77	-16.10	-2.94
Division Needs Quantitative Score (Out of 50)	-9.22	-16.84	-2.39
Criteria: Benefit/Cost (Statewide Mobility, Regional Impact)	1.00	-64.53	-1.72
Criteria: Benefit/Cost (Division Needs)	-42.01	-84.63	-6.73
Criteria: Safety	-24.33	-37.28	-13.79
Measure: Benefit/Cost Raw (SW, REG)	4.00	-1.25	-0.07
Measure: Benefit/Cost Scaled (SW, REG)	-12.88	-64.53	0.00
Measure: Benefit/Cost Raw (Division Needs)	-0.27	-1.26	-0.02
Measure: Benefit/Cost Scaled (Division Needs)	-42.01	-84.63	-6.73
Measure: Safety Benefits - Raw	$(6,253,821)	$(29,419,600)	$(312,400)
Measure: Safety Benefits - Scaled	-60.83	-93.19	-34.47
Data: Annual Safety Benefits ($)	$(625,382)	$(2,941,960)	$(31,240)
Data: Safety Benefits over 10 years ($)	$(6,253,821)	$(29,419,600)	$(312,400)

5.5.3. Install Two-Way Left Turn Lane on a Two-Lane Roadway (2U to 3T) – Rural

As shown in Exhibit 26 and Exhibit 27, this sample included 29 projects from P5.0 and overall, the integration of the recommended SBF resulted in only slightly higher scores. Monetized benefits also increased.

Exhibit 26. Sensitivity Analysis Sample Characteristics: Install Two-Way Left Turn Lane on a Two-Lane Roadway (2U to 3T) – Rural

Number of Projects	29
Previous SBF	N/A, although NCDOT is currently using the SBF for 1C (SBF = 20) for this project type due to a lack of area-specific SBF
New SBF	30%

Exhibit 27. Sensitivity Analysis Sample Characteristics: Install Two-Way Left Turn Lane on a Two-Lane Roadway (2U to 3T) – Rural

Change in Results with Recommended SBF	Average Change	Minimum Change	Maximum Change
SBF Value	10%	10%	10%
Statewide Mobility Quantitative Score (Out of 100)	1.48	0.40	0.40
Regional Impact Quantitative Score (Out of 70)	1.62	0.33	2.67
Division Needs Quantitative Score (Out of 50)	1.29	0.40	2.37
Criteria: Benefit/Cost (Statewide Mobility, Regional Impact)	1.00	1.35	11.70
Criteria: Benefit/Cost (Division Needs)	6.68	2.32	9.88
Criteria: Safety	1.92	0.47	3.29
Measure: Benefit/Cost Raw (SW, REG)	4.00	0.01	0.42
Measure: Benefit/Cost Scaled (SW, REG)	5.10	0.00	11.70
Measure: Benefit/Cost Raw (Division Needs)	0.12	0.01	0.42
Measure: Benefit/Cost Scaled (Division Needs)	6.68	2.32	9.88
Measure: Safety Benefits - Raw	$3,422,366	$69,800	$15,969,800
Measure: Safety Benefits - Scaled	4.80	1.16	8.22
Data: Annual Safety Benefits ($)	$342,237	$6,980	$1,596,980
Data: Safety Benefits over 10 years ($)	$3,422,366	$69,800	$15,969,800

5.5.4. Convert Four-Lane Undivided Roadway (4U) to Four-Lane Divided Roadway (4D) – Urban (NCDOT Special Request)

As shown in Exhibit 28 and Exhibit 29, this sample included 10 projects from P5.0. Due to the different SBFs used in P5.0 in place of a recommended SBF, the integration of the recommended SBF resulted in both increases and reductions in values. Negative score values may also be related to the project scaling applied in the prioritization process.

Exhibit 28. Sensitivity Analysis Sample Characteristics: Convert Four-Lane Undivided Roadway (4U) to Four-Lane Divided Roadway (4D) – Urban

Number of Projects	10
Previous SBF Range	N/A, appears that NCDOT used 0-25% in P5.0
New SBF	20%

Exhibit 29. Sensitivity Analysis Results: Convert Four-Lane Undivided Roadway (4U) to Four-Lane Divided Roadway (4D) – Urban

Change in Results with Recommended SBF	Average change	Minimum change	Maximum Change
SBF Value	2%	-5%	20%
Statewide Mobility Quantitative Score (Out of 100)	N/A	0.00	0.00
Regional Impact Quantitative Score (Out of 70)	1.53	-1.40	-0.56
Division Needs Quantitative Score (Out of 50)	1.11	-1.18	0.64
Criteria: Benefit/Cost (Statewide Mobility, Regional Impact)	1.00	-6.4	40.89
Criteria: Benefit/Cost (Division Needs)	2.71	-6.07	37.20
Criteria: Safety	5.94	-1.86	35.28
Measure: Benefit/Cost Raw (SW, REG)	4.00	-0.37	0.30
Measure: Benefit/Cost Scaled (SW, REG)	4.17	-6.4	40.89
Measure: Benefit/Cost Raw (Division Needs)	-0.06	-0.37	0.29
Measure: Benefit/Cost Scaled (Division Needs)	2.71	-6.07	37.20
Measure: Safety Benefits - Raw	$1,012,420	$(5,409,800)	$20,554,800
Measure: Safety Benefits - Scaled	14.84	-4.65	88.21
Data: Annual Safety Benefits ($)	$101,242	$(540,980)	$2,055,480
Data: Safety Benefits over 10 years ($)	$1,012,420	$(5,409,800)	$20,554,800

6. Conclusion and Future Research

Accurately predicting the safety effects of engineering countermeasures by determining the most optimal safety factors can improve the safety component of the transportation decision-making process (Herbel et al., 2010). Based on the literature review conducted by the project team, there are a limited number of studies that assess the safety impacts and the level of safety improvements realized from new location or widening projects. This research directly addresses this gap in the literature by developing (using multiple methods and approaches that are appropriate for the available data) and providing safety benefit factors for multiple types of new location and highway widening projects.

Taking into account the limited amount of data available at the time projects are scored, the research team developed Safety Benefit Factors (SBFs) and guidance that can be easily integrated into NCDOT's current project prioritization process. For new location projects involving the introduction of a bypass roadway, the research team applied a naïve empirical Bayesian (EB) before-after method to develop SBFs. This approach considers the before period to comprise only the original roadway, whereas the after period to comprise of both the original roadway and the bypass. SBFs for relevant widening project types were developed use of Safety Performance Functions from the 1st edition of the HSM that were calibrated using North Carolina data. Additionally, other SBFs were recommendations based on an analysis of relevant studies in the FHWA Crash Modification Factors Clearinghouse that provided SBFs with a quality rating of 4 (out of 5) stars or higher.

The resulting findings and SBF recommendations are summarized in Exhibit 30 below. These recommendations are detailed in Exhibit 13, Exhibit 19, Exhibit 20, and Exhibit 21. In addition, the research team developed brief guides explaining SBF recommendations for specific project types in the form of one-page summaries. These guides are presented in Appendix 7.

In total, this study resulted in the generation of 11 new SBFs for NCDOT and the confirmation of 2 SBFs already utilized by NCDOT. Additionally, approaches for developing SBFs using North Carolina project and crash data were also developed through this research. These findings and approaches can be used by NCDOT into the future to develop more reliable estimations of safety benefits for proposed projects, and ultimately improve the quality of North Carolina transportation projects developed in the future.

The SBF recommendations outlined in this study are based on the data and methods available to NCDOT and the research team during this study. In the future, NCDOT can benefit from collecting targeted data for project types of interest. For example, knowing the volumes that can be expected for new location projects after bypass installation under certain conditions and capturing driveway density data can increase the accuracy of SBF results. NCDOT can enhance the reliability of SBFs for new location and widening projects by incorporating additional CMFs (4 starts or higher), refined HSM methods, new research like NCHRP Project 17-72, and project data as such resources become available.

Exhibit 30. Summary of All Recommended SBF Updates

Specific Improvement Type (SIT) Group	Project Type	Area Type	Current NCDOT SBF	Recommended SBF	Source of Recommendation
5 - Construct Roadway on New Location	Freeway Bypass	Urban/ Rural	10	20	Developed through this study
	Superstreet Bypass	Urban/ Rural	5	30	Developed through this study
	All other projects	Urban/ Rural	-	30	Developed through this study
1 - Widen Existing Roadway	Widen 2 lane roadway to 4 lane divided roadway	Rural	55	60	Developed through this study
	Widen 2 lane roadway to 4 lane divided roadway (w/o controlled access)	Urban	-	0*	CMF Clearinghouse
	Install two-way left turn lane on a two lane roadway	Urban/ Rural	20	20	CMF Clearinghouse
	Install two-way left turn lane on a two lane roadway	Urban	-	0	Developed through this study, matches CMF Clearinghouse
	Install two-way left turn lane on a two lane roadway	Rural	-	30	Developed through this study
	Widen 4 lane undivided roadway to 4 lane divided roadway	Urban	-	20**	Developed through this study
	Widen 4 lane undivided roadway to 5 lane roadway	Urban	-	30	Developed through this study, matches CMF Clearinghouse
	Widen 4 lane divided roadway to 5 lane roadway	Urban	-	0	Developed through this study
	Widen 4 lane divided roadway to 6 lane divided roadway	Urban	15	15	CMF Clearinghouse

*Use with caution: SBF developed through this study shows no change in crashes, while CMF Clearinghouse SBF shows 65% crash reduction based on multiple sections of the same roadway

**Use with caution due to limited sample available for calculations

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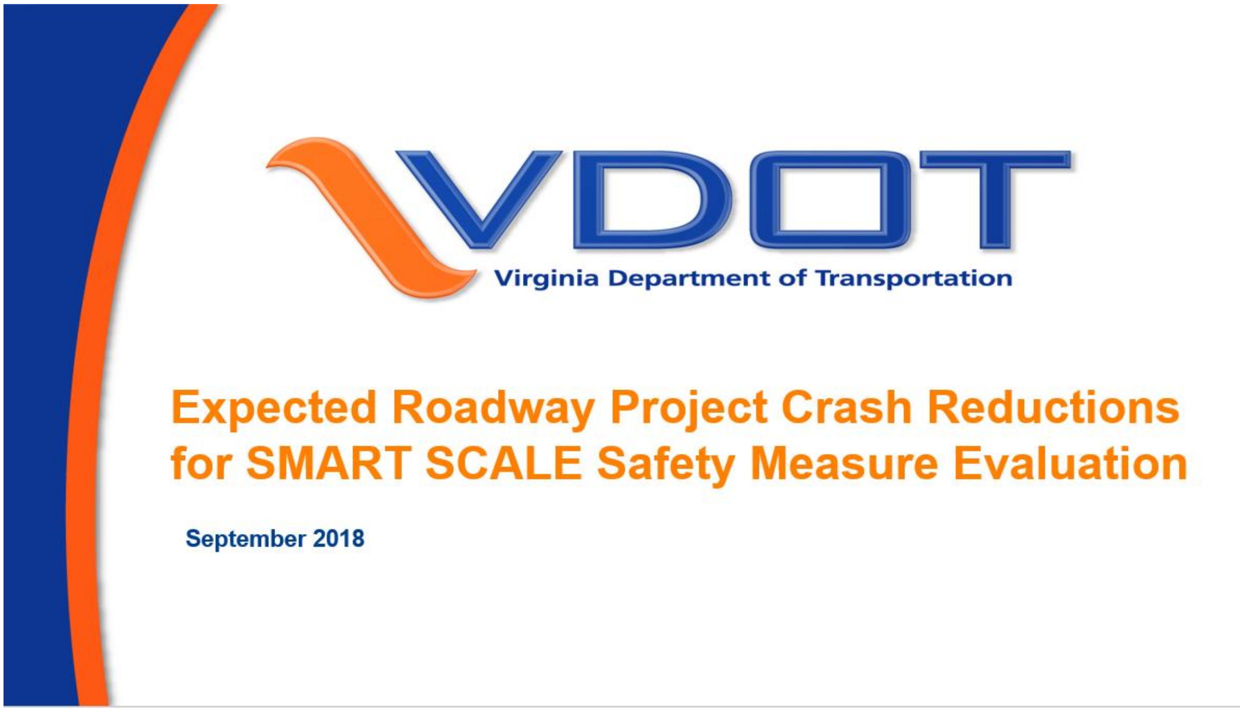
Appendix 1. Virginia Case Study: Planning-Level Crash Modification Factors



Click to add title

1. Using Crash Modification Factors for SMART SCALE Safety Evaluation

SMART SCALE Safety Measures

ID	Measure Name (% Weight)	Measure Description	Measure Objective
S.1	EPDO of Fatal and Injury crashes (50%)*	Equivalent property damage only (EPDO) of fatal and injury crashes expected to be avoided due to project implementation	Estimate number of fatalities and injury crashes (weighted by "equivalent property damage only" crash value used by FHWA) at the project location and the expected effectiveness of project specific countermeasures in reducing crash occurrence
S.2	EPDO Rate of Fatal and Injury crashes (50%)	Equivalent property damage only (EPDO) of fatal and injury crashes per 100 million vehicle miles traveled (VMT) expected to be avoided due to project implementation	Similar to S.1, but by focusing on the change in fatality and injury crashes (weighted by "equivalent property damage only" value used by FHWA) per VMT. The measure considers projects that address areas with a high rate of crashes that may be outside of high-volume roadways

Source: SMART SCALE Technical Guide table 3.1 (Note- * Transit projects are weighted 100% on S.1)

Determining Project Expected Crash Reductions

Safety Measures assessment approach for Roadway Improvements Based on the SMART SCALE Technical Guide :

Roadway projects on existing alignments -

- Project potential or expected crash reduction percentage developed using FHWA's Crash Modification Factors (CMF) Clearinghouse website, related safety research and Virginia crash rate summaries and models.

Roadway projects on new alignments –

- The crash reduction is difference between the expected crashes on the alternative route(s) due to changes in vehicle miles traveled and the expected crashes on the proposed build segment and connection intersections.

Transit; Travel Demand Management; and Freight Rail Improvement Project measures approach are explained in the SMART SCALE Technical Guide.

Click to add title

2. Developing Planning Level Fatal and Injury Crash CMFs

Developing Planning Level CMFs

Each project extent has several improvement categories -

Project Extents:

1. Intersection
2. Interchange
3. Segments
4. Bicycle and Pedestrian
5. Bridges

1. Intersection: Improvement Features

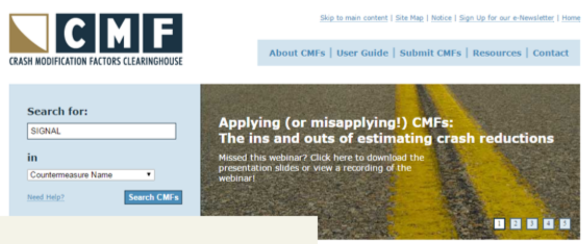
- Signal: New
- Roundabout: New
- New Turn Lane
- Add Turn Lane
- Remove minor approach left-turns (use right-turn and downstream u-turn)
- Improve skew angle

Developing Planning Level CMFs

Compile improvement category values from the CMF Clearinghouse

1. Intersection

- Signal: New



Countermeasure: Install a traffic signal

CMF	CRF(%)	Quality	Crash Type	Crash Severity	Area Type	Reference	Comments
0.56 [B]	44	★★★★★	All	All	Rural	Harkey et al., 2008	Countermeasure name has been slightly ... [read more]
0.23 [B]	77	★★★★★	Angle	All	Rural	Harkey et al., 2008	Countermeasure name changed to match ... [read more]
0.33	67	★★★★☆	Angle	Fatal,Serious Injury,Minor Injury	Urban	McGee et al., 2003	Countermeasure name has been slightly ... [read more]

Developing Planning Level CMFs

Define range of CMFs for various conditions to select applicable planning level value.

1. Intersection
   - Signal: New

Countermeasure: Install a traffic signal

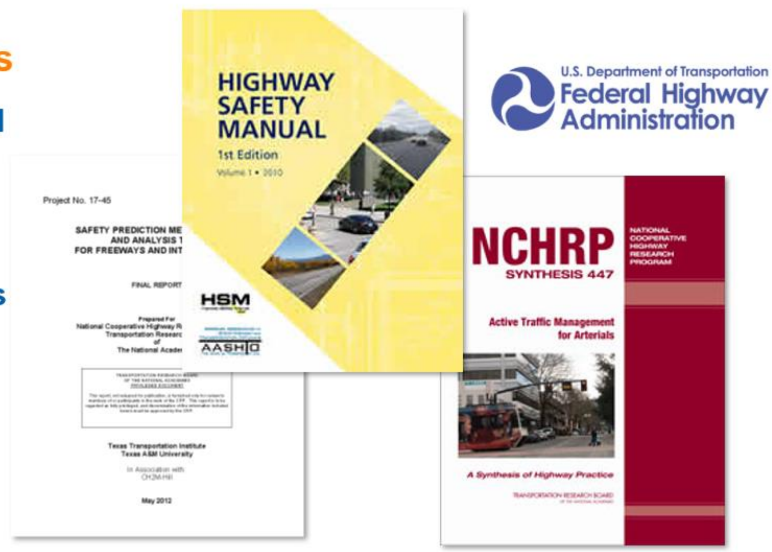
CMF	CRF(%)	Quality	Crash Type	Crash Severity	Area Type	Reference
0.56 [B]	44	★★★★★	All	All	Rural	Harkey et al., 2008
0.23 [B]	77	★★★★★	Angle	All	Rural	Harkey et al., 2008
0.33	67	★★★★☆	Angle	Fatal,Serious Injury,Minor Injury	Urban	McGee et al., 2003
0.4 [B]	60	★★★★☆	Left turn	All	Rural	Harkey et al., 2008
1.58	-58	★★★★☆	Rear end	All	Rural	Harkey et

Project Extent	Improvement Type	MIN	MAX	AVE	MEDIAN	STDEV	Planning Level CMF
Intersection							
	Signal: New	0.33	0.86	0.65	0.67	0.18	0.65

Developing Planning Level CMFs

Other sources for CMFs

- Highway Safety Manual
- FHWA
- NCHRP Reports
- VDOT Safety Performance Functions
- Virginia Crash Rates



CMFs for Roadway Widening Projects

Since roadway widening projects involve multiple improvement CMFs, Virginia SPF and crash rates were also used to determine planning CMFs:

- A safety performance function (SPF) is an equation for a given roadway type and number of lanes used to predict the average number of crashes per year at a location as a function of exposure (Annual Average Daily Traffic - AADT).
- SPF Predicted # Crashes = Function[AADT, Segment Length]
- Comparison of predicted crashes per mile for adding lanes → CMFs

The CMFs developed using SPFs are dependent on AADT, which is why the min, max, and average were calculated to show the range in CMFs

Improvement Type	MIN	MAX	AVE	Planning Level CMF
Rural Freeway: Widening 2 to 3 Lanes	0.25	1.24	0.66	0.7

CMFs for Roadway Widening Projects

Since roadway widening projects involve multiple improvement CMFs, Virginia crash rates were also used to determine planning CMFs:

:

- Virginia crashes and traffic volume were categorized by rural and urban functional classes and number of lanes to determine crash rates by severity
- The ratio of fatal and injury crash rates for adding a number of lanes to the existing number of lanes, was selected as the CMF –

For example, Urban arterial widening from 4 to 6 lanes crash rate ratios ranged from 0.7 to 0.9. A CMF of 0.85 was chosen based on the confidence limits of the estimates, VMT and miles of roadway used to determine the rates.

Click to add title

4. Fatal and Injury Crash CMFs for SMART SCALE

SMART SCALE Planning Level CMFs

Project Extent	Improvement Type/Features	F+I CMF
Intersections		
	Signal: New	
	Convert stop/yield control to signal	0.65
	Signal Upgrade	
	Convert pedestal to mast arm	*0.55*
	Enhanced conspicuity	*0.85*
	Roundabout:	
	Roundabout: Convert signal to roundabout	0.40
	Roundabout: Convert stop/yield control to roundabout	0.20

SMART SCALE Planning Level CMFs

Project Extent	Improvement Type/Features	F+I CMF
Intersections		
	Turn Lane(s)	
	New Turn Lane (none present)	0.85
	Add Turn Lane (to existing)	0.97
	Extend Turn Lane	*0.97*
	Access Management - Close median opening (allow right-in right-out only)	0.40
	Improve skew angle	
	3 Leg Intersection	0.70
	4 Leg Intersection	0.60
	Increase intersection radii	0.95

SMART SCALE Planning Level CMFs

Project Extent	Improvement Type/Features	F+I CMF
Intersections		
	Intersection Lighting	0.45
	Convert Unsignalized Intersection Warning Beacons from Static to Dynamic	0.95
	Reduce Conflicts	
	Two-way Stop Control to RCUT	~~0.65~~ **0.45**
	Signal Control to Signalized RCUT	~~0.80~~ **0.65**
	Signal Control to Continuous Green T Signal	0.85
	Displaced Left Turn	0.80
	Median U-Turn	0.70
	Median Acceleration Lane	0.85
	New Quadrant Roadway	Design Dependent

SMART SCALE Planning Level CMFs

Project Extent	Improvement Type/Feature	F+I CMF
Interchange		
	At Grade to New interchange	0.50
	Non-Freeway Segment: Convert Diamond to DDI	0.30
	Non-Freeway Segment: Convert Diamond to SPUI	0.60
	Non-Freeway Segment: Replace Arterial Turns with Loops or Directional Ramps	0.65
	Freeway Segment: Add Freeway Collector-Distributor Roads	0.90
	Add Freeway Independent Loop or Directional Ramp Entrances	0.95
	Extend ramp length	
	Extend ramp acceleration length (250')	0.80
	Extend ramp acceleration length (500')	0.65
	Extend ramp acceleration length (1000')	0.45
	Extend ramp deceleration length (250'-500') up to 700' in total length	0.85<700', 1.0≥700'

SMART SCALE Planning Level CMFs

Project Extent	Improvement Type/Feature	F+I CMF
Interchange		
	Add Ramp Lane(s)	
	Add entrance ramps (1 to 2 lanes)	1.60
	Add exit ramps (1 to 2 lanes)	1.65

SMART SCALE Planning Level CMFs

Project Extent	Improvement Type/Feature	F+I CMF
Segments	**Non-Freeway: (including 2 or more intersections)**	
	Rural Non-Freeway : Widening 2 lanes to multi-lane divided	0.70
	Urban Non-Freeway : Widening 2 lanes to 4-lane divided	0.80
	Urban Non-Freeway : Widening 2 lanes to 6-lane divided	0.75
	Urban Non-Freeway : Widening 4 lanes to 6+-lane divided	0.85
	Addition of truck climbing/passing lanes	0.80
	Addition of TWLTL	
	Non-Freeway: Four to Five Lane Conversion (TWLTL)	*0.45*
	Non-Freeway: Two to Three Lane Conversion (TWLTL)	*0.75*

SMART SCALE Planning Level CMFs

Project Extent	Improvement Type/Feature	F+I CMF
Segments	**Non-Freeway: (including 2 or more intersections)**	
	Non-Freeway: Signal Optimization / Adaptive	0.92
	Non-Freeway: ITS for ATM	0.90
	Non-Freeway: Alignment Reconstruction	0.85
	Non-Freeway: Widen Travel Lanes (by 2 - 3 ft.)	0.80
	Non-Freeway: Shoulder/Clear Zone Improvement	0.65
	Adding shoulder where not provided (0-4')	*0.75*
	Adding shoulder where not provided (4' or greater)	*0.65*
	Non-Freeway: Pavement Re-utilization (Road Diet)	0.55
	Non-Freeway: Access Management	
	Reduce Driveway Density (Eliminate/close)	0.70
	Provide median (Right-in Right-out only)	0.40
	Non-Freeway: Lighting	0.70
	Adding shoulder where not provided	*0.65*

SMART SCALE Planning Level CMFs

Project Extent	Improvement Type/Feature	F+I CMF
Segments	Freeways: (including 2 or more interchanges)	
	Freeway: ITS for Incident Management	0.85
	Freeway: ITS for ATM	0.80
	Freeway: ITS for Variable Speed Limits	0.90
	Freeway: Add Aux Lanes between Ramps	0.80
	Rural Freeway: Directional Widening 2 to 3 Lanes	0.70
	Urban Freeway: Directional Widening 2 to 3 Lanes	0.90
	Urban Freeway: Directional Widening 2 to 4+ Lanes	0.75
	Urban Freeway: Directional Widening 3 to 4+ Lanes	0.80
	Freeway: Lighting	0.70

SMART SCALE Planning Level CMFs

Project Extent	Improvement Type/Feature	F+I CMF
Bike and Pedestrian		
	Add Sidewalk	0.90
	Add Bike Lane	0.85
	Add Separate 10ft. Mixed-Use Trail	0.80
	Improve At-Grade Crossing	0.85
Bridges	Widen Shoulders	0.95
	Add Lanes	See segment values

Appendix 2. Colorado Case Study: Calculating Level Service of Safety

STEP 1: Determine the quantity of property damage only crashes, injury crashes, and fatal crashes; for predicted crashes, use one of the following methods:

- Federal Highway Safety Manual guidelines,
- Estimated by comparison to similar location (locations must have similar AADT and geometry); and/or
- Other FHWA approved methods.

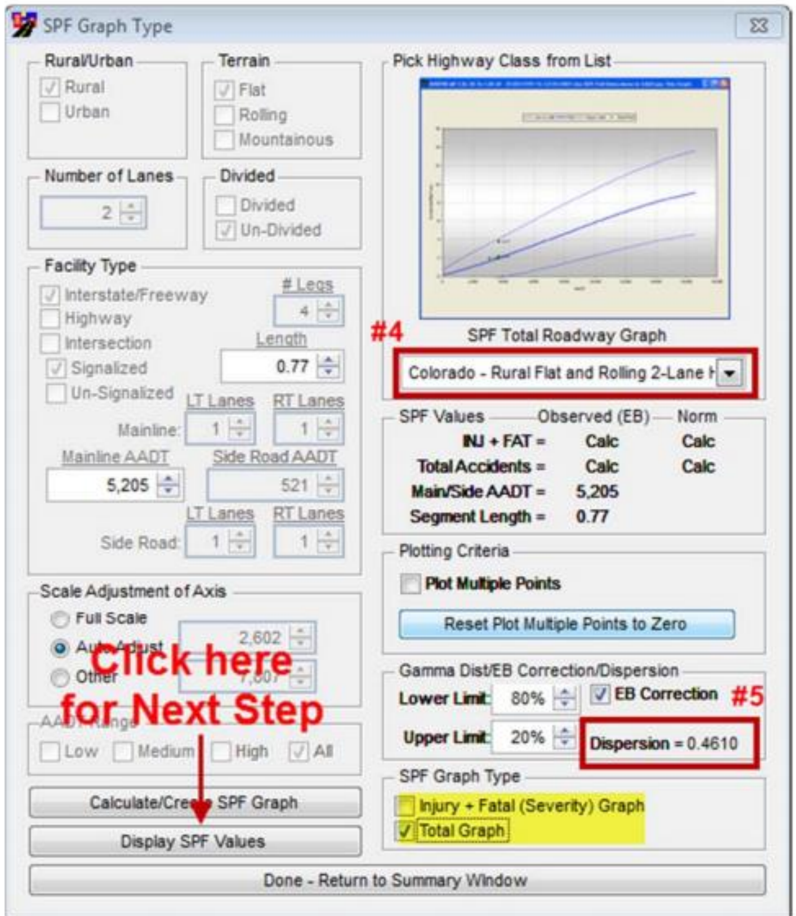
STEP 2: Determine the number of years of crash data used for analysis. The typical number of years of crash data used are as follows:

- 3 to 5 years of crash data for urban locations,
- 5 to 10 years of crash data for rural locations,

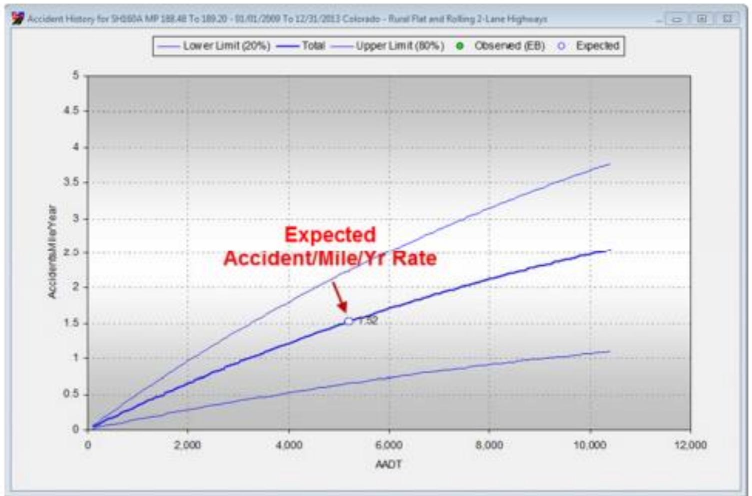
STEP 3: Determine the true length of the segment (using Vision Zero Suite traffic engineering software).

STEP 4: Determine the highway classification (i.e. Rural Flat and Rolling 2-Lane Highway, etc).

STEP 5: Determine the dispersion factor for the highway classification. The dispersion factor depends on the type of SPF graph (Total vs. Injury + Fatal) highlighted in yellow.



STEP 6: Determine the expected accidents/mile/year rate (APMPY) for the highway classification. The expected crash rate is dependent on the type of SPF graph highlighted in the above image.



STEP 7: Calculate the Accident Frequency.

$$Accident\ Frequency\ (\boldsymbol{\eta}) = \frac{\boldsymbol{Acc}}{\boldsymbol{LN}}$$

Where: $\boldsymbol{Acc} = PDO + INJ + FAT$ **for all crash SPF - LOSS**

$\boldsymbol{Acc} = INJ + FAT$ **for injury SPF – LOSS**

$\boldsymbol{L} = Length\ of\ the\ highway\ segment$

$\boldsymbol{N} = No.of\ years\ of\ data$

STEP 8: Calculate the Empirical Bayes (EB) Corrected Weight.

$$Weight\ (w) = \frac{1}{1 + \mu\boldsymbol{\alpha N}}$$

Where: $\mu = Expected\ Accident\ Rate$
$\boldsymbol{\alpha} = Dispersion\ Factor$
$\boldsymbol{N} = No.of\ years\ of\ data$

STEP 9: Calculate the EB Corrected Estimated Crash Rate.

$$EB\ Corrected\ Estimated\ Crash\ Rate = (\boldsymbol{w}\mu) + (1 - \boldsymbol{w})\ x\ \boldsymbol{\eta}$$

STEP 10: Plug the *EB Corrected Estimated Crash Rate* into the corresponding SPF graph to determine the LOSS of the segment.

Appendix 3. Kentucky Case Study: Comparison of Risk Rating and Crash Rates for Roads with Annual Average Daily Traffic Less Than or Equal to 400

Table 1. Kentucky Comparison of Risk Rating and Crash Rates for Roads with Annual Average Daily Traffic Less Than or Equal to 400

Number of Risk Factors Present	Roadway Miles	Sum of Vehicle Miles of Travel	Fatal Crash Rate	Serious Injury Crash Rate	Severe (fatal plus serious injury) Crash Rate
3	98	12,658,000	0.063	0.095	0.158
4	101	14,127,000	0.099	0.071	0.170
5	15	910,600	0.220	0.220	0.439

Appendix 4. Ohio Case Study: Economic Crash Analysis Tool (ECAT)

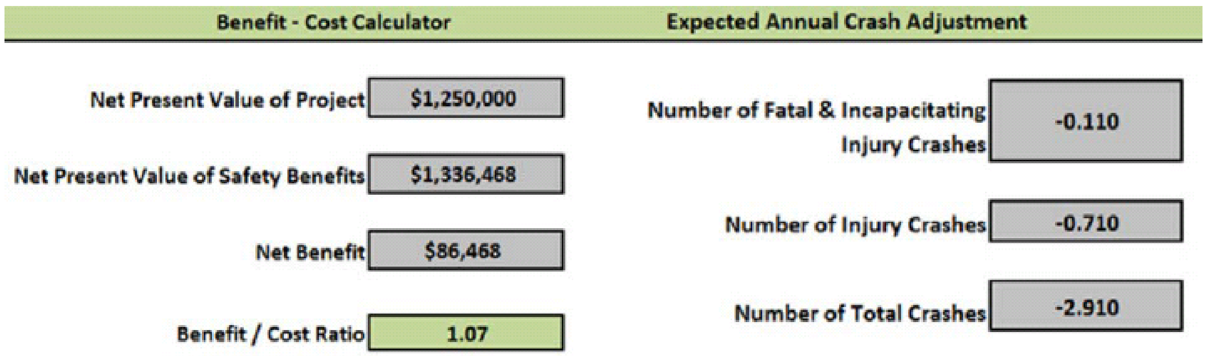
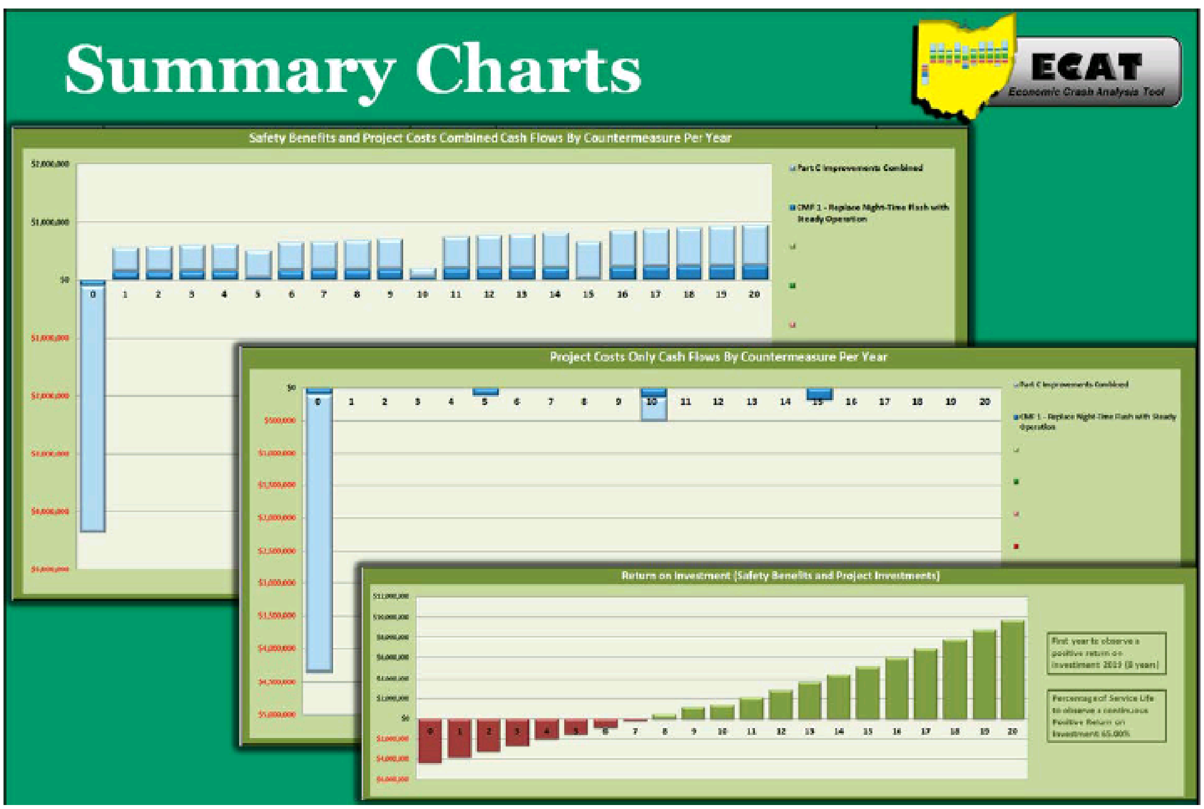
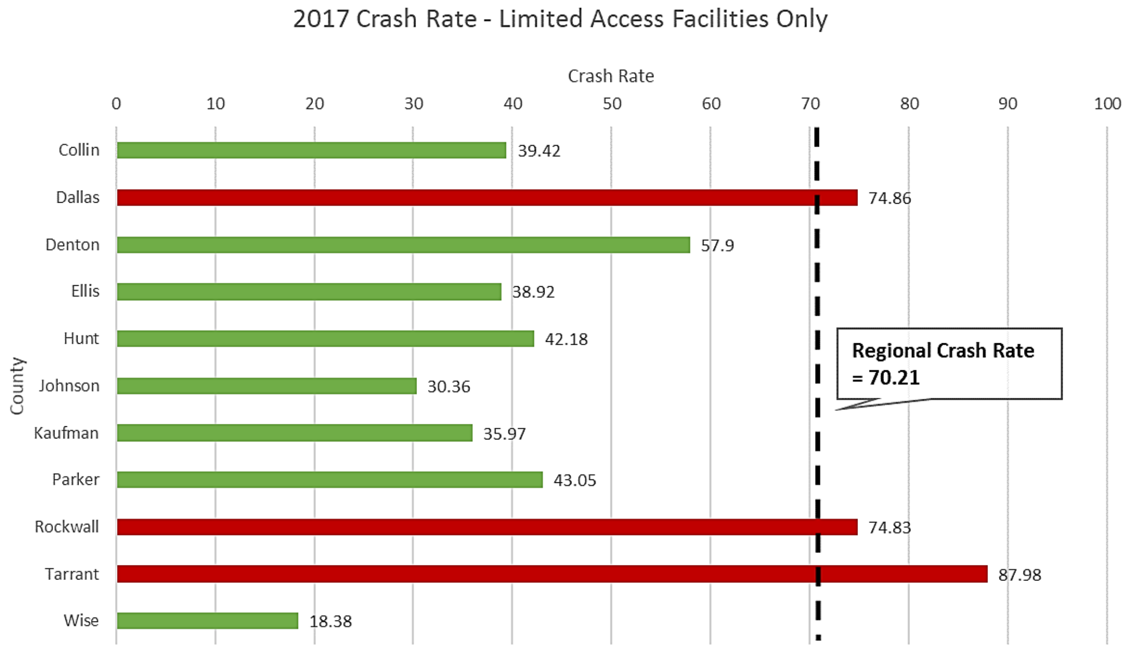


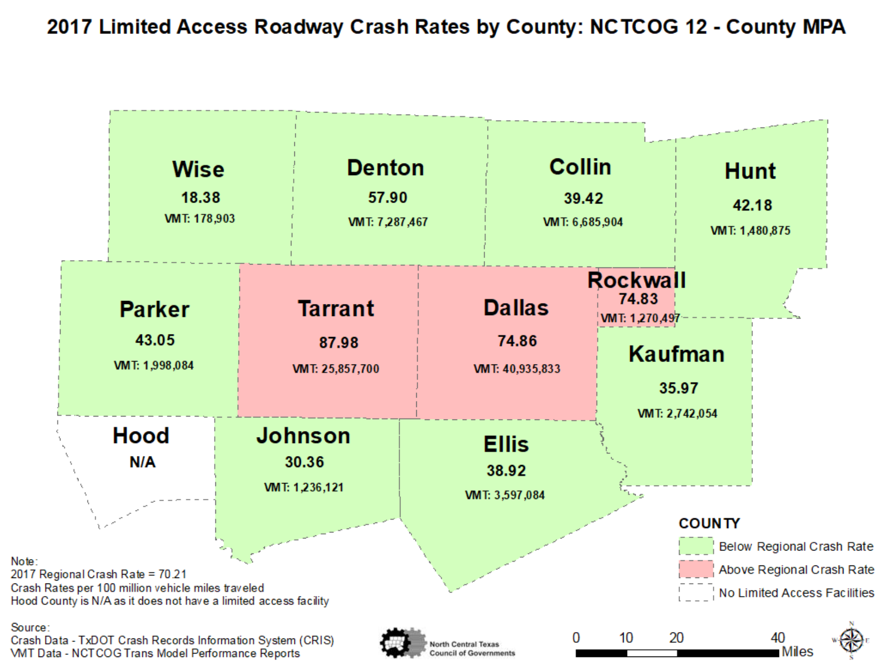
Figure 1. Sample economic analysis summary tables from ECAT.

Figure 2 shows an example of the economic analysis summary charts from ECAT. The upper left chart presents a summary of the combined projected cash flows by countermeasure by year. Negative cash flows represent an expenditure (greater investment than return) and positive cash flows represent a return on investment. The middle chart presents a summary of cash flows by year for project costs only. This example shows an initial project cost in year 0, and either maintenance or rehabilitation costs in years 5, 10, and 15. The bottom right chart shows the return on investment (i.e., cumulative annual benefits minus cumulative annual cost). Users can quickly identify the breakeven year as the first year with a positive return on investment. In this example, the breakeven year is year 8.



Appendix 5. North Central Texas Council of Governments (NCTCOG)Case Study Crash Rates and Contributing Factors





2018 TOP TEN CONTRIBUTING FACTORS

	Contributing Factors	Percentage
1	Speeding - (Overlimit/Unsafe Speed/Failed to Control Speed)	34.23%
2	Driver Related (Distraction in Vehicle/Driver Inattention/Road Rage/Drove Without Headlights/ Cell or Mobile Device Use - (Talking / Texting / Other / Unknown) [0.53%])	11.41%
3	Changed Lane when Unsafe	11.31%
4	Faulty Evasive Action	9.49%
5	Following too Closely	8.72%
6	Failed to Drive in Single Lane	8.26%
7	Under Influence (Had been Drinking / Alcohol /Drug)	5.61%
8	Fatigued or Asleep	2.16%
9	Disabled in Traffic Lane	1.79%
10	Pedestrian Failed to Yield Right of Way to Vehicle	1.26%

2017 TOP TEN CONTRIBUTING FACTORS

	Contributing Factors	Percentage
1	Speeding - (Overlimit/Unsafe Speed/Failed to Control Speed)	33.15%
2	Failed to Drive in Single Lane	10.44%
3	Driver Related (Distraction in Vehicle/Driver Inattention/Road Rage/Drove Without Headlights/ Cell or Mobile Device Use - (Talking / Texting / Other / Unknown) [0.07%])	10.24%
4	Under Influence (Had been Drinking / Alcohol /Drug)	9.10%
5	Faulty Evasive Action	7.88%
6	Changed Lanes when Unsafe	6.81%
7	Following too Closely	3.98%
8	Pedestrian - Failed to Yield ROW to Vehicle	3.71%
9	Disabled in Traffic Lane	2.36%
10	Fatigued or Asleep	2.09%

2016 TOP TEN CONTRIBUTING FACTORS

	Contributing Factors	Percentage
1	Speeding - (Overlimit/Unsafe Speed/Failed to Control Speed)	34.63%
2	Changed Lanes when Unsafe	13.02%
3	Driver Related (Distraction in Vehicle/Driver Inattention/Road Rage/Drove Without Headlights/ Cell or Mobile Device Use - (Talking / Texting / Other / Unknown) [0.68%])	12.23%
4	Following too Closely	10.83%
5	Faulty Evasive Action	7.09%
6	Failed to Drive in Single Lane	6.95%
7	Under Influence (Had been Drinking/Alcohol/Drug)	3.19%
8	Failed to Yield ROW (To Pedestrian/Turning Left/Yield Sign)	2.79%
9	Fatigued or Asleep	1.50%
10	Turned Improperly (Cut Corner on Left/Wide Right/Wrong Lane)	1.13%

2015 TOP TEN CONTRIBUTING FACTORS

	Contributing Factors	Percentage
1	Speeding - (Overlimit/Unsafe Speed/Failed to Control Speed)	32.10%
2	Driver Related (Distraction in Vehicle/Driver Inattention/Drove Without Headlights/Road Rage)	11.56%
3	Faulty Evasive Action	9.68%
4	Changed Lanes when Unsafe	8.75%
5	Following too Closely	8.36%
6	Failed to Drive in Single Lane	6.59%
7	Under Influence (Had been Drinking/Alcohol/Drug)	4.57%
8	Disabled in Traffic Lane	2.24%
9	Fatigued or Asleep	1.94%
10	Sick or Ill (Explain in Narrative)	1.01%

Appendix 6. Empirical Bayes (EB) Methodology

In the EB approach, the estimated change in safety for a given crash type at a site is given by the equation in Figure A6-1.

Exhibit A6-1. Equation. Estimated Change in Safety

$$\Delta Safety = \lambda - \pi$$

Where:

λ = Expected number of crashes that would have occurred in the after without the treatment.

π = Number of reported crashes in the after period.

The sum of the annual SPF estimates for the before period (P) was combined with the count of crashes (x) in the before period at a treatment site to obtain an estimate of the expected number of crashes (m) before the treatment was applied.

Exhibit A6-2. Equation. Empirical Bayes Estimates of Expected Crashes in the Before Period

$$m = w(P) + (1 - w)(x)$$

Where the EB weight, w, was estimated from the mean and variance of the SPF estimate using the equation in Figure A6-3.

Exhibit A6-3. Equation. Empirical Bayes Weight

$$w = \frac{1}{1+kP}$$

Where:

k = Overdispersion parameter of the negative binomial distribution.

The expected number of crashes in the after period, λ, was calculated by applying a factor to m as seen in the equation in Figure A6-4Exhibit . This factor was the sum of the annual SPF estimates for the after period (A) divided by P.

Exhibit A6-4. Equation. Empirical Bayes Estimates of Expected Crashes in the After Period

$$\lambda = m \times \left(\frac{A}{P}\right)$$

The estimate of λ and variance of λ, were then summed over all sites to obtain λ_{sum} and $Var(\lambda_{sum})$. λ_{sum} was then compared with the sum of count of crashes observed during the after period over all sites (π_{sum}) to obtain the CMF (θ). The safety effect θ was calculated using the equation in Figure A6-5 and the standard error of θ was calculated using the equation in Figure A6-6.

Exhibit A6-5. Equation. CMF

$$\theta = \frac{\pi_{sum}/\lambda_{sum}}{1 + \left(\frac{Var(\lambda_{sum})}{\lambda_{sum}{}^{2}}\right)}$$

Exhibit A6-6. Equation. Standard Error of CMF

$$Standard\ Error\ of\ \theta = \sqrt{\frac{\theta^{2}\left(\frac{Var(\pi_{sum})}{\pi_{sum}{}^{2}} + \frac{Var(\lambda_{sum})}{\lambda_{sum}{}^{2}}\right)}{\left(1 + \frac{Var(\lambda_{sum})}{\lambda_{sum}{}^{2}}\right)^{2}}}$$

The percent change in crashes is calculated as $100(1-\theta)$. Therefore, a value of $\theta = 0.9$ with a standard of error of 0.05 indicates a 10% reduction in crashes with a standard error of 5%. Conversely, a value of $\theta = 1.2$ with a standard of error of 0.1 indicates a 20% increase in crashes with a standard error of 10%.

Appendix 7. SBF Recommendation One-Page Summaries

The following section outline the results of this study for relevant project types in the form of one-page summaries. These summaries were developed for project types that met the following criteria:

1. A recommended SBF was developed or identified through this study
2. The recommended SBF differs from that currently recommended by NCDOT
3. The SBF is not a special request that requires additional discussion with NCDOT

Full-page PDF versions of these documents will be provided to NCDOT with the final version of this report.

Exhibit A7-1. Summary: Construct Roadway on New Location - Freeway Bypass - Urban/Rural

NCDOT Prioritization > Safety Benefit Factors > **New Location Projects**

5A – Construct Roadway on New Location

Freeway Bypass – Urban/Rural*

SBF Development Method

This SBF was developed based on a type of before-after analysis that examined change in safety due to the addition of a bypass route. The "before" condition of the original roadway was compared to the "after" condition of the original roadway and the bypass with the expectation that safety on the original route would worsen in the absence of the bypass. This analysis incorporated data from NC bypass projects, historic NC safety data, and approaches supported by the Highway Safety Manual.

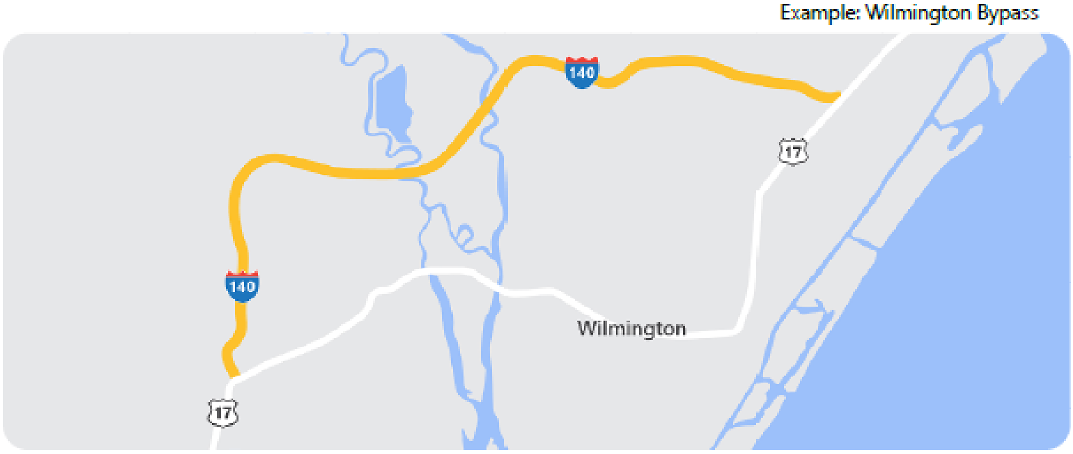
SBF Considerations

Total crashes saw a statistically significant crash reduction with the construction of a bypass on a new location. This recommended SBF is more conservative than other types in the SIT 5 group due to the small number of sites of this type in the sample used to develop the SBF paired with the research team's expertise related to safety outcomes.

Recommended Safety Benefit Factor (SBF) for all crash types for SIT 5A – Construct Roadway on New Location:

20

Example: Wilmington Bypass



**SIT name and number based on P5.0 data*

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Exhibit A7-2. Summary: Construct Roadway on New Location - Superstreet Bypass - Urban/Rural

NCDOT Prioritization | Safety Benefit Factors | **New Location Projects**

5B – Construct Roadway on New Location

Superstreet Bypass – Urban/Rural*

SBF Development Method

This SBF was developed based on a type of before-after analysis that examined change in safety due to the addition of a bypass route. The "before" condition of the original roadway was compared to the "after" condition of the original roadway and the bypass with the expectation that safety on the original route would worsen in the absence of the bypass. This analysis incorporated data from NC bypass projects, historic NC safety data, and approaches supported by the Highway Safety Manual.

Recommended Safety Benefit Factor (SBF) for all crash types for SIT 5B – Construct Roadway on New Location:

30

SBF Considerations

Total crashes saw a statistically significant crash reduction with the construction of a bypass on a new location.

Example: US 401 Rolesville Bypass

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Exhibit A7-3. Summary: Construct Roadway on New Location - All Other Projects - Urban/Rural

NCDOT Prioritization | Safety Benefit Factors | **New Location Projects**

5C – Construct Roadway on New Location

All Other Projects – Urban/Rural*

SBF Development Method

This SBF was developed based on a type of before-after analysis that examined change in safety due to the addition of a bypass route. The "before" condition of the original roadway was compared to the "after" condition of the original roadway and the bypass with the expectation that safety on the original route would worsen in the absence of the bypass. This analysis incorporated data from NC bypass projects, historic NC safety data, and approaches supported by the Highway Safety Manual.

Recommended Safety Benefit Factor (SBF) for all crash types for SIT 5B – Construct Roadway on New Location:

30

SBF Considerations

Total crashes saw a statistically significant crash reduction with the construction of a bypass on a new location.

Example: Jacksonville Parkway

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Exhibit A7-4. Summary: Widen 2 Lane Roadway to 4 Lane Divided - Rural

NCDOT Prioritization > Safety Benefit Factors > Widen Existing Roadway Projects

1B – Widen Existing Roadway

Widen 2 Lane Roadway to 4 Lane Divided – Rural*

SBF Development Method

This SBF was developed using Safety Performance Functions from the 1st edition of the Highway Safety Manual that were calibrated using NC data. This approach involves estimating the predicted number of crashes for the before and after facility types using predictive models.

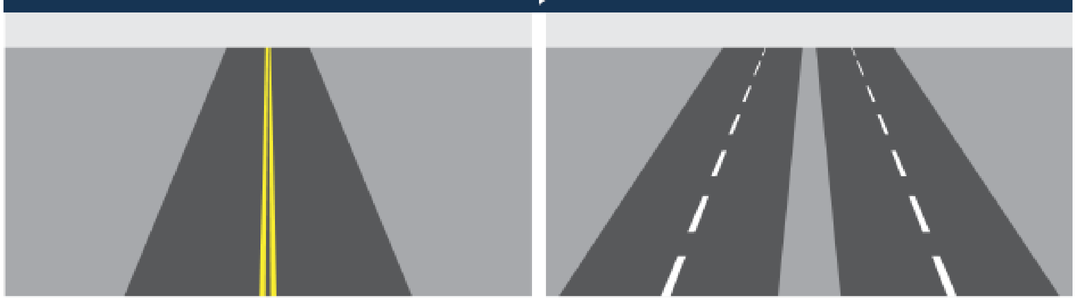
SBF Considerations

The SBF developed through this study (60) is consistent with the current NCDOT SBF (55).

Recommended Safety Benefit Factor (SBF) for all crash types for SIT 1B – Widen Existing Roadway:

60

2 Lane Roadway → 4 Lane Divided Roadway



**SIT name and number based on P5.0 data*

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Exhibit A7-5. Summary: Widen 2 Lane Roadway to 4 Lane Divided - Urban (without controlled access)

NCDOT Prioritization > Safety Benefit Factors > Widen Existing Roadway Projects

1G.1 – Widen Existing Roadway

Widen 2 Lane Roadway to 4 Lane Divided Roadway – Urban (without controlled access)*

SBF Development Method

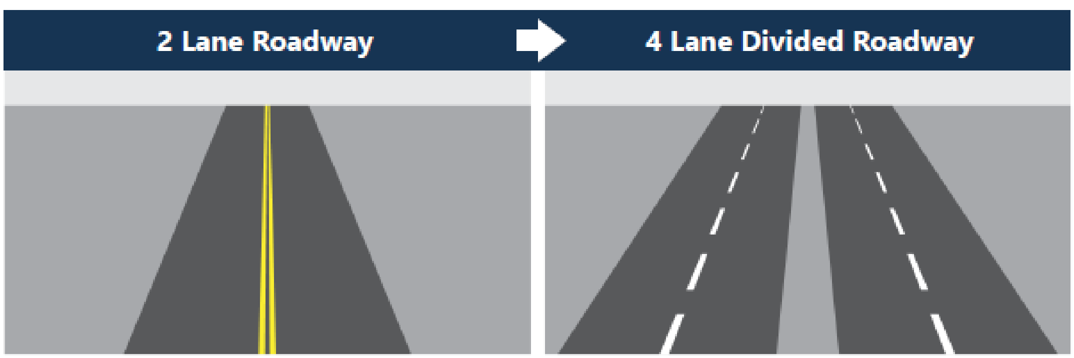
This SBF was developed using Safety Performance Functions from the 1st edition of the Highway Safety Manual that were calibrated using NC data. This approach involves estimating the predicted number of crashes for the before and after facility types using predictive models.

SBF Considerations

The SBF developed for NCDOT by the research team using NC data was lower than that presented in a CMF Clearinghouse study. However, the SBF from the study in the CMF Clearinghouse using Florida data may be overestimating the safety effect due to the small sample used for the estimation.

Recommended Safety Benefit Factor (SBF) for all crash types for SIT 1G.1 – Widen Existing Roadway:

0



**SIT name and number based on P5.0 data*

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Exhibit A7-6. Summary: Widen 4 Lane Undivided Roadway to 5 Lane Divided – Urban

NCDOT Prioritization > Safety Benefit Factors > Widen Existing Roadway Projects

1G.2 – Widen Existing Roadway

Widen 4 Lane Undivided Roadway to 5 Lane Divided Roadway – Urban*

SBF Development Method

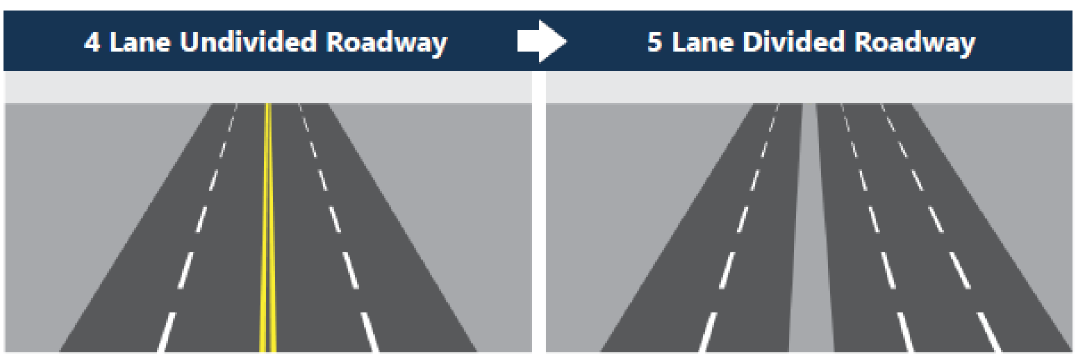
This SBF was developed using Safety Performance Functions from the 1st edition of the Highway Safety Manual that were calibrated using NC data. This approach involves estimating the predicted number of crashes for the before and after facility types using predictive models.

SBF Considerations

The SBF developed through this study is consistent with a sound SBF in the CMF Clearinghouse.

Recommended Safety Benefit Factor (SBF) for all crash types for SIT 1G.2 – Widen Existing Roadway:

30



**SIT name and number based on P5.0 data*

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Exhibit A7-7. Summary: Widen 4 Lane Divided Roadway to 5 Lane Divided – Urban

NCDOT Prioritization > Safety Benefit Factors > **Widen Existing Roadway Projects**

1G.2 – Widen Existing Roadway

Widen 4 Lane Divided Roadway to 5 Lane Divided Roadway – Urban*

SBF Development Method

This SBF was developed using Safety Performance Functions from the 1st edition of the Highway Safety Manual that were calibrated using NC data. This approach involves estimating the predicted number of crashes for the before and after facility types using predictive models.

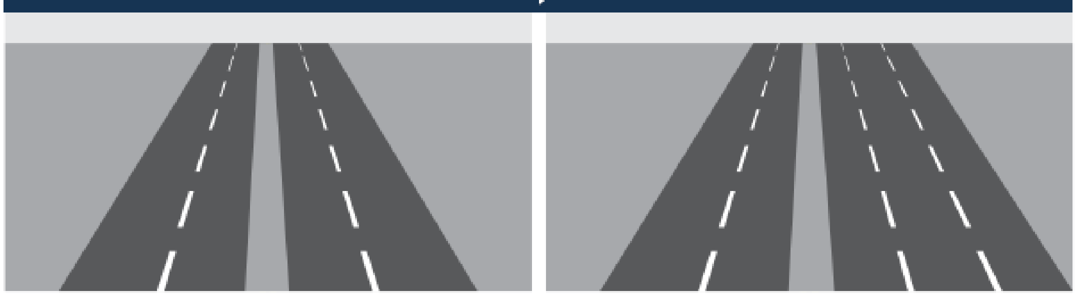
SBF Considerations

This SBF indicates no expected increase in safety benefits with the conversion.

Recommended Safety Benefit Factor (SBF) for all crash types for SIT 1G.2 – Widen Existing Roadway:

0

4 Lane Divided Roadway → 5 Lane Divided Roadway



**SIT name and number based on P5.0 data*

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Exhibit A7-8. Summary: Install Two-Way Left Turn Lane on a Two-Lane Roadway – Urban

NCDOT Prioritization > Safety Benefit Factors > Widen Existing Roadway Projects

1G.4 – Widen Existing Roadway

Install Two-way Left Turn Lane on a 2 Lane Roadway – Urban*

SBF Development Method

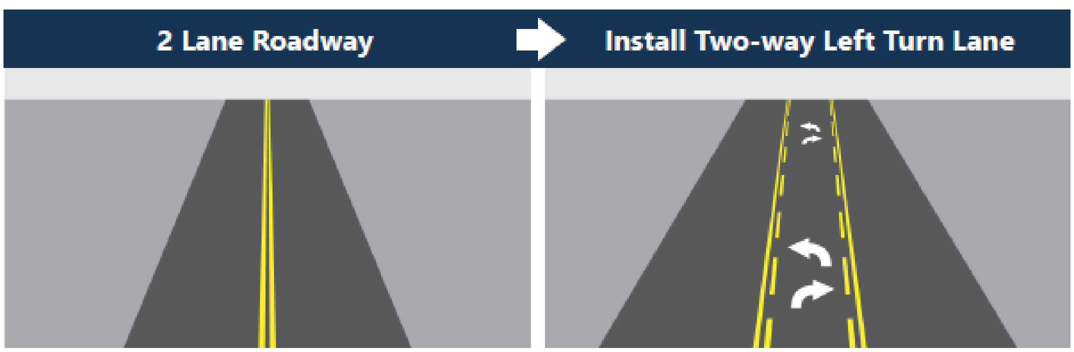
This SBF was developed using Safety Performance Functions from the 1st edition of the Highway Safety Manual that were calibrated using NC data. This approach involves estimating the predicted number of crashes for the before and after facility types using predictive models.

SBF Considerations

The SBF developed through this study is consistent with a sound SBF in the CMF Clearinghouse that uses NC data.

Recommended Safety Benefit Factor (SBF) for all crash types for SIT 1G.4 – Widen Existing Roadway:

0



**SIT name and number based on P5.0 data*

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Exhibit A7-9. Summary: Install Two-Way Left Turn Lane on a Two-Lane Roadway – Rural

NCDOT Prioritization > Safety Benefit Factors > Widen Existing Roadway Projects

1G.5 – Widen Existing Roadway

Install Two-way Left Turn Lane on a 2 Lane Roadway – Rural*

SBF Development Method

This SBF is based on a sound study in the FHWA Crash Modification Factors Clearinghouse.

SBF Considerations

The SBF in the CMF Clearinghouse uses NC data.

Recommended Safety Benefit Factor (SBF) for all crash types for SIT 1G.5 – Widen Existing Roadway:

30

2 Lane Roadway → Install Two-way Left Turn Lane

**SIT name and number based on P5.0 data*

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