FINAL REPORT

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State of Wyoming
Department of Transportation

CALIBRATING CRASH MODIFICATION FACTORS FOR WYOMING-SPECIFIC CONDITIONS: APPLICATION OF THE HIGHWAY SAFETY MANUAL, PART D – PHASE 2

Final Report
February 2020

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16. Abstract

The Highway Safety Manual (HSM) provides a quantitative measure of safety of various countermeasures known as Crash Modification Factors (CMF). CMFs provided in the HSM are calibrated based on data collected from a few states with specific roadway and climate characteristics in the US, which may not represent the same safety efficacy of countermeasures implemented in other regions. In this regard, Phase 1 of this project was aimed towards validating the applicability of the HSM to Wyoming conditions. Phase 2 of this project was carried out to fulfil the same objectives with conducting analysis to other countermeasures. The countermeasures which were analyzed in this study included 1) combined shoulder and centerline rumble strips, 2) centerline rumble strips only, 3) adding lane and divide, 4) snow fences, 5) variable speed limit corridors, 6) non-conventional intersections/interchanges (roundabout and diverging diamond interchange), and 7) urban/suburban five lane arterial corridors. Massive data collection efforts have been made to develop crash modification factors.

This study provided a set of methodologies to collect and impute data required for the application of the HSM. Moreover, the study verified and confirmed the suitability of other statistical techniques to assess the safety efficacy of countermeasures where data needed are not available. The results indicated that the majority of these countermeasures are statistically significant in reducing crash frequencies and/or severity.

17. Key Words
Highway Safety Manual; Crash Modification Factors; Safety Effectiveness; Shoulder Rumble Strips; Centerline Rumble Strips; Four-lane divided highway; Intersections; Roundabout; Diverging Diamond Interchange; Two-way left turn lane; Snow Fences; Variable Speed Limit; Wyoming

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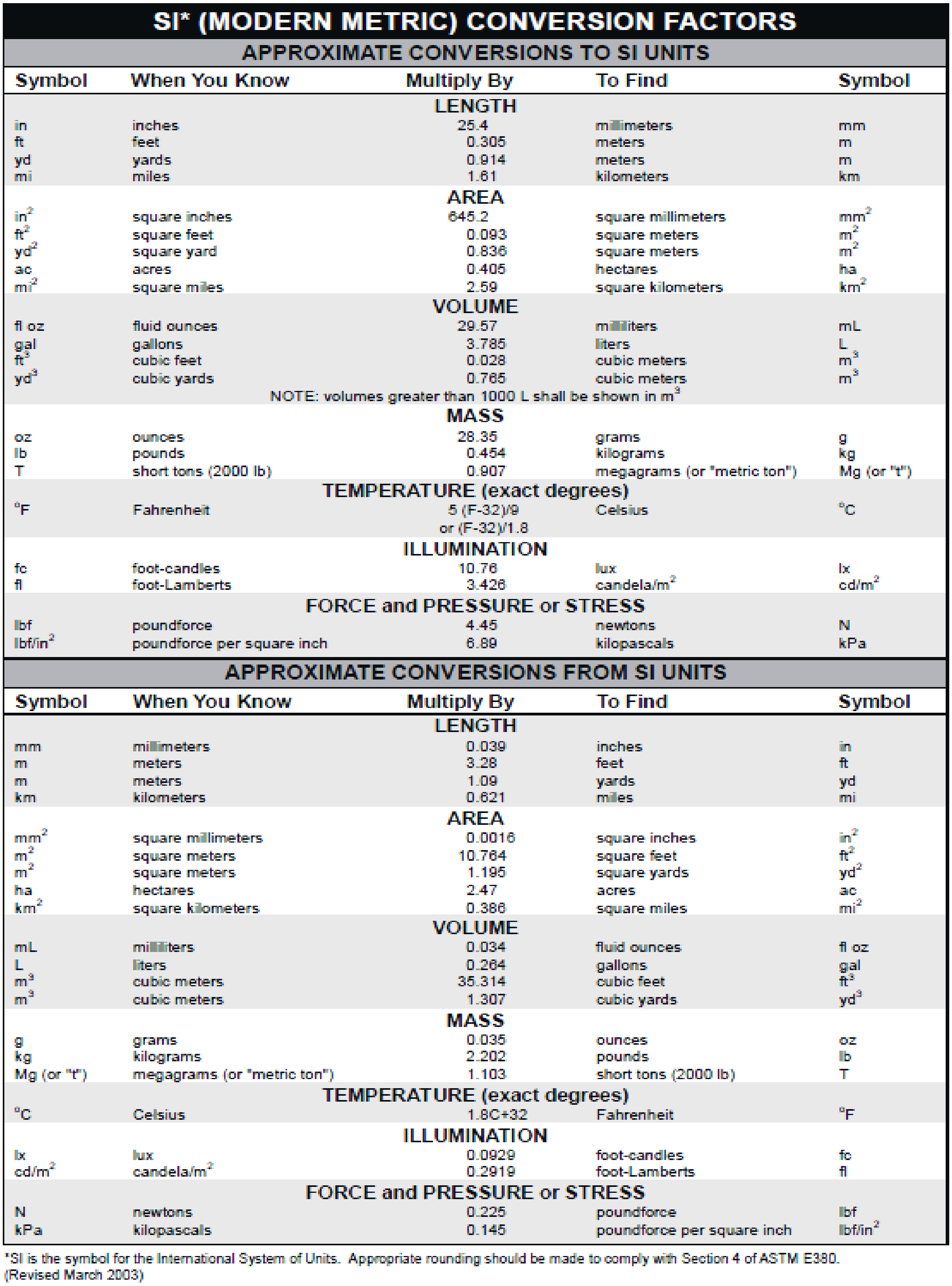

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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LIST OF ACRONYMS/ABBREVIATIONS

Acronym	**Description**
4SG	Four-leg signalized Intersections
AADT	Average Annual Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
AIC	Akaike Information Criterion
AICc	Corrected Akaike Information Criterion
C	Calibration Factor
CARE	Critical Analysis Reporting Environment
CI	Confidence Interval
CMFs	Crash Modification Factors
DOC	Degree of Curvature
DOT	Department of Transportation
DRL	Daytime Running Lights
EB	Empirical Bayes
exp	Exponential
F+I	Fatal and Injury
FARS	Fatality Analysis Reporting System
FHWA	Federal Highway Administration
FMVSS	Federal Motor Vehicle Safety Standard
GIS	Geographic Information System
HSM	Highway Safety Manual
ITS	Intelligent Transportation Systems
MARS	Multivariate Adaptive Regression Splines
MUTCD	Manual on Uniform Traffic Control Devices
MVMT	Million Vehicle Miles Traveled
NB	Negative Binomial
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NOAA	National Oceanic and Atmospheric Administration
PDO	Property Damage Only
RTM	Regression to the Mean
SE	Standard Error
SHSP	Wyoming Strategic Highway Safety Plan
SMoS	Surrogate Measures of Safety
SPaT	Signal Phasing and Timing
SPFs	Safety Performance Functions

SRS	Shoulder Rumble Strips
SW	Shoulder Width
TRB	Transportation Research Board
VG	Vertical Grade
VMT	vehicle miles traveled
vpd	vehicle per day
WY	Wyoming
WYDOT	Wyoming Department of Transportation
ZINB	Zero Inflated Negative Binomial
ZIP	Zero Inflated Poisson

CHAPTER 1- EXECUTIVE SUMMARY

Phase 1 of this project was aimed toward validating the applicability of the Highway Safety Manual (HSM) to the conditions in Wyoming. HSM provides a quantitative measure of safety of various countermeasures known as Crash Modification Factors (CMFs). CMFs are provided for four distinct groups of treatments; roadway segments (e.g., rumble strips, passing lanes, etc.), intersections (e.g., flashing yellow arrows), special facilities (e.g., highway-rail crossing), and road networks. CMFs provided in the HSM were calibrated based on data collected from a few states with specific roadway and climate characteristics in the United States (US) that may not represent the same safety efficacy of countermeasures implemented in other regions with different characteristics. The objectives of this study were:

- To validate the applicability of HSM to the conditions in Wyoming.
- To calibrate CMFs for various countermeasures in Wyoming.
- To provide recommendations in terms of data requirements, how to mitigate data shortcoming, and to examine the applicability of alternative data collection, imputation techniques, and analytical methodologies in case of missing key data.

Phase 2 of this project was carried out to extend the safety assessment to other countermeasures implemented on Wyoming roadways and intersections. The countermeasures which were analyzed in this study included 1) combined shoulder and centerline rumble strips, 2) centerline rumble strips, only, 3) adding lane and divide, 4) snow fences, 5) variable speed limit corridors, 6) unconventional intersections (roundabout and diverging diamond interchange), and 7) urban/suburban five lane arterial corridors. Massive data collection efforts have been taken place to develop CMFs. Various data sets were obtained from WYDOT, which included construction dates of countermeasures, crash data acquired from the Critical Analysis Reporting Environment (CARE) software, roadway geometry, and traffic characteristics. Other manual data were collected by utilizing non-traditional data sources. Pathway video logs, as well as satellite imagery from Google Earth Pro® and Google Maps, were manually reduced to substitute missing construction dates, countermeasures locations, and the different types of the investigated countermeasures.

Depending on the quality and availability of the developed datasets, various statistical methodologies were utilized to conduct this study. These methodologies included descriptive and preliminary analysis, observational before-after analysis, and cross-sectional techniques. Several

Wyoming-specific safety performance functions (SPFs) were calibrated as part of the CMFs development process.

This study provided a set of methodologies to collect and impute data required for the application of HSM. Moreover, the study verified and confirmed the suitability of other statistical techniques to assess the safety efficacy of countermeasures where data needed are not available. The results indicated that the majority of these countermeasures were statistically significant in reducing crash frequencies and severity.

CHAPTER 2-INTRODUCTION

Roadway network and transportation systems in the US are extremely important as they accommodate approximately 269 million registered vehicles with about 222 million licensed drivers [1], [2]. Frequency and severity of crashes are considered the main indicators of the traffic safety performance for different roadway facility types. The primary tasks of traffic safety analysts and decision-makers is to provide insight that would help to reduce crash frequencies, as well as crash severities of the injuries sustained by those involved in crashes. Crash severity is categorized into five levels using the "KABCO" Scale, in which K represents fatalities, A, B, and C are three levels of road traffic injuries and O represents property damage only crashes. According to the World Health Organization (WHO) report, traffic fatalities are predicted to become the seventh leading cause of death by 2030 [3]. Moreover, road traffic injuries (i.e. A, B, and C levels) are the leading cause of death among the age group of 15 to 29 [3].

The economic impacts of crashes are also notable. In the US, total societal crash costs (i.e., comprehensive crash costs) resulting from motor vehicle crashes amounted to $836 billion in 2010 [4]. The majority of this value represents the monetary value of lost quality-of-life, and the rest is consequential economic impacts. The comprehensive crash cost of each fatality is estimated to be $9.6 million (2016 dollars) [5]. In the US, motor vehicle crashes resulted in 37,461 fatalities in 2016, which was an increase of 5.5 percent from 2015 [6].

Since society is so reliant on roadway systems, transportation organizations, not limited to state DOTs, have been working to identify contributing factors and hazardous locations that may help explaining why there is such a high traffic-related fatality rate in the US. Through these investigations, it was found that winter weather-related conditions to be concerning contributing factors. In 1990, a study concluded that the effects of adverse weather conditions "can lead to an increase in traffic accidents by 100 percent or more when compared with normal weather conditions" [7]. Between the years of 2007 and 2016, the Federal Highway Administration (FHWA) stated that 21 percent of vehicle crashes in the US were weather-related. Through further investigation, FHWA was able to relate approximately 47 percent of those weather-related crashes to having snow/sleet weather conditions and/or icy/snowy/slushy pavement conditions at the time the crashes occurred [8]. Adverse weather conditions in states that experience harsh winters are commonly defined as snowfall, blizzard, fog, wind, and rain [9].

Combinations of these conditions create hazardous road conditions with higher potentials of injuries and fatalities.

Wyoming has been identified as an area of concern due to the consistently high fatality rates that exceeded the national fatality rates for many years, as shown in Figure 2.1. Concerns of USDOT are further heightened by the fact that Wyoming has the smallest population of the 50 US states, at 573,720 residents as of 2018 [10]. However, Wyoming is known for having harsh winters filled with frigid temperatures, high-speed winds, and heavy snowfalls. Since 1917, when the roadways in Wyoming were being constructed, Wyoming Department of Transportation (WYDOT) has battled to keep the roadways surface clear. During the winter season, Wyoming drivers are constantly facing blowing snow, icy roads, and consistent road closures. These conditions contribute to reduced visibility for drivers, poor road surface conditions, excessive snow drifting, and increased number of crashes [11]. In addition to snow plowing being costly, snow removal crews struggle to keep the roads clear within an effective timeframe throughout the state.

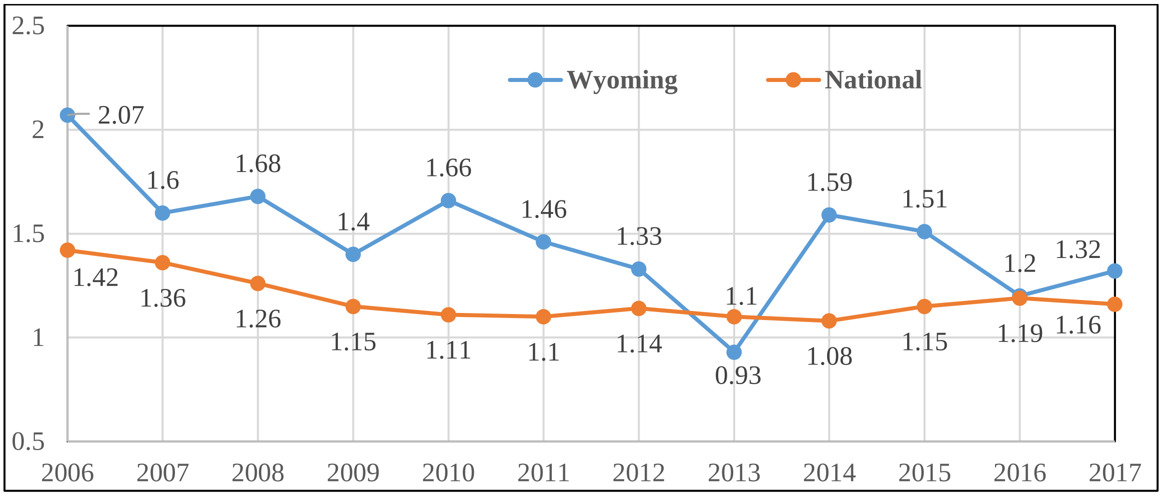


Figure 2.1 National and Wyoming Fatality Rates per 100 MVMT (2006-2017)
(Source: Fatality Analysis Reporting System Encyclopedia)

HSM provides the practitioners with analytical tools and techniques to evaluate the safety performance of roadway facilities [1]. Their performance could be evaluated by estimating the expected crash frequency using the observed and predicted crashes. These analyses are conducted with the aim to identify and evaluate options to reduce the frequency and/or severity of crashes. The American Association of State Highway and Transportation Officials (AASHTO) published the HSM in 2010 to provide a consistent state-of-practice on conducting quantitative safety studies. Previously, researchers and practitioners utilized descriptive methods to analyze crash frequency and severity. Introduction of quantitative and predictive methods in the HSM has allowed transportation professionals to make improved decisions to enhance the traffic safety.

The National Cooperative Highway Research Program (NCHRP) project 17-50, entitled “Lead State Initiative for Implementing the Highway Safety Manual” goal was to advance the implementation of the HSM in the US. As a result, the Implementation Guide for Managers was published in 2011 to assist highway agencies in implementing the HSM [1]. Twenty-one states participated in the NCHRP 17-50 project, 13 of them were considered lead states and 8 were considered as supporting states. Lead and supporting states are shown in Figure 2.2, with lead states in purple, and support states in orange.

Figure 2.2 Lead States and Support States in the

(Source: NCHRP 17-50 HSM Lead State Initiative Project)

The HSM should also be integrated into the different highway project development processes. In 2012, FHWA provided a guide on how to apply the HSM into highway planning, alternatives development and analysis, design, operations, and maintenance [2]. The purpose of this guide was to provide the practitioners with examples and ideas for integrating safety performance measures into the project development process.

The implementation and application of the HSM has gained a lot of interest from practitioners and researchers since its publication. State DOTs and researchers are keen to work on adopting and calibrating HSM approaches to match their specific conditions. Florida [3], [4], and [5], Utah [6], Kansas [7], and Oregon [8], have already worked on calibrations and modifications of the SPFs in the HSM on their own roadways. Although other states have calibrated their own SPFs and CMFs, it was clearly found that the HSM, in its current format, may not be transferrable to Wyoming conditions. Developing accurate CMFs representing Wyoming-specific conditions will help in prioritizing and selecting the most appropriate and cost-effective countermeasures for the situation.

OVERVIEW OF THE HIGHWAY SAFETY MANUAL

The primary objective of the practitioners working with traffic safety is to reduce the number and severity of crashes. HSM provides the practitioners with analytical tools and techniques to estimate the expected crash frequency and severity with the aim to identify and evaluate options to reduce the number and severity of crashes. AASHTO published the HSM in 2010. Previously, researchers and practitioners utilized descriptive methods to analyze crash frequency and severity. Introduction of quantitative, predictive methods in HSM has allowed transportation professionals to make improved decisions based on data-driven predictive safety performance. HSM consists of 4 main parts and 17 chapters [12]. Figure 2.3 shows a flowchat that represents the organization of the parts and chapters included in the HSM. Part A consists of Chapter 1 to 3, which includes introduction and overview of the HSM, an overview of the human factors related to road safety and fundamental concepts that are necessary to understand and implement the predictive method, and CMFs or evaluation methods described in the HSM in the later chapters. Part B describes the steps in the roadway safety management process. The arrangement of the chapters is chronological, and one should follow the steps in the order described when investigating an existing roadway network with an objective of reducing crash frequency and severity. Six chapters (i.e., chapters 4 to 9) describe the six steps for a roadway management process, shown in Figure 2.4, which include requirements and methods to select improvement sites, diagnosis, countermeasure selection based on the improvement required, economic appraisal, project prioritization, and safety effectiveness evaluation.

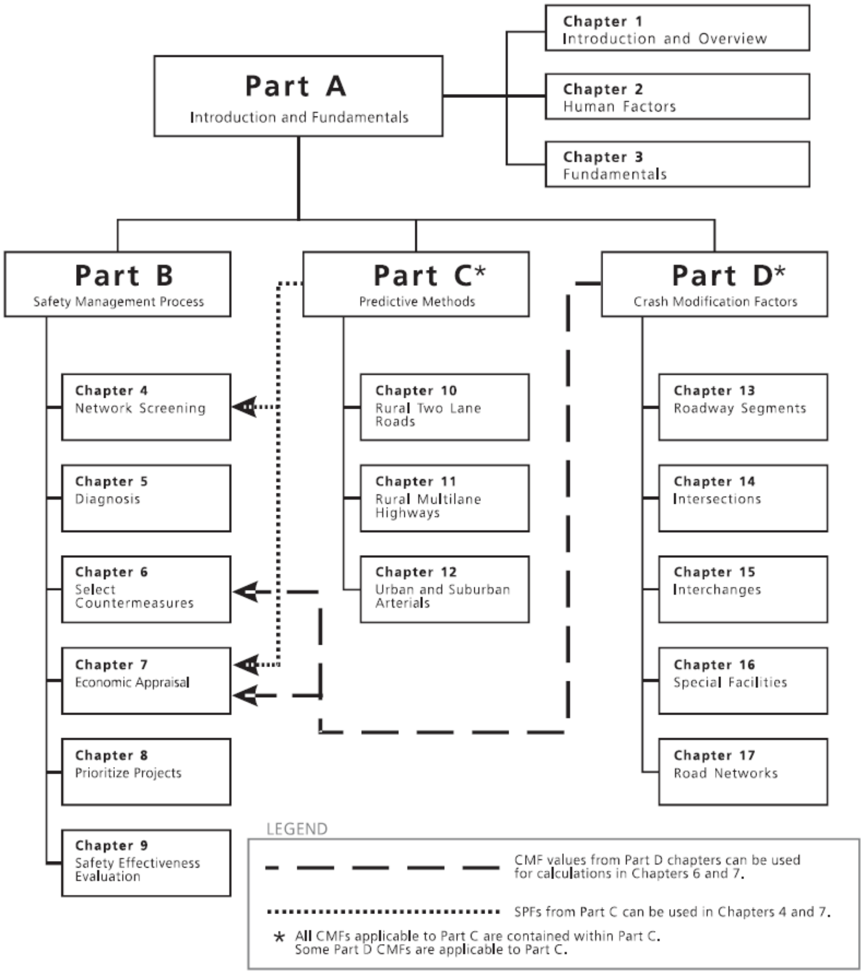


Figure 2.3 Organization of the Highway Safety Manual. Source: HSM 2010

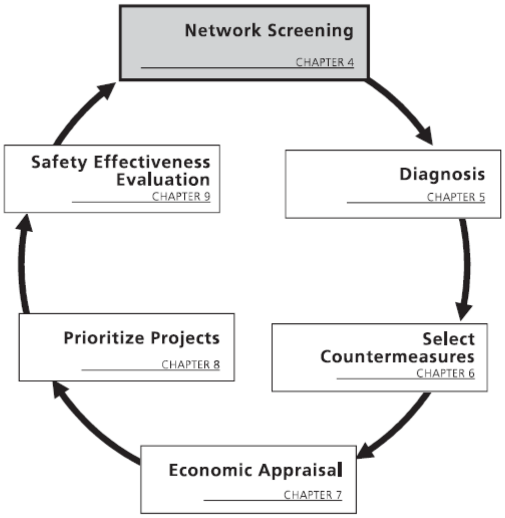


Figure 2.4 Roadway management process. Source: HSM 2010

Part C provides predictive methods to estimate expected crash frequency of different types of roadway network or individual site for existing conditions, alternative conditions or proposed new roadways. Predictive Models in Part C include SPFs, CMFs and Calibration Factors. Part C of the HSM provides detailed predictive methods for the following three types of roadway facilities; chapter 10- Rural Two-Lane Two-Way Roads, chapter 11- Rural Multilane Highways, chapter 12- Urban and Suburban Arterials.

The HSM provides CMFs in four different categories: Roadway segments (e.g., roadside elements, alignment, signs, rumble strips, etc.), intersections (e.g., traffic control), special facilities (e.g., Highway-rail crossings, and interchanges), and road networks. CMFs are defined as a measure of the safety effectiveness of a particular treatment or a design element. They could be applied individually if a single treatment is proposed or multiplicatively if multiple treatments are implemented. Other possibilities for multiple treatments are to divide or interpolate CMFs. To calibrate CMFs, various statistical techniques are found in the literature. Among these techniques, the observational before-after Empirical Bayes (EB) is considered the most common and reliable approach to quantify the safety effectiveness of a countermeasure. The EB method can overcome various limitations faced by naïve before-after evaluation (mostly used by transportation agencies for its simplicity and minimum data requirements) and observational before-after with Comparison Group (CG) methods by not only accounting for regression to the mean (RTM) effects, but also accounting for traffic volume changes when identifying the crash modification factors. Using EB when possible will increase the reliability of the CMF and increase the likelihood of achieving the same change in crash frequency if the treatment is implemented elsewhere within the region. Therefore, crash modification factors can play a vital role as an important tool to enable practitioners within WYDOT to:

- Estimate the safety effects of various countermeasures (e.g. installing guardrails, rumble strips, widening shoulders, implementing variable speed limit during inclement weather, etc.).
- Understand the impact of cross-sectional elements (lane width, shoulder width, median, roadside elements, etc.).
- Identify the most cost-effective strategies to reduce the number of crashes (or severe crashes) at problematic locations.
- Check the validity of assumptions in cost-benefit analyses.

LIMITATIONS OF THE HSM

Safety Performance Functions in the HSM

Expected crash frequency can be estimated using SPFs provided in Part C of the HSM. SPFs are regression equations used to estimate crash frequency as a function of a set of explanatory variables. The SPFs provided in the HSM are simple SPFs with Average Annual Daily Traffic (AADT) and segment length as the main exposures. They were developed using observed crash data collected from six states (California, Minnesota, Michigan, New York, Texas, and Washington), as shown in Figure 2.5. Furthermore, in a recent supplemental issue, the HSM introduced two new chapters in Part C that includes predictive models for freeways and ramps [12]. The SPFs for freeways and ramps were developed using crash data from three states- (California, Maine, and Washington).

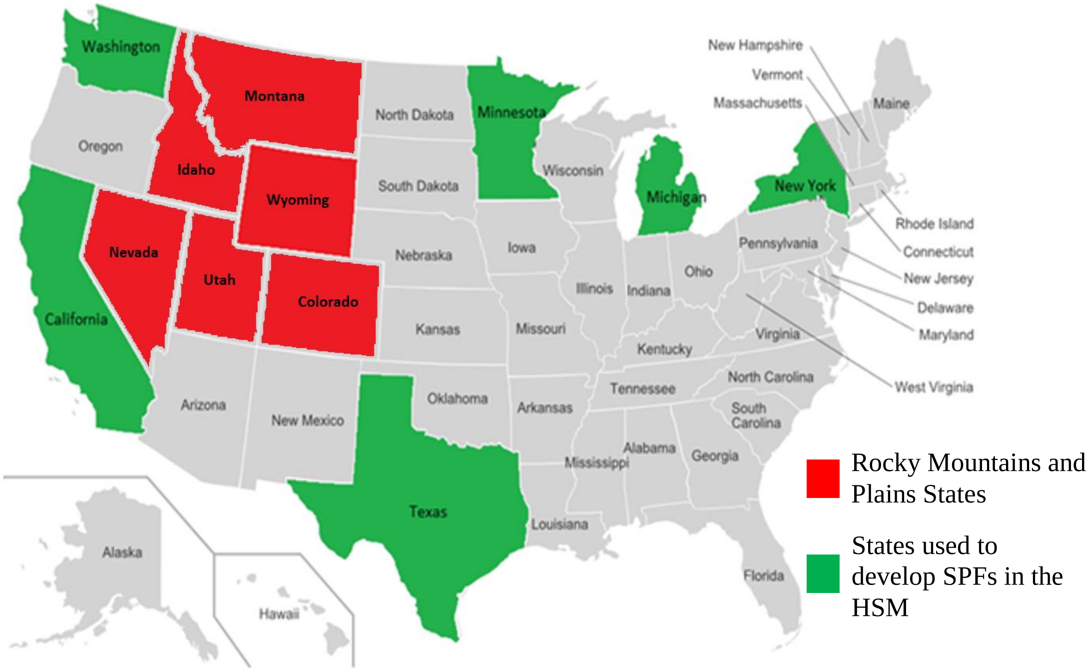


Figure 2.5 HSM data collection states

The SPFs provided in the HSM can be used for certain base conditions. Hence the SPFs must be modified using calibration factors to match local conditions. Part C of the HSM provides the procedure to calibrate SPFs according to the needs of local jurisdictions.

Although factors provided in the HSM Part C Appendix A can be used to calibrate SPFs, often local conditions are entirely different from the conditions under which the crash data were collected and used for developing the SPFs. For example, the roadway geometry of mountainous regions like Wyoming is different from the flat terrain of California. Furthermore, the extreme weather conditions and the rural/ remote nature of Wyoming may result in a large number of crashes and frequent closures. This raises the need to a state-wide implementation of the HSM to quantify the safety effectiveness of different countermeasures on different roadway types and intersections in Wyoming. This would help in identifying the most cost-effective strategies and countermeasures to reduce crash frequency and severity. However, the simple SPFs presented in the HSM cannot be directly used as an accurate prediction, as it is not calibrated to Wyoming conditions.

STUDY OBJECTIVES AND GOALS

There are a few specific issues related to the implementation of the HSM without calibration in the Rocky Mountains and plain regions, in general, and in Wyoming specifically. These issues could be concluded as:

- Certain facility types are not addressed, including rural roadways with low traffic volumes, challenging roadway geometry and high percentage of heavy trucks.
- Variation in the crash reporting thresholds and dissimilarities in the reporting forms.
- Differences in the driving behaviors and regulations between states.
- Adverse weather conditions within the Mountain Plains region were not considered.
- The effect of specific activities (e.g., energy-related activities) were not addressed.

To address the above-mentioned issues, this study aimed at validating the applicability of the HSM to Wyoming conditions and calibrating Wyoming-specific CMFs. The specific tasks of the project that were carried out in two phases included:

- Develop Wyoming-specific SPFs to overcome the limitations of the HSM SPFs.
- To calibrate CMFs for various countermeasures in Wyoming.
- To provide recommendations in terms of data requirements, how to mitigate data shortcoming, and to examine the applicability of alternative data collection and imputation techniques and analytical methods in case of missing key data.

PHASE 1 RESULTS

Phase 1 of the project was completed and a final report was published in 2017, WY17/04F, Calibrating Crash Modification Factors for Wyoming Specific Conditions: Application of the Highway Safety Manual – Part D. The results from Phase 1 are summarized below.

Shoulder Rumble Strips

Observational before-after EB method was used to quantify the safety effectiveness of shoulder rumble strips. Full safety performance functions were developed to predict crashes. Shoulder rumble strips were found to reduce 55 percent of F+I crashes on rural two-lane two-way highways in Wyoming. Comparisons between oil and non-oil counties, shoulder rumble strips were found to be more effective in counties with oil activities. Crash modification factors for oil counties were calculated as 0.40, and 0.18 for total and F+I crashes, respectively. For non-oil counties, shoulder rumble strips were effective to reduce F+I crashes but not effective to reduce total crashes. A research paper based on this study has been accepted for presentation in the upcoming 99th Transportation Research Board Annual Meeting [13]

Passing Lanes

Passing lanes were found to be statistically significant to reduce total and F+I crashes in rural two-lane two-way highways in Wyoming. Passing lanes reduce 42 to 34 percent of total and F+I crashes, respectively. Passing lanes were more effective to reduce crashes in oil counties by 61 to 59 percent for total and F+I crashes, respectively. In non-oil counties, passing lanes were found to reduce F+I crashes but not effective to reduce total crashes.

Headlight Signs

The results of observational before-after and cross-sectional analyses showed no significant effect of the headlight use signs. The design of the ratio of odds ratio analysis accounted for other confounding factors as the Daytime Running Lights (DRL) equipped in vehicles, and hence provided the most reliable results of the effect of the headlight signs. The odds ratio analysis showed that 77 percent of vehicles involved in crashes were not equipped with DRL. There was no significant difference between DRLs and non-DRL equipped vehicles on sections with or without headlight signs on total, head-on and sideswipe opposite crashes. This could be mistakenly explained that there are no added safety benefits of headlight use signs. The field study showed a very low compliance rate of only 12 percent to the headlight signs. Headlight signs are behavior-based countermeasure; compliance rates should be considered when evaluating the safety effectiveness of behavior-based countermeasures such as headlight signs [14]–[17].

Intersections

The traffic related and geometric variables that were most significant for crash predictions for four-leg signalized intersections were traffic volume (AADT) for major and minor approaches, number of lanes, and presence of turning lanes at intersections. The Negative Binomial (NB) model turned out to be the best to predict the safety performance of four-leg signalized intersections in Wyoming.

This study compared the variation of crash frequency and severity including different collision types with the HSM provided crash prediction models. Angle, rear-end, and sideswipe crashes showed different results than the HSM. Intersection crash proportions for Wyoming were found higher than the HSM proportions for angle crashes by 5 percent for F+I crashes, and 10 percent for Property Damage Only (PDO) crashes.

The safety effectiveness of adding turn lanes at four-leg signalized intersections were also investigated. Adding right-turn lanes on major approaches showed an increase in crash frequencies for total and PDO crashes by 25 and 29 percent, respectively. Adding right-turn lanes at minor approaches increased total and PDO crashes by 38, and 35 percent, respectively. Adding left-turn lanes at major approached reduces total crashes and PDO crashes by 22, and 33 percent, respectively. Meanwhile, adding left-turn lanes at minor approach and adding right-turn lane both at major and minor approaches increases total and PDO crashes [18].

Snow Fences

It was found that snow fences in Wyoming have significant impacts on traffic safety for freeway travel during the winter months. The odds ratio (OR) associated with total crashes was found to be 0.72 and the OR associated with fatal and injury (F+I) crashes was found to be 0.77. The calculated ratio of OR, 1.07 indicates that there has been less of an increase in fatal and injury crashes since the implementation of snow fences when compared to the total crashes.

The naïve before-after analysis indicated that of the total crashes that occurred during all-weather types, 31 percent were F+I before the implementation of snow fences and 23 percent were F+I after, showing a 31 percent decrease in fatal and injury crashes after the implementation of snow fences. Additionally, there was about 3 percent increase in PDO crashes after the implementation of snow fences. The crashes that occur under adverse weather conditions during winter months are typically expected to be more representative of those that occur while influenced by true effect of the snow fences. There was a 10 percent decrease seen in F+I crashes that occurred in adverse weather, but about 46 percent increase in PDO crashes and about 28 percent increase in total crashes.

The before-after analysis utilizing EB calculated CMFs of 0.75 and 0.84 for total crashes in all weather conditions and in adverse weather conditions, respectively, indicating very significant safety effectiveness. Also, the CMFs for F+I crashes in all weather conditions and in adverse weather conditions were found to be 0.41 and 0.38, respectively, again, indicating significant safety increases as a result of snow fences. The results of this study was published in the journal of Transportation Research Record [9]

PHASE 2 OVERVIEW

In Phase 2 of the project the following countermeasures were analyzed by developing SPFs, CMFs, and determining the countermeasures’ safety effectiveness relative to Wyoming conditions.

- Combined Effect of Shoulder and Centerline Rumble Strips (Roadway Segments)
- Centerline Rumble Strips only (Roadway Segments)
- Adding Lane and Divide (Roadway Segments)
- Snow Fences (Intelligent Transportation Systems (ITS) and Special Facilities)
- Variable Speed Limits (ITS and Special Facilities)
- Access Management (Roadway Corridors)
- Roundabout (Non-conventional intersections)
- Diverging Diamond Interchange (Non-conventional intersections)

Figure 2.6 shows the complete list of countermeasures analyzed in Phase 1 and Phase 2 of the project.

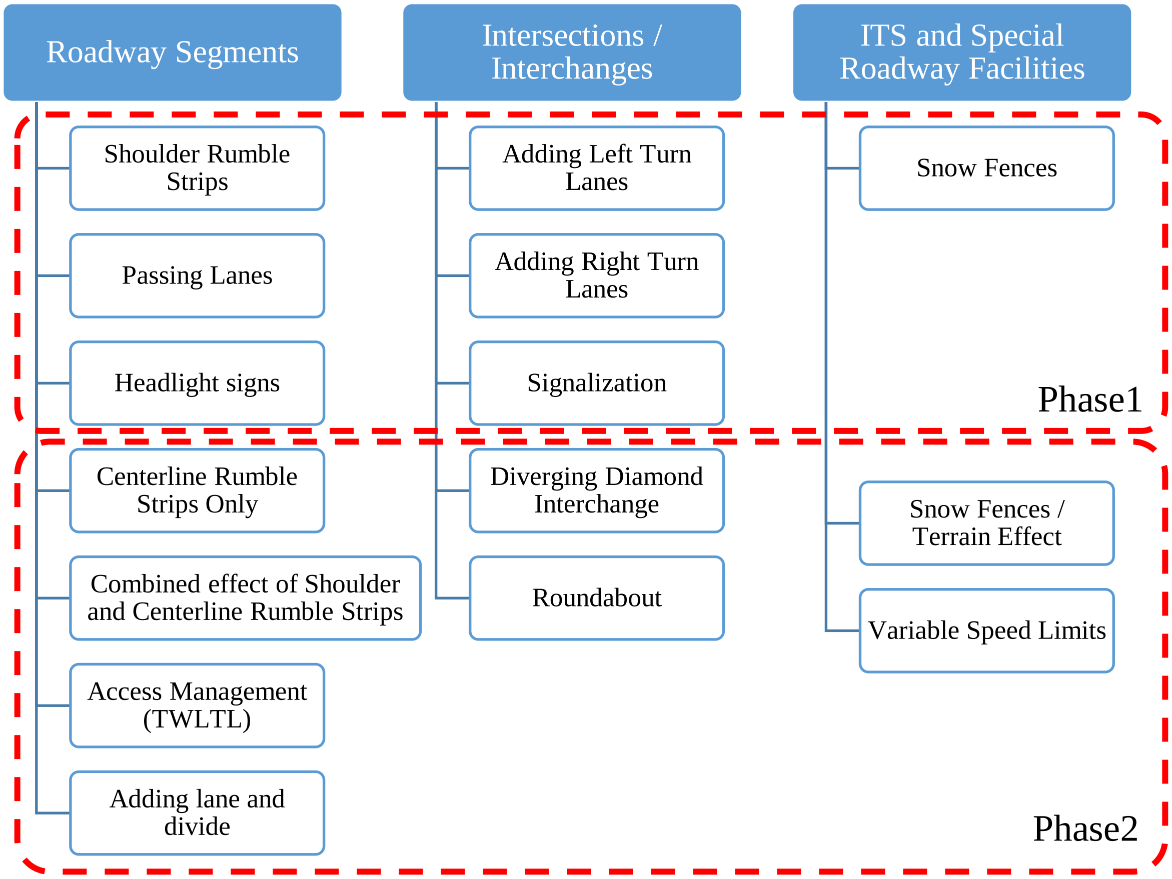


Figure 2.6 Countermeasures analyzed in Phase 1 and Phase 2

REPORT ORGANIZATION

The remainder of the report is organized as follows:

- CHAPTER 3-Roadway Segments: includes the analysis of some common lane departure crash countermeasures such as rumble strips, adding lane and divide. The chapter also provides a case study on passing lanes.
- CHAPTER 4-ITS and Special Facilities: presents the investigation of Variable Speed Limits and Snow Fences.
- CHAPTER 5-Roadway Corridors: provides analysis of five-lane arterials with a center two-way left-turn lane, and urban/suburban arterial signalized four-leg intersections in Wyoming.

- CHAPTER 6-Non-Conventional Intersection/Interchange: includes preliminary discussion of the performance of Roundabouts and Diverging Diamond Interchange in Wyoming.
- Conclusions and Recommendations: presents project summary, conclusions, limitations of the project, and recommendations.

CHAPTER 3-ROADWAY SEGMENTS

Wyoming has approximately 800 miles of interstates and 4,000 miles of state and US highways. Most of the state and US highways are two-lane two-way rural roadways which provide a single lane for each direction of travel. When drivers make passing maneuvers, they must occupy the opposing lanes, and if the roadway geometrics or traffic volumes are not favorable, then a crash is inevitable which are classified as lane departure crashes. A lane departure crash occurs when a vehicle departs the roadway colliding to another vehicle, or a fixed object, or rolls over [19]. Lane departure crashes are considered a major leading cause of traffic fatalities on highways, which is a significant problem in traffic safety. On average 53 percent of all traffic fatalities resulted from a roadway departure crash in the US, from 2014-2016 [19]. It was found that nearly 72 percent of critical crashes, in Wyoming, for the time period from 2008 to 2010, were related to lane departure crashes. The Wyoming's Strategic Highway Safety Plan (SHSP) included lane departure crashes as one of the safety emphasis areas to be considered [20]. Research and statistics showed that a significant number of fatal and serious injury crashes result from roadway or lane departure crashes. Lane departure crashes include angle, head-on, sideswipe and run-off-road crashes. Factors such as driver fatigue and drowsiness, distracted driving, poor road surface condition, adverse weather, challenging roadway geometry preventing easy passing maneuvers might result in increased lane departure crashes. Some of these contributing factors could be mitigated by providing countermeasures, such as rumble strips, that can alert drivers when they tend to drift off the roadway, provide opportunities to pass or overtake safely by adding passing lanes on a two-lane two-way roadway, and eventually prevent cross-over crashes by dividing the roadway into a four-lane divided highway. Phase 1 report presented the analysis of some of these countermeasures, such as the shoulder rumble strips and passing lanes [21]. This chapter includes the study of the combined effect of shoulder and centerline rumble strips, centerline rumble strips only, and adding lane and divide. Furthermore, feasibility of passing lanes on a rural two-lane two-way highway of Wyoming is investigated, and the results of the study are presented as a case-study in this chapter.

LITERATURE REVIEW

Lane Departure Crashes

FHWA defines roadway and lane departure crashes as those that occur when a vehicle crosses the edge of the road, center line or leaves the roadway altogether [19]. Lane departure crashes include target crashes, such as angle (same and opposite direction), sideswipe (same and opposite direction), run-off-road, and head-on crashes. The impact of lane departure crashes has been studied extensively, and researchers have identified it as one of the major causes of traffic fatalities. According to FHWA, on average, 18,779 fatalities have resulted from lane departure crashes that makes up 53 percent of all traffic fatalities in the US, from the year 2014 to 2016 [19]. In Wyoming, the percentage of total fatalities that results from lane departure crashes is much higher and amounts to 70 percent, in 2016 [22].

Although these types of crashes are related to driver errors, more forgiving roadway and roadside treatments could potentially reduce the number and severity of lane departure crashes. Researchers have investigated the engineering countermeasures that have been implemented by state and local transportation agencies to mitigate lane departure crashes. The principal objectives in implementing those countermeasures fall under the following categories [23]; 1) keeping vehicles on the roadway, 2) Reducing the consequences and severity, if involved, in a roadway departure crash, and 3) eliminating head-on crashes and those occurring from vehicles crossing the median.

Rumble Strips

To achieve the first objective, state and local transportation agencies have implemented rumble strips on two-lane two-way highways as an effective countermeasure for reducing lane departure crashes. Rumble strips help drivers stay on their designated lane or travel way by alerting them through noise and vibration inside the vehicle as they drift away across the center or edge line. This draws the attention of a distracted or drowsy driver, who can immediately steer into the proper lane or roadway, and avoid a potentially fatal crash. Major categories of rumble strips that are often implemented to keep vehicles on the roadway, include centerline rumble strips, and shoulder rumble strips.

Centerline rumble strips (CLRS) are primarily implemented on two-lane two-way roadways to alert drivers of crossing centerlines. As a result, CLRS are effective countermeasures to reduce target crashes such as head-on collisions and opposite-direction sideswipe crashes. Torbic et al.

(2010) reported an expected 40 percent reduction in total target crashes and 64 percent reduction in fatal and injury (F+I) target crashes when CLRS are implemented on urban two-lane roads [24]. On rural two-lane roads, CLRS are expected to reduce total target crashes by 9 percent and FI target crashes by 44 percent [24]. Results from similar studies show an expected reduction of 24.9 percent total target crashes on Washington's two-lane rural highways [25], estimated 25 percent target crash reduction in seven states: California, Colorado, Delaware, Maryland, Minnesota, Oregon, and Washington [26], 67.19 percent estimated reduction in target crashes on several roads in Kansas state [27].

Shoulder rumble strips (SRS) are primarily provided to alert drivers from moving away from the traveled path and prevent single vehicle run-off-road (SVROR) crashes on two-lane roads and freeways. The study conducted by Torbic et al. (2010) reports that SRS on urban/rural freeways reduce expected SVROR crashes by 18 percent, SVROR F+I crashes by 13 percent in addition to an expected reduction of 15 percent SVROR total and 29 percent SVROR F+I crashes on rural two-lane roads [24]. Similar studies evaluating the safety effectiveness of SRS only, revealed an expected reduction of 14 percent in all ROR crashes in rural two-lane highways in Idaho [28], and 21.1 percent reduction in SVROR crashes in rural freeways in California and Illinois [29].

Combination of CLRS and SRS have also been analyzed in numerous studies. The results of those studies found an expected reduction of crashes by 32.8 percent on two-lane rural highways, in Michigan [30], lane-departure crash reduction by 26.7 percent in rural two-lane roads, in Kentucky, Missouri, and Pennsylvania [31], and 63.3 percent reduction in lane-departure crashes in rural two-lane two-way highways in Washington State [32].

Passing Lanes

Passing lanes are provided in two-lane two-way roadways to allow drivers to safely overtake a slow vehicle without being involved in a crash with opposing traffic. Passing lanes provide a cost-effective solution to problems such as limited sight distance, high traffic volumes, and limited passing opportunities on two-lane roadways [33]. Studies related to safety effectiveness evaluation of passing lanes are rare in the literature, and only some utilized the complete before-after study with the EB method to analyze the safety benefits of passing lanes. Persaud et al., (2013) utilized an EB and cross-sectional analysis to develop CMFs for passing lanes, in Michigan, and concluded that there were significant safety benefits from passing lanes [34]. Schumaker et al., (2017) utilized observational before-after EB method and presented that adding passing lanes reduces expected F+I crashes by 20 percent and total crashes by 32 percent on a rural two-lane two-way roadway, in Wyoming [35]. Phase 1 report includes a safety effectiveness analysis of passing lanes using cross-sectional method [21].

Adding Lane and Divide

The final level of upgrading a two-lane roadway involves conversion to a four-lane divided highway. Conversion of two-lane roadway to a four-lane divided roadway eliminates the head-on and opposite sideswipe crashes. Hence, there are obvious safety benefits of the countermeasure but whether the conversion is cost-effective for a low-volume rural road is a question that must be answered through extensive research. Currently, there is a lack of research aimed at evaluating the safety effectiveness of converting a two-lane roadway to a four-lane divided highway due to the challenging data requirements needed to carry out such research [36]. The limited number of studies carried out to analyze the safety benefits of the conversion show that expected reduction in crashes per kilometer of 40 percent to 60 percent, in four states: North Carolina, California, Washington and Minnesota [36]; expected F+I crash reduction of more than 63 percent on urban roadways and 45 percent reduction on rural roadways, in Florida, as reported by Ahmed et al., (2015) [37].

DATA REQUIREMENTS AND SOURCES

In order to achieve the study objectives, data requirements and needs to implement the HSM were identified. Multiple data sources were used in this study. The main dataset used in this study was the historical crash data in Wyoming. WYDOT records and digitizes crashes occurred on Wyoming’s road network. Raw crash data could be accessed via the CARE software. Traffic data including annual average daily traffic (AADT), truck percentages, implementation dates of countermeasures, and roadway characteristics, such as vertical and horizontal road geometry, were obtained from roadway inventory files maintained by the WYDOT. However, several gaps and limitations were encountered in the datasets used in this study. External data sources were utilized to overcome these data gaps. Implementation dates for different countermeasures are one of the most crucial information needed to conduct a before-after analysis. Some of the information related to implementation dates of the countermeasures were obtained from the WYDOT design squad at the University of Wyoming. Missing implementation dates were imputed by utilizing Pathway video logs, as well as by navigating through the Google Earth Pro® and Google Map Street Views.

RESULTS AND DISCUSSION

Shoulder and Centerline Rumble Strips

The methodologies employed to develop the SPFs and CMFs for this study have already been explained in the Phase 1 report [38]. To determine the combined safety effectiveness of shoulder and centerline rumble strips using before-after EB method, it was necessary to identify roadway segments that did not have any of the shoulder and centerline rumble strips in the before period. Furthermore, it was imperative to make sure the consistent presence of both treatments in the after period. SRS were widely implemented in the State of Wyoming starting 2002, and CLRS were implemented starting 2015. Information on the implementation of rumble strips was obtained from the project plans provided by the WYDOT design squad at the University of Wyoming. Now, the project plans might indicate that a certain roadway segment received the treatment of rumble strips but after an overlay project the rumble strips are likely to be removed. Hence, to verify the implementation status of the rumble strips in Wyoming, Pathway video logs was utilized. The video logs indicated that SRS were reinstalled after several years for the locations where an overlay was applied. This intermittent presence of SRS is due to cost effective project management strategies adopted in Wyoming [13], [38].

After a rigorous scrutiny of the project plans and the Pathway video logs, the following locations, shown in

Table 3.1, were selected as they fulfilled the data requirements of the before-after EB analysis. The roadway segments consist of 3 different routes with route ID ML13B, ML34B, and ML43B in Wyoming with the total length of the roadway segments equal to 123 miles. The location of the routes along with hotspots of the crashes are shown in

Figure 3.1.

Table 3.1 Routes selected to estimate the combined effect of SRS and CLRS

No	Route	Route ID	Beg MP	End MP	Length (mi)	Before Period	After Period
1	US 189/191	ML13B	142	147	5	2003-2005	2016-2018
2	US 191	ML13B	93	110	17		
3	US 20/26	ML34B	52	68	16		
4	WY 59	ML43B	71	106	35		
5	WY59	ML43B	120	170	50		

Total Length	123

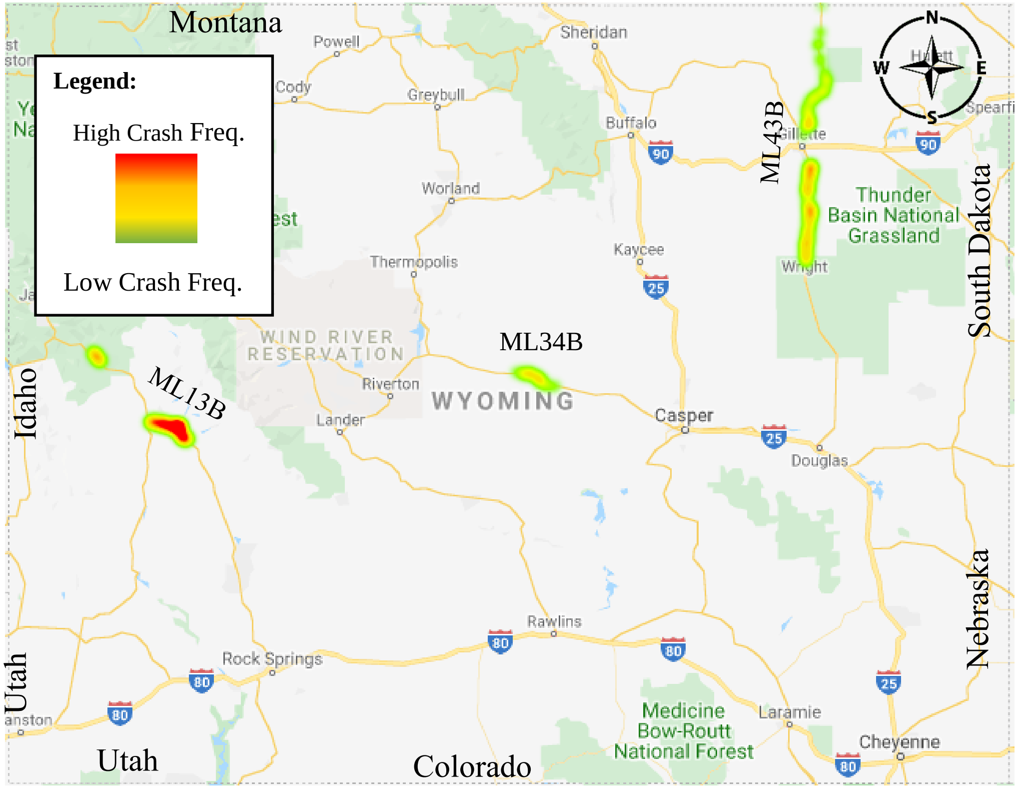


Figure 3.1 Hotspots of the crashes in the before period (SRS+CLRS locations)

The summary statistics of the total crashes, property damage only crashes, and fatal and injury crashes show that there is a decrease in crashes per year per mile in the after period. Since it is not possible to conclude whether this is statistically significant, the before-after EB analysis is carried out. Table 3.2 shows the variables used in the development of SPFs.

The HSM recommends the use of homogeneous segments with no segments less than 0.1 mile [12]. A study, by Cafiso et al. (2018), concluded that best results for SPFs are obtained with homogeneous segmentation based on two curves and two tangents within a segment and with fixed length segmentation [39]. A study by Green (2018), suggests that the decision to use homogeneous or fixed length segmentation largely depends on the data needs and there is not a single method that can be applied in all situations [40]. The roadway segments used for this study are relatively short and have been combined using different routes. Homogeneous segmentation based on two curves and two tangents would have resulted in long segments with very few observations for each site.

Hence, fixed length segmentation procedure was first adopted to divide the roadway segments into equal 0.1 mile segments. This resulted in number of segments for which a satisfactory model fit was obtained. Roadway characteristics, such as vertical grade, horizontal alignment, traffic data, and crash data, were assigned to the respective routes and mileposts.

Table 3.2 Summary statistics of the safety analysis of the combined effect of SRS and CLRS

Dependent Variables (crash per year per mile)		Mean		St. Dev.		Min.		Max.	
		Before	After	Before	After	Before	After	Before	After
Total crashes		1.02	0.88	2.87	2.50	0	0	43.33	30
Property damage only crashes		0.74	0.74	2.37	2.23	0	0	26.67	26.67
Fatal and Injury (F+I) crashes		0.27	0.14	1.09	0.71	0	0	16.67	6.67
Continuous Variables									
Variable type	Variable Name	Mean		St. Dev.		Min.		Max.	
		Before	After	Before	After	Before	After	Before	After
Traffic Data	Average of AADT (veh/day)	2178	2687	1549	2096	367	423	5343	7793
	Vehicle Miles Traveled (LNVMT)	5.02	5.19	0.94	0.92	3.60	3.75	6.28	6.61
Roadway Characteristics	Delta - degree	5.27		11.96		0		69	
	Vertical Curve Length – ft	321.72		119.05		50		500	
	Total Width - ft	39.18		8.47		25		76	
	Shoulder width - ft	6.2		1.39		0		12	

before period: 2003-2005; after period: 2016-2018

There have been numerous studies where SPFs specific to the conditions in Wyoming were developed using crash data from the interstates and the Wyoming highways [9], [41]–[46]. However, it was critical to develop SPFs to predict crashes on roadways with no shoulder and centerline rumble strips in the before period. As a result, none of the previously developed SPFs in Wyoming matched this criterion and new SPFs had to be developed for this study.

The SPFs shown in Table 3.3 were developed in Statistical Analysis System (SAS) 9.4 using the negative binomial regression model (NB) [38]. The results presented are all significant at 95 percent confidence interval ($\alpha = 0.05$). The model results show that the natural log transformation of vehicle miles traveled, which is an indicator of traffic volume, is significant predictor of all types of crashes and the relationship with the response variables is positive. This means that with the increase in vehicle miles traveled, it is expected that all types of crash counts will increase. Delta is the deflection angle of a horizontal curve, and zero degree delta indicates a straight segment. A more appropriate parameter to represent the curvature of the roadway could be degree of curvature (DOC). However, from the modelling it was found that DOC was not a significant predictor. A positive relation of delta with the response indicates that total and PDO crashes are expected to increase in horizontal curves. The vertical curve length is presented in feet and a unit increase in vertical curve length on a particular segment is expected to reduce all types of crashes. Expected total crashes are found to increase with the increase in total width, while the increase in shoulder width was associated with an increase in all types of crashes. It can be hypothesized that with the increase in roadway or shoulder widths drivers tend to become more reckless and eventually end up in crashes. Furthermore, increase in number of lanes was associated with increase in fatal and injury crashes.

Table 3.3 Wyoming-specific combined SPFs developed for ML13B, ML34B, and ML43B

Equation	Total crashes		PDO crashes		F+I crashes	
Term/Response	Estimates	SE	Estimates	SE	Estimates	SE
Intercept	-6.7488	0.5185	-7.4845	0.6221	-0.3928	1.7047
LN (VMT)	0.6796	0.0972	0.7551	0.11	-0.6941	0.312
Deflection angle	0.0252	0.0097	0.0341	0.0113	-	-
Vertical Curve Length	-0.0006	0.0001	-0.0005	0.0002	-0.0006	0.0002
Total Width	0.0189	0.0089	-	-	-	-
Shoulder Width	0.2223	0.0531	0.3295	0.0555	0.2617	0.0932
No of lanes	-	-	-	-	0.4511	0.2259
Dispersion	1.4095	0.2626	1.8635	0.3839	0.4053	0.4481

PDO = Property Damage Only; F+I= Fatal and Injury; LN (VMT) = Natural log transformation of Vehicle Miles traveled

Considering these results, the next step was to develop CMFs. Table 3.4 presents CMFs for the combined safety effectiveness of SRS and CLRS. CMFs were developed using two methods, simple before-after naïve and before-after EB. As already discussed, before-after EB method is the most accurate, if the data requirements are fulfilled. The CMFs obtained using the Naïve method was over-estimated as can be seen in the table. Before-After EB method provides an expected reduction of 33 percent for total crashes, expected 25 percent reduction in property damage only crashes, and expected 79 percent reduction in fatal and injury crashes. The statistical significance of the CMFs was examined as well, and the CMFs were found to be significant at 95 percent confidence interval.

Table 3.4 CMFs for the combined safety effectiveness of SRS and CLRS

	Method			
	Naïve Before-After		EB Before-After	
Severity/Type of crashes	**CMF (Safety Effectiveness)**	**S.E. (%)**	**CMF (Safety Effectiveness)**	**S.E. (%)**
Total crashes	0.40 (59.82%)	0.22 (21.70%)	0.67 (32.79%)	0.05 (4.89%)
PDO crashes	0.39 (61.40%)	0.20 (20.15%)	0.75 (24.69%)	0.06 (6.16%
F+I crashes	0.12 (87.77%)	0.07 (6.52%)	0.21 (79.20%)	0.03 (3.08%)

Centerline Rumble Strips

Since the implementation of shoulder rumble strips took place before the implementation of CLRS, it was a very difficult task to identify locations with no rumbles strips in the before period and only centerline rumble strips in the after period. Nevertheless, the task was accomplished using Pathway video logs. The following locations (Table 3.5) were selected to carry out the before-after EB analysis to determine the safety effectiveness of the CLRS only. The total length of the roadway segments selected for this study is equal to 67.1 miles in the northeastern region of Wyoming. Similar to the previous analysis, fixed length segmentation was again adopted in this study to divide the roadway segments into equal 0.1 mile segments. Roadway characteristics, traffic data, weather data, and crash data were assigned to the respective routes and mileposts.

Table 3.5 Routes selected for the before-after EB analysis of the CLRS

No	Route	Route ID	Beg MP	End MP	Length (mi)	Before Period	After Period
1	WY 50	ML300B	6.1	52.6	46.5	2011-2013	2016-2018
2	WY 450	ML2300B	45.6	66.2	20.6		
		Total Length			67.1		

It can be seem from

Table 3.6 that the observed crashes have increased in the after period. There is no significant change in the average annual daily traffic in the after period from the before period. The results of the SPF and the CMF developed are discussed in the following section.

Table 3.6 Summary statistics of the safety analysis of the CLRS on rural two-lane two-way highways in Wyoming

Selected Roadways: ML300B: MP 6.1 – 52.6; ML2300B: MP 45.6 – 66.2								
Dependent Variables (crash per year per mile)	**Mean**		**St. Dev.**		**Min.**		**Max.**	
	Before	After	Before	After	Before	After	Before	After
Total crashes	0.27	0.57	1.03	1.70	0	0	6.67	23.33
Property damage only crashes	0.17	0.47	0.80	1.44	0	0	6.67	16.67
Fatal and injury crashes	0.10	0.10	0.58	0.69	0	0	3.33	6.67
Continuous Variables	**Mean**		**St. Dev.**		**Min.**		**Max.**	
	Before	After	Before	After	Before	After	Before	After
Average of AADT (veh/day)	1351	1338	335	414	559	607	2579	3232
Vehicle Miles Traveled (LNVMT)	4.88	4.86	0.24	0.24	4.02	4.11	5.55	5.78
Number of days of precipitation per year	88.2	91.47	13.23	20.31	68.33	61	97	105
Categorical Variable	**Percentage in each category**							
Horizontal alignment								
Straight	76.8%							
Curve	23.2%							

Before period: 2011-2013; After period: 2016-2018

Due to the very low traffic volumes which fortunately resulted in low crash counts on the roadway segments, the Negative Binomial (NB) model failed to create a statistical relationship between the response (crash counts have very low sample mean) and the predictor variables. After the segmentation of the roadways and crash assignment, almost 72 percent of the segments consisted of zero crashes. Presence of such high percentage of zero counts justified the use of zero-inflated models. The parameter estimates of the zero-inflated negative binomial (ZINB) are shown in Table 3.7. Despite the use of ZINB, the modeling, results are not satisfactory. Only 3 variables were found to be significant in predicting total crashes of which LN (VMT) was significant at a 90 percent confidence interval, and the other two significant at a 95 percent confidence interval. Due to low crash counts in these roadways and consequently low sample mean, it was not possible to fit a statistical model for other crash severities (PDO and F+I) and target crashes. More detailed explanation is provided in the Limitations and Recommendations section. Nevertheless, the SPF was used to develop the CMF for total crashes and the results provided in Table 3.8. As expected, the results show that there is negative impact of the implementation of the CLRS. That is using before-after EB analysis it was found that crashes are expected to increase after the introduction of the CLRS. However, this could be due to many reasons which would require further investigation.

Table 3.7 Wyoming-specific SPFs developed for ML300B and ML2300 combined

Equation Term/Response	Total crashes Estimates	Total crashes SE
Intercept	-1.9776	3.9586
LN (VMT)	1.0552	0.6498
Presence of curve	0.6827	0.3277
Average Precipitation	-0.0598	0.0276
Dispersion	0.5392	0.9003

Table 3.8 Crash Modification Factors for the CLRS

Severity/Type of crashes	**Method**			
	Naïve Before-After		**EB Before-After**	
	CMF (Safety Effectiveness)	**S.E. (%)**	**CMF (Safety Effectiveness)**	**S.E. (%)**
Total crashes	2.11 (-110.91%)	0.15 (15.15%)	1.44 (-44.50%)	0.18 (18.22%)

Adding Lane and Divide

For this study, it was imperative to select a two-lane roadway segment that has been converted to the four-lane divided highway. About 10 miles of US 287 between Laramie and the Wyoming-Colorado Stateline was converted to four-lane divided highway in two parts. The first part of the conversion between mileposts 415.6 and 419.8 was completed in 2012, and the second part between mileposts 419.8 and 425.4 was completed in 2015. Prior to 2009, the 23-mile highway (mileposts 402.6-425.4) between Laramie and the Wyoming-Colorado Stateline was a two-lane two-way highway. To develop the SPFs, the 26-mile highway was segmented homogeneously using horizontal alignment and vertical grades. Changes in the horizontal alignment or vertical grades would result in a new segment. It was made sure that no segment was less than 0.1 mile by combining those with the segments prior to or after the smaller ones that had similar physical characteristics. Equivalent vertical grades were calculated by average and composite grade methods provided in the HCM [46]–[48]. It should be mentioned that adopting fixed length segmentation for this particular roadway resulted in the following issues: either long segments with number of observations less than what is recommended in the HSM, or short segments with too many zero crash counts which caused the models to not converge. As a result, homogeneous segmentation was adopted for this particular roadway.

After the segmentation process, explanatory variables, such as Average Annual Daily Traffic (AADT), crash data, and other roadway geometry data were assigned to the segments based on the beginning and ending mileposts. The CMFs were developed using three years of data in the before period (2006-2008) and three years in the after-period (2015-2017). Summary statistics for the before and the after period of the conversion is presented in

Table 3.9.

Table 3.9 Summary statistics of the four-lane divided highway (US 287 MP 402.6-425.4)

Dependent Variables (crash per year per mile)		Mean		St. Dev.		Min.		Max.	
		Before	After	Before	After	Before	After	Before	After
Total crashes		2.30	1.91	2.45	1.94	0	0	9.09	8.18
Fatal and Injury (F+I) crashes		0.71	0.44	1.12	0.80	0	0	5.05	3.06
Continuous Variables									
Variable type	Variable Name	Mean		St. Dev.		Min.		Max.	
		Before	After	Before	After	Before	After	Before	After
Traffic Data	Average of AADT (veh/day)	3290	3897	67.90	307	3260	3762	3440	4576
	Vehicle Miles Traveled (LOGVMT)	2.83	2.90	0.20	0.20	2.53	2.60	3.35	3.41
Roadway Characteristics	Segment Length - miles	0.28	0.23	0.15	0.12	0.11	0.11	0.82	0.68
	Total Width - feet	36.9	37.24	3.03	3.97	35	36	52	52
	Shoulder width - feet	5.4	4.10	1.6	0.98	2	2	8	8
Categorical Variables									
Variable Name (Abbreviation)	Level (Code Value)	Percentage in each category							
Grade Category	Grade < -2%	18.29%							
	-2% < Grade < 0%	25.61%							
	0% < Grade < 2%*	39.02%							
	Grade > 2%	17.07%							
Shoulder Rumble Strips	Present (1)	63.41%							
	Not Present (0) *	36.58%							

*reference category used in the models; before period: 2006-2008; after period: 2016-2018

SPFs for US 287 were developed using the Poisson and Negative Binomial (NB) regression models for total crashes and crash severity level (F+I). SPFs specific to the study location, US 287 were developed using six years of crash data (2003-2008). The construction of the conversion to four-lane highway began in 2009. Hence crash data up to 2008 were considered for developing the SPFs to predict crash frequency on US 287. The parameter estimates with the corresponding p-values for all the SPFs developed are presented in Table 3.10. Based on the corrected Akaike Information Criterion (AIC) values (lower the better) [49], Poisson models appears to provide better fit. The dispersion parameter for the NB models indicate that there was no over dispersion in the crash data [50].

Table 3.10 Wyoming-specific SPFs developed for US 287 (total and F+I crashes)

Equation Term/Response	Estimates (Standard Error)			
	Total crashes		F+I crashes	
	Poisson	NB	Poisson	NB
Intercept	-5.4333 (1.0116)	-5.4333 (1.0116)	-0.1996 (3.5981)	-0.2134 (3.6164)
LN (VMT)	2.5014 (0.3801)	2.5014 (0.3801)	2.5406 (0.5853)	2.543 (0.5906)
Grade < -2%	0.3477 (0.2155)	0.3477 (0.2155)	0.1724 (0.3228)	0.171 (0.3253)
-2% < Grade < 0%	-0.1818 (0.2187)	-0.1818 (0.2187)	-0.3302 (0.3196)	-0.3315 (0.322)
Grade > 2%	-0.3937 (0.2425)	-0.3937 (0.2425)	-0.6751 (0.3771)	-0.6766 (0.3802)
Shoulder Width	-0.1581 (0.0615)	-0.1581 (0.0615)	-	-
Total Width	-	-	-0.1872 (0.1014)	-0.187 (0.1018)
SRS presence = yes	-0.4261 (0.1821)	-0.4261 (0.1821)	-0.7066 (0.2971)	-0.7058 (0.2988)
Dispersion	1	0.0192	1	0.0114
Model: AICc	292	295	211	213

F+I= Fatal and Injury; SRS= shoulder rumble strip; VMT= Vehicle Miles traveled; AICc= Corrected Akaike information criterion

CMFs are used to indicate the change in crash frequency after the implementation of a countermeasure. Typically, three to five years of crash data for the before and the after periods were used to develop CMFs. The second phase of the conversion to four-lane on US 287 was completed in 2015. Hence, three years, the before period (2006 - 2008) and the after period (2016 - 2018), of crash data were utilized to develop the CMFs for the conversion to the four-lane divided highway. The CMFs for this study were developed using before-after naïve and EB methods (Table 3.11).

Based on the crash rates, before-after naïve approach was first used to evaluate the safety effectiveness of the countermeasure. The average crash rate per year per million vehicle miles traveled (MVMT) was observed to be 1.92 and 1.39 in the before and after period, respectively for the conversion to four-lane divided highway, representing about 28 percent expected reduction in the total crash rate. For F+I crashes, the crash rate was reduced from 0.60 crashes per MVMT to 0.32 crashes per MVMT.

The before-after EB method is a more reliable method than the before-after naïve since the EB method accounts for the RTM bias. The results of the safety effectiveness analyses using EB method show that for the conversion of the two-lane roadway to the four-lane divided highway, total crashes are expected to be reduced by 37 percent, and F+I crashes by 64 percent. The CMF for the total crashes (0.63) is quite similar to the CMF obtained in the study by Ahmed et al., (2015) where they found the CMF to be 0.71 using the before-after EB method [37]. The CMF for F+I crashes on rural roads was found to be 0.59 by Ahmed et al., (2015), and the CMF found in this study is 0.36 [37].

Table 3.11 CMF's for the conversion to the four-lane divided highway on US 287

	Method			
	Naïve Before-After		**EB Before-After**	
Severity/Type of crashes	**CMF (Safety Effectiveness)**	**S.E.**	**CMF (Safety Effectiveness)**	**S.E.**
Total crashes	0.72 (28.08%)	0.09 (8.63%)	0.63 (37.31%)	0.11 (11.45%)
F+I crashes	0.52 (48.06%)	0.12 (11.89%)	0.36 (64.38%)	0.12 (11.88%)

CONCLUSIONS

It was observed that all head-on and opposite sideswipe crashes were eliminated after the implementation of the four-lane divided highway. Cross-over crashes such as head-on and opposite sideswipe crashes often result in higher severity. Dividing the roadway with a median completely eliminated the cross-over crashes that may result in a greater reduction in more severe F+I crashes than the PDO crashes. A study by Ahmed and Ahmed (2019) compared the safety effectiveness of passing lanes and conversion to the four-lane divided highway and found that the benefits in monetary terms associated with the conversion to the four-lane divided highway is higher in this case of a relatively low-volume rural road [51] . The impact of adding staggered passing lanes was assumed to improve the whole corridor safety, but the fact remains that severe crashes (head-on and sideswipe) are still possible if there is no median present. Adding lanes and dividing the roadway also improves level of service (LOS) of the roadway and provides an opportunity to meet future mobility needs.

It may appear that a countermeasure is always the solution, however, this may not always be the case. Recently, another study was carried out on a low volume two-lane two-way roadway in Wyoming; WY 50. The addition of proposed passing lanes on certain segments of the roadway was investigated. The results from the analysis provided in Appendix 1 showed that passing lanes on WY 50 are not needed in the near future from a safety perspective.

CHAPTER 4-ITS AND SPECIAL FACILITIES

This chapter focuses on the safety effectiveness of the snow fences and VSL corridors, on I-80, in Wyoming. VSL are ITS related countermeasures that are mainly used to provide the appropriate operating speed according to enhance the safety and/or mobility of roadways. Operational-based and weather-based VSLs are the two main types of VSLs. Due to the harsh weather conditions that could limit the visibility and cause crashes on I-80, in Wyoming, during the summer (rain, fog and strong wind) and winter (snow, fog, and wind), four weather-based VSL corridors were implemented. The locations of the four VSL corridors were mainly selected based on safety measures as crash frequencies and rates. The selected corridors are characterized with the most challenging roadway geometry and the most severe weather conditions compared to the other non-VSL sections. These locations encounter the highest crash frequencies even after implementing the VSL technology. To efficiently evaluate the safety effectiveness of the implemented VSL corridors, a comprehensive before-after study was conducted. Parametric and non-parametric approaches were used to develop reliable CMFs for the weather based VSL on I-80. This chapter presents the results and conclusions of this study.

Snow fences are countermeasures that has proven to significantly affect the traffic safety by preventing snow from accumulate on the roadways. Snow fences have several types, heights, effective widths, and designs that are suitable for different conditions. The primary objective of the snow fences study presented in this chapter is to not only to identify whether snow fences have a positive effect on traffic safety and mobility on I-80, but also to identify the ideal snow fence type to be implemented that is more suitable for the existing terrain type to obtain the maximum effectiveness. This will allow for transportation practitioners and officials in Wyoming to make more informed decisions regarding the design of the snow fence to be implemented statewide.

VARIABLE SPEED LIMITS

Introduction

I-80 is considered one of the heavily instrumented rural freeways in the US. Between 2009 and 2011, the corridor was equipped with four weather-based VSL sections with a total of 147 miles, supported by 94 speed sensors. Moreover, the corridor was equipped with 44 weather stations to support the operation of the VSL system, 54 electronic message signs, and 52 closed circuit television (CCTV) cameras along the route. These weather-based VSL sections were built with the aim of improving traffic safety by reducing crash frequency and/or severity [52]. The VSL corridors are characterized with challenging roadway geometry as well as severe weather conditions, which encounters the highest crash frequencies compared to non-VSL sections. This study utilized a before-after EB approach to evaluate the safety effectiveness of the weather-based VSL, on I-80. Parametric and not parametric approaches were used to develop the CMFs. The results of this study was presented in the Transporation Research Board Annual Meeting 2018 [53] and published in the journal of Transportation Safety and Secutity [54].

Literature Review

CMFs are used to quantify the impact of different roadway characteristics, countermeasures, and other variables that might influence crash frequency and severity. The HSM provides several approaches to develop crash modification factors. The two most commonly used methodologies are before-after studies [35], [37], [63], [55]–[62] and cross-sectional studies [64]–[66]. It is believed that the cross-sectional studies might suffer from several limitations that makes before-after studies superior in developing sound CMFs [67]–[70]. These limitations could be concluded as following:

- All locations should be similar to each other in all other factors affecting crash risk, which is a reflection on the unmeasured factors that might affect crashes.
- Due to insignificancy of some of the explanatory variables or multicollinearity between variables, the developed CMFs might be imprecise due to the omitted factors in the modeling phase.
- It is highly affected by the sample size. Having a small sample size might provide biased CMFs.
- The relationship between cause and effect might not be properly captured for dependent and independent variables.

However, cross-sectional studies might be suitable in particular cases, in which fewer years of data is available in the after period, or there are not enough treated sites [67].

VSLs are ITS technologies that provide the adequate speed limit for the prevailing traffic and/or weather conditions to increase the throughput and to enhance the overall traffic safety on roadways. VSL works on harmonizing operating speeds for road users [71]–[76]. High variability in vehicles speeds might increase the probability of having a crash [37]. Another study presented a comprehensive review of previous studies assessing the effect of VSL on traffic safety [77]. The study categorized the evaluation techniques into three groups; 1) simulations for algorithm development and evaluations, 2) VSL implementation and field testing, and 3) a combination of VSLs with ramp metering. The literature concerning the microsimulation and field testing of VSL systems will be briefly discussed, however, the literature on the combination of VSL with ramp metering will not be presented as it is not in line with the scope of this study.

Several studies investigated the safety effectiveness of VSL using microsimulation [78]–[84]. One study simulated the effect of VSL on changing traffic conditions using a microscopic traffic simulation model [78]. The results indicated that during risky traffic conditions, the crash potential could be reduced by 5 to 17 percent, by temporarily reducing speed limits. Islam et al., (2013), proposed a control strategy for VSL and evaluated its safety and mobility impacts [80]. The results showed that VSL could improve roadway safety by approximately 50 percent and mobility by 30 percent. Another study used the Surrogate Safety Assessment Model to quantify the benefits of VSL and to show the importance of compliance with VSL [81]. The study showed that the safety benefits of VSL did not affect travel time. In addition, the benefits of the VSL was significantly affected by drivers' compliance. Another study showed that crash risk and crash occurrence could be reduced in free-flow conditions using VSL [79].

The benefits of VSL were also examined using field experiments. A study proposed a set of algorithms based on traffic conditions for setting variable speeds [85]. The results showed that higher throughput, stable traffic condition, and shorter travel time could be achieved using proper real-time speed controls. Hoogendoorn et al., (2013) evaluated VSL with respect to traffic operations, air quality, noise level, and traffic safety [86]. The results showed that traffic throughput was increased by 20 percent, and an improvement in driver behavior was observed. However, the study showed a slight deterioration in air quality and an increase in noise level during peak hours. In agreement with the previous results, VSL showed a significant effect in increasing traffic throughput [85], [87].

Apart from simulation-based studies, very few studies investigated the safety effectiveness of the VSL using the HSM methodology. A study showed that VSL would provide a reduction in crashes of 13 percent and 2 percent for weather-based VSL [88]. However, the developed CMFs were not significant. Saha et al., (2015) Examined the interaction between roadway geometry and adverse weather conditions within one VSL corridor in Wyoming using forecasted 7-day weather data [41]. The results showed that the interaction between roadway geometry with weather variables significantly influence crash probability. In addition, a reduction of 0.78 crashes per week per 100 mi of VSL corridor length was concluded. Another study investigated the impact of VSL to improve the freeways operation using real-time risk assessment techniques [89]. The study utilized a spatial-temporal analysis applied on a real-world traffic data to investigate the performance of roadways with and without VSL. The investigated VSL was based on traffic congestion and operation, where several VSL schemes were investigated. The results showed that the corridor performance improved having the VSLs in place, in which crash likelihoods and congestions were reduced. However, the study did not offer a quantified measure; CMF, for the VSL.

Data Description and Processing

To have reliable crash modification factors using EB before-after analysis, HSM recommended using at least three years in the before and after analysis period. In this study, six years of crash data before implementing the VSL, from 2003 to 2008, and five years after implementing the VSL, from 2012 to 2016 were utilized. Data in the before period was used to develop the safety performance functions from sections that have VSL on I-80. Afterwards, both datasets were employed to conduct the before after analysis using the EB. The years from 2009 to 2011 were excluded from the analysis as they were the years the VSL corridors were being constructed. The first implemented VSL section was by Elk Mountain, in February 2009, with a length of 52 miles, followed by the Green River section, in February 2011, with a length of 25 miles. In October 2011, the last two sections shortly implemented [41], [71], [90], with a length of 23 miles for the Evanston section and 47 miles for the Laramie-Cheyenne section.

Several data sources were utilized to construct the dataset used in this study. WYDOT was the main source preserving the extracted datasets. The CARE database was mainly used to extract detailed information about the crashes. Roadway geometric characteristics, cross-section elements, pavement type, and traffic data were extracted using the WYDOT Roadway Data Portal (RDP). Although the RDP provides comprehensive information about roadways in Wyoming, other important roadway information was not provided. Missing information is mainly related to the treatments implemented on I-80 (i.e implementation dates and locations). To obtain this missing information, non-traditional data sources were used. To extract information about the locations and implementation dates for the applied treatments, pathway video logs, Google Earth®, and Google Maps® were employed.

Manual extraction was used to obtain the needed roadway information from these non-traditional data sources. Pathway video log is a visual tool that archives captured videos for Wyoming's road network. Videos for I-80 were investigated for both directions to extract roadway information on a yearly basis. While extracting the data, the research team figured out an intermittent existence of shoulder rumble strips. This intermittent existence was a result of maintenance strategy adopted by WYDOT. This provided more complication to the dataset formation to account for temporal discontinuation of this countermeasure. In addition, Google Earth® and Google Maps® were used to check, confirm, and obtain missing data that could not be obtained from the pathway videos.

Information about snow fences locations, types, and heights were requested from WYDOT. Detailed information of snow fences was obtained in Google KMZ format files. An additional effort was exercised to manually extract snow fences information and to combine them within the investigated dataset.

The National Oceanic and Atmospheric Administration (NOAA) website was also used to extract weather data. Weather stations with complete datasets close to I-80 corridor were targeted to obtain the weather data information. Only weather stations with above 90 percent complete datasets were considered. The weather was assigned to the different roadway sections based on proximity to the used weather stations.

Roadway segmentation is considered an initial and essential step in data preparation. Variable length segmentation based on roadway geometry characteristics, known as homogeneous segmentation, was adopted in this study. A total of 597 segments were obtained for the I-80 corridor with scrutinizing the homogeneity in vertical and horizontal roadway geometry for both directions. Crashes were assigned to the 597 developed segments as each segment was identified as a site. To avoid the low exposure problem, a minimum threshold length of 0.1 miles was considered in the segmentation process [12]. Equivalent grades were calculated and considered in the segmentation process. Average and composite grades methods, provided in the HCM [48] were followed to determine the equivalent grades [47].

To consider the effect of the interchanges influence area on crashes, the roadway was sub-divided into two facility types; roadway segments and interchange segments. Due to the rural nature of Wyoming and the low traffic volumes, only three roadway classifications intersecting I-80 were considered. The three roadway classifications were interstate roads, principal arterials, and minor arterial. A total of 43 interchanges were identified for the eastbound and the westbound directions. A buffer zone of 0.3 miles, measured from the painted nose of the gore area, was considered to identify the interchange influence area [91]. All the possible resources were utilized to include as many variables as possible to provide an efficient model estimation. However, including all variables that could potentially determine the crash likelihood is impossible [92]. Table 4.1 shows the descriptive statistics for the variables used in this analysis.

Table 4.1 Descriptive statistics of the investigated variables

Dependent Variables (Crash per segment per year)		Mean		St. Dev.		Min.		Max.	
		Before	After	Before	After	Before	After	Before	After
Total Crashes		7.54	4.60	9.23	5.50	0	0	96	48
Property Damage Only (PDO) Crashes		5.40	3.72	6.87	4.59	0	0	73	42
Fatal and Injury (FI) Crashes		2.13	0.88	2.83	1.34	0	0	27	12
Truck Crashes		2.93	1.94	4.33	3.04	0	0	58	33
Continuous Response Variables		Mean		St. Dev.		Min.		Max.	
Variable type	Variable Name (Abbreviation - Unit)	Before	After	Before	After	Before	After	Before	After
Traffic Data	Average Annual Daily Traffic (AADT - vpd)	6296	6313	1162	1326	4153	3917	11557	11534
	Average Annual Daily Truck Traffic (AADTT - vpd)	3106	2842	349	359	2124	1190	3888	3580
	Vehicle Miles Travelled (VMT - MVMT)	3017	2991	3122	3047	438	436	35505	34154
	Truck Percentage (TPER - %)	50	46	5	5	34	29	59	55
Vertical and Horizontal Characteristics	Segment Length (L - mile)	0.49		0.53		0.10		5.84	
	Grade (GRADE - %)	0.10		1.93		-6.21		5.57	
	Delta (DELTA - Degree)	10.44		17.31		0		102.47	
	Radius (RAD - mile)	2856		5513		0		85852	
	Degree of Curvature (DOC-Degree)	0.61		1.82		0		44.33	
Cross-Sectional Elements	Median Width (MDWDTH - ft)	93.47		70.55		18		956	
	Total Width (WTOT - ft)	38.29		3.73		28		80	
	Left shoulder width (WLSH- ft)	3.79		0.61		2		4	
	Right shoulder width (WRSH- ft)	9.42		1.32		2		16	
	Number of Lanes (NLANE - #)	2.08		0.30		2		5	
Countermeasure	Height of Snow Fences (SFH - ft)	1.91		3.79		0		14	
	Bridge Count (BRGCOUNT - #)	0.20		0.43		0		3	
	Shoulder Rumble Strips (SRS - %)	46		35		0		100	
Weather Conditions	Number of Snow Days (SNWDAY- #)	30	34	14	14	11	14	59	69
	Number of Rainy Days (RNDAY- #)	75	82	19	18	40	51	110	114
	Number of Windy Days (WINDAY- #)	18	25	3	5	7	9	23	44

Categorical Response Variables Variable Name (Abbreviation)	Level (Code Value)	Percentage in each category
Grade Category (GCAT %)	VG<-2 (1)*	3.41
	-2<VG<0 (2)	33.71
	0<VG<2 (3)	40.75
	VG>2 (4)	22.12
Median Type (MEDTYP)	Depressed (1)*	71.25
	Raised (2)	28.75
Left Shoulder Type (LSHTYP)	Asphalt (1)*	71.49
	Concrete (2)	28.51
Right Shoulder Type (RSHTYP)	Asphalt (1)*	71.49
	Concrete (2)	28.51
Lane Type (LANTYP)	Asphalt (1)*	46.89
	Concrete (2)	48.60
	Combined (3)	4.52
Facility Type (FACTYP)	Roadway (1)*	89.19
	Interchange (2)	10.81
Climbing Lane (CLIMLANE)	Present (1)	2.63
	Not Present (0)*	97.37
Snow Fence Type (SFTYP)	No Fence (0)*	72.34
	Living Fences (1)	0.67
	Inclined Fences (2)	5.43
	Vertical Fences (3)	21.55

***Reference category for variable**

Preliminary Analysis

Wyoming is distinguished by its mountainous roadways and the severe weather conditions. Accordingly, this preliminary analysis was conducted to visualize the effect of weather and challenging roadway geometry on crashes at VSL sections along I-80. Figure 4.1 shows the geometric characteristics, weather information, and crash frequencies occurred in the before and after periods of VSL implementation on I-80. A general map of I-80 corridor is provided in Figure 4.1a, and shows the four VSL sections marked in red. The vertical profile of I-80 and the number of horizontal curves per the five mile streatches is shown in Figure 4.1b,. shaded red zones are provided to show the locations of the VSL sections within the corridor. A higher number of horizontal curves within the VSL sections was observed, compared to non-VSL sections. In addition, Figure 4.1b shows that the vertical grades within the VSL sections are steeper compared to the other non-VSL sections. The average number of snowy, rainy, and windy days per year, per five mile stretch encountered on I-80 is also presented in Figure 4.1c. It could be concluded that the two VSL sections (Elk Mountain and Laramie-Cheyenne) encounter more severe weather conditions throughout the winter season, as an increase in snowy and rainy days was observed. It could generally be concluded from Figure 4.1b and Figure 4.1c that VSL sections have more challenging roadway geometry and encounter more severe weather conditions.

Figure 4.1 (d-1 to d-4) shows the average crash frequency per year for total, PDO, F+I, and truck crashes occurred in the before and the after periods. It could be observed that VSL sections experienced higher crash frequencies than non-VSL sections. This might be a result of the challenging roadway geometry and the severe weather conditions faced within the VSL sections. Additionally, the crashes for the before period are slightly higher than the crashes for the after period. However, higher crash frequencies in the VSL sections were still observed in the after period. These crash spikes might misleadingly indicate that the implemented VSL treatment was not effective in decreasing crashes on I-80.

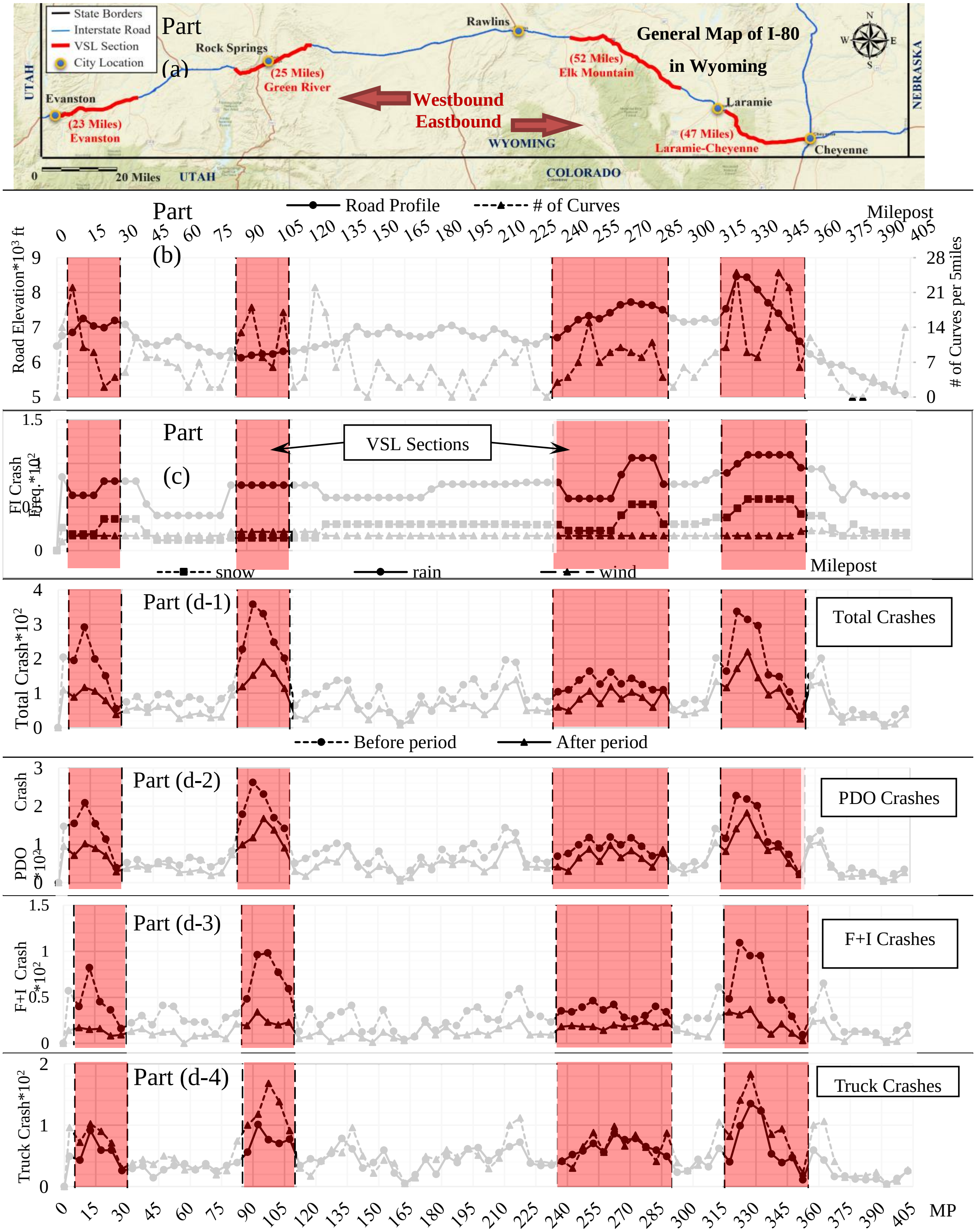


Figure 4.1 Observed crashes for before- after periods of VSL implementation for I-80.

Safety Effectiveness of VSL Corridors in Wyoming

To estimate the crash modification factors for the weather-VSL, development of SPFs are needed for the before period. It is recommended that full SPFs should be used over simple ones, as full SPFs provide more reliable results by accounting for confounding factors, especially when adopting a before-after study with EB [37]. Prior to model development, checking for multicollinearity should be carried out as it is considered a fundamental problem in statistical modeling [93]. The existence of redundant variables could increase the standard errors of the estimated effects, which influence the reliability of the developed model [94]. Checking for collinearity was conducted using person product-moment correlation. Redundancies among variables were eliminated from the predictor variables used in developing the SPFs. One of the main advantages of the Multivariate Adaptive Regression Splines (MARS) models is that it reduces the possibility of having variables that are highly correlated in the model. This is achieved in the forward selection procedure by the Generalized Cross Validation (GCV) criterion [95]. The GCV procedure is used to determine the variables to be kept in the model and the variables to be eliminated. Furthermore, it is used in the ranking procedure, where GCV values with and without each variable is calculated, then variables are ranked according to their importance.

Negative Binomial (NB) Model

Statistical Analysis System (SAS) 9.4 was used to develop the NB [38] analysis presented in this paper. The safety performance functions obtained using the NB model are provided in Table 4.2. It includes variables estimates, standard error (SE), significance level, and the Akaike Information Criterion (AIC) as the goodness of fit parameter. Table 4.3 shows the odds and the percentage effect of the variables on crashes. Results showed that VMT, steep down grades, sharp curves, narrow medians, raised medians, existence of inclined type to snow fences, increase in bridge count, and having a major interchange would increase the probability of all the investigated crash types. It was also noticed that one day increase in the number of rainy days would increase total, PDO, and F+I crashes, which is in line with results of previous studies [96], [97].

Table 4.2 Results of Negative Binomial (NB) Model

Total crashes

Variables	Estimates	S.E	*P*-value
Intercept	-5.512	0.310	<.0001
gcat (2)	-0.230	0.063	0.0003
gcat (3)	-0.291	0.065	<.0001
gcat (4)	-0.012	0.072	0.8687
DOC	0.042	0.012	<.0001
Medtyp (2)	0.3223	0.046	<.0001
medwdth	0.001	0.0002	0.0438
Lantyp (2)	0.137	0.0407	0.0008
Lantyp (3)	0.228	0.0885	0.0099
nlane	0.128	0.0569	0.0250
LOGVMT	1.968	0.0553	<.0001
AADTT	0.0001	0.0001	0.0218
SFTYP (1)	-0.500	0.2225	0.0245
SFTYP (2)	0.461	0.0744	<.0001
SFTYP (3)	0.019	0.0484	0.6887
rnday	0.005	0.0010	<.0001
winday	-0.032	0.0092	0.0004
Factyp (2)	0.337	0.0571	<.0001
Brgcount	0.436	0.0383	<.0001
Dispersion factor (K)	0.291	0.0173	
AIC		8764.66	

FI crashes

Variables	Estimates	S.E	*P*-value
Intercept	-6.1073	0.3317	<.0001
gcat (2)	-0.1609	0.0821	0.0500
gcat (3)	-0.2610	0.0851	0.0021
gcat (4)	0.0808	0.0929	0.3844
DOC	0.0491	0.0116	<.0001
medtyp (2)	0.2629	0.0602	<.0001
medwdth	0.0008	0.0003	0.0029
Lshtyp (2)	0.2080	0.0567	0.0002
LOGVMT	1.8904	0.0717	<.0001
SFTYP (1)	-0.5224	0.2714	0.0542
SFTYP (2)	0.3753	0.0958	<.0001
SFTYP (3)	-0.0357	0.0615	0.5619
rnday	0.0055	0.0014	<.0001
winday	-0.0210	0.0110	0.0562
Factyp (2)	0.2337	0.0744	0.0017
Brgcount	0.4384	0.0457	<.0001
Dispersion factor (K)	0.248	0.0284	
AIC		5555.41	

PDO crashes

Variables	Estimates	S.E	*P*-value
Intercept	-6.178	0.3374	<.0001
gcat (2)	-0.210	0.0684	0.0021
gcat (3)	-0.259	0.0701	0.0002
gcat (4)	-0.005	0.0774	0.9519
DOC	0.039	0.0102	0.0001
medtyp (2)	0.290	0.0506	<.0001
medwdth	0.001	0.0002	0.0501
Lshtyp (2)	0.204	0.0587	0.0005
Lantyp (2)	0.0610	0.0546	0.2634
Lantyp (3)	0.2863	0.0949	0.0025
nlane	0.1457	0.0612	0.0173
LOGVMT	1.9814	0.0600	<.0001
AADTT	0.0002	0.0001	0.0014
SFTYP (1)	-0.5767	0.2407	0.0166
SFTYP (2)	0.4544	0.0799	<.0001
SFTYP (3)	0.0641	0.0527	0.2233
rnday	0.0053	0.0011	<.0001
winday	-0.0356	0.0098	0.0003
Factyp (2)	0.3369	0.0617	<.0001
Brgcount	0.4078	0.0407	<.0001
Dispersion factor (K)	0.300	0.0201	
AIC		7881.67	

Truck crashes

Variables	Estimates	S.E	*P*-value
Intercept	-6.8274	0.3876	<.0001
gcat (2)	-0.1637	0.0836	0.0501
gcat (3)	-0.2453	0.0863	0.0045
gcat (4)	0.1146	0.0943	0.2240
DOC	0.0380	0.0123	0.0020
medtyp (2)	0.1438	0.0603	0.0171
medwdth	0.0010	0.0003	0.0008
Lantyp (2)	0.1923	0.0555	0.0005
Lantyp (3)	0.4631	0.1086	<.0001
LOGVMT	1.9991	0.0731	<.0001
AADTT	0.0003	0.0001	<.0001
Climlane	-0.3445	0.1526	0.0240
SFTYP (1)	-0.2297	0.2967	0.4389
SFTYP (2)	0.5785	0.0950	<.0001
SFTYP (3)	0.1077	0.0637	0.0909
snwday	0.0093	0.0020	<.0001
winday	-0.0376	0.0128	0.0033
Factyp (2)	0.2176	0.0776	0.0050
Brgcount	0.3814	0.0485	<.0001
Dispersion factor (K)	0.378	0.0301	
AIC		6381.26	

Table 4.3 Odds and Percentage Effect on Crashes per Unit Increase in Variable Measurement Using NB Model

	Total crashes		PDO crashes		F+I crashes		Truck crashes	
Significant Variables	Odds	% Effect	Odds	% Effect	Odds	% Effect	Odds	% Effect
gcat (2)	0.7945	-20.55	0.8106	-18.94	0.8514	-14.86	0.849	-15.1
gcat (3)	0.7475	-25.25	0.7718	-22.82	0.7703	-22.97	0.7825	-21.75
gcat (4)	0.9881	-1.19	0.995	-0.5	1.0842	8.42	1.1214	12.14
DOC	1.0429	4.29	1.0398	3.98	1.0503	5.03	1.0387	3.87
Medtyp (2)	1.3803	38.03	1.3364	33.64	1.3007	30.07	1.1547	15.47
medwdth	1.001	0.1	1.001	0.1	1.0008	0.08	1.001	0.1
Lantyp (2)	1.1468	14.68	1.2263	22.63	-	-	1.212	21.2
Lantyp (3)	1.2561	25.61	1.0629	6.29	-	-	1.589	58.9
Lshtyp (2)	-		1.3315	33.15	1.2312	23.12	-	-
nlane	1.1366	13.66	1.1568	15.68	-	-	-	-
LOGVMT	7.1563	615.63	7.2529	625.29	6.622	562.2	7.3824	638.24
AADTT	1.0001	0.01	1.0002	0.02	-	-	1.0003	0.03
SFTYP (1)	0.6065	-39.35	0.5617	-43.83	0.5931	-40.69	0.7948	-20.52
SFTYP (2)	1.5857	58.57	1.5752	57.52	1.4554	45.54	1.7834	78.34
SFTYP (3)	1.0192	1.92	1.0662	6.62	0.9649	-3.51	1.1137	11.37
Climlane	-	-	-	-	-	-	1.0093	0.93
snwday	-	-	-	-	-	-	0.7086	-29.14
rnday	1.005	0.5	1.0053	0.53	1.0055	0.55	-	-
winday	0.9685	-3.15	0.965	-3.5	0.9792	-2.08	0.9631	-3.69
Factyp (2)	1.4007	40.07	1.4006	40.06	1.2633	26.33	1.2431	24.31
Brgcount	1.5465	54.65	1.5035	50.35	1.5502	55.02	1.4643	46.43

Increase in snowy days would increase truck crashes, which is consistent with Ahmed et al., (2018) [98]. Interestingly, the increase in the number of windy days would decrease crashes for all crash types, which is in agreement with previous studies [99], [100]. This might be due to the more cautious motorists are when encountering strong winds.

Multivariate Adaptive Regression Splines (MARS) Model

The MARS Model was first introduced by Friedman (1991) as a nonparametric regression technique. This technique develops knots to split the domain of the independent variables into several regions. Polynomial Basis Function (BF) for each region is then fitted into each region, in which splines are used to connect the developed BFs at the defined knots [93], [101]–[103]. To fit a MARS model, two phases should be followed, 1) model generation and 2) model selection. In the model generation phase, two stages are performed to develop the model. Forward selection is the first stage in model generation. Using Equation 4-1, the BF’s could be generated and added to the model. Prior to develop the BF’s, the maximum number of BFs should be identified. There is no identified threshold of the maximum number of BFs that should be used in the analysis. The larger the number of BFs used in the analysis, the better least squares goodness-of-fit criterion, however, it might introduce overfitting issues. As a common practice in transportation research field, 20 to 30 BFs are usually selected as the maximum number of BFs [101]–[103].

$$\hat{Y}(x) = \sum_{m=1}^{M} a_m \, BF_m(x) \qquad \text{Equation 4-1}$$

Where $\hat{Y}$ is the predicted response variable, a_m is the coefficient of the Basis Function number (m), $BF_m(x)$ is the Basis Function number (m) for the independent variable x, and M is the total number of Basis Functions (BF).

In this stage, an initial model is developed starting only with a constant, then it begins to add variable-knot combination that would improve the model. The model is improved based on the lowest obtained Mean Square Predicted Errors (MSPE) and the lowest Mean Absolute Deviance (MAD), given by Equation 4-2 and Equation 4-3. Interactions are developed in this stage as well to improve model fit. MARS determine all the significant interactions automatically, even though; the maximum number of interaction terms should be identified prior to the generation phase. This process is repeated, identifying the best variable-knot combination, until the identified maximum number of BFs is reached.

$$MSPE = \frac{1}{n \times \bar{y}} \sum (y_i - \mu_i)^2 \qquad \text{Equation 4-2}$$

$$MAD = \frac{1}{n \times \bar{y}} \sum |y_i - \mu_i| \qquad \text{Equation 4-3}$$

Where n is the sample size for the dataset, $\bar{y}$ is the average of the dependent variable, y_i is the observed crash frequency for the $i\ th$ roadway segment, and μ_i is the predicted crash frequency.

The second model generation stage is the backward elimination, where BFs are deleted based on variable importance and contribution to avert overfitting of the model. Residual sum of squares (RSS) criteria is used to determine the eliminated BFs, where lower RSS values would indicate a better model. RSS could be calculated as given in Equation 4-4.

$$\boldsymbol{RSS} = \sum_{\boldsymbol{i=1}}^{\boldsymbol{n}} (\boldsymbol{y_i} - \boldsymbol{\hat{y}}(\boldsymbol{x_i}))^{\boldsymbol{2}} \qquad \text{Equation 4-4}$$

Where $\hat{y}(x_i)$ is the predicted value for the i^{th} roadway segment.

In the model selection phase, which is the second phase to fit a MARS model, Generalized Cross-Validation (GCV) criterion or closeness between the training Mean Square Error (MSE) and the test MSE are used to select the final model, given by Equation 4-5 and Equation 4-6. For the GCV criterion, a penalty for model complexity is applied, which is based on the degrees of freedom charged for each developed knot.

$$GCV(M) = \frac{1 \sum_{i=1}^{n}(y_i - \hat{y}(x_i))^2}{n\,(1 - C(M)/n)^2} \tag{Equation 4-5}$$

$$C(M) = M + dM \tag{Equation 4-6}$$

Where $C(M)$ is the complexity penalty function, d is the defined cost for each BF, and recall, M is the number of BFs.

MARS modeling has two main advantages in modeling crash data: 1) It automatically provides the predictive model, where it determines the significant variables and their functional form, 2) Causal relationships are obtainable for multiple BFs over the split regions, which provides flexibility to fit a nonlinear relationship.

Salford Predictive Modeler 8.2 (SPM) software was used to run the MARS models developed in this study. To run the MARS model, data was divided into two parts; training and validating. Seventy percent of the data were randomly selected to develop the calibrated model, and 30 percent was used in the validation phase, in which the Generalized Cross-Validation (GCV) criterion or closeness between the training MSE, and the test MSE were used to select the final model. Prior to developing the model, the maximum number of allowed Basis Function (BF) and maximum number of interacted variables should be identified. As a common practice in the transportation field, the maximum number of allowed interacted variables are limited to two to provide interpretable models. Higher interaction levels might possibly provide a better fit for the data; however, more than two interactions provide complexity to the obtained model. In addition, a maximum number of BFs was limited to 25 BFs. Previous studies showed that an adequate number of BFs would range from 20 to 30 BFs [101], [102], [104], [105]. Increasing the number of BFs would provide a better least squares goodness-of-fit criterion. Yet, it might introduce overfitting issues.

Table 4.4 shows the obtained results for the four developed models using MARS and provides the goodness of fit and the prediction validation. Two types of BFs were obtained from the MARS model, elementary BFs and complex BFs. The BFs, which include only one variable, are called elementary BF, and the complex BFs are the ones allowing interaction between variables. It can be noticed from Table 4.4 that most of the significant variables had a non-linear relationship with crashes, as they are presented in more than one BF. Several truncated functions were developed with identifying the knot separating the domain space.

For example, a knot with a value of 54 was developed for median width in the total crash model, represented in BF6. This means that the rate of impact for the median width is divided into two domains, which affect total crashes differently. To clarify the total impact of median width on total crashes, BF6 and BF8 truncated functions should be considered together. BF8 is a complex BFs, as median width interacted with the logVMT. Due to this interaction term, the impact of median width on total crashes is influenced by the VMT. To obtain the rate of impact expression for the median width, the first derivative of the impact expression should be considered. Finally, the conditions under which the rate of impact expression would be positive or negative would identify the direction of impact.

Table 4.4 Results of Multivariate Adaptive Regression Splines Model

(A) MARS model for total crashes

BFs	Basis function information	Estimates	SE	*p*-value
BF0	CONSTANT	6.83327	0.4545	<.0001
BF1	max (0, LOGVMT - 4.03905)	92.4488	6.3804	<.0001
BF4	max (0, 1 - BRGCOUNT)	-3.6082	0.4481	<.0001
BF6	max (0, 54 - MEDWDTH)	0.28458	0.0258	<.0001
BF8	max (0, 3.47449 - LOGVMT) * BF6	-0.50466	0.0682	<.0001
BF13	max(0, LOGVMT - 3.45847)		Not. Sig.	
BF15	(FACTYP in (1)) * BF13	-35.1589	3.5723	<.0001
BF17	max (0, DELTA - 10.58) * BF13	2.47662	0.1836	<.0001
BF18	max (0, 10.58 - DELTA) * BF13	5.24172	0.3242	<.0001
BF23	max (0, SNWDAY - 39.714) * BF13	1.53401	0.1999	<.0001
	Goodness-of-fit (Calibration)	Prediction Assessment		
R^2	0.61	MAD	4.17	
AIC	3005.9	MSPE	38.68	
K	0.156	#of obs.	492	
#of obs.	1146			

(B) MARS model for F+I crashes

BFs	BF function information	Estimates	SE	p-value
BF0	CONSTANT	1.0130	0.0811	<.0001
BF1	max(0, LOGVMT - 3.98752)	23.7952	2.7147	<.0001
BF2	max(0, 3.98752 - LOGVMT)		Not. Sig.	
BF3	max(0, BRGCOUNT - 1)	4.7584	0.4707	<.0001
BF7	(LANTYP in (1)) * BF1	-18.7385	2.9960	<.0001
BF13	max(0, 0.515562 - TPER)	30.7284	3.2569	<.0001
BF15	max(0, 0.496168 - TPER) * BF2	-44.4340	6.4253	<.0001
BF20	max(0, LOGVMT - 3.41172)	6.4628	0.4729	<.0001
BF22	max(0, DELTA - 53.96) * BF20	1.2030	0.1728	<.0001
BF24	max(0, LOGADTT - 3.50718) * BF20	-7.3351	0.9412	<.0001
	Goodness-of-fit	Prediction Validation		
R^2	0.51	MAD	1.53	
AIC	2986.5	MSPE	5.27	
K	0.117	#of obs.	492	
#of obs.	1146			

(C) MARS model for PDO crashes

BFs	BF function information	Estimate	SE	p-value
BF0	CONSTANT	4.1626	0.3840	<.0001
BF1	max (0, LOGVMT - 4.0917)	85.0418	5.7804	<.0001
BF4	max (0, 1 - BRGCOUNT)	-3.0120	0.3390	<.0001
BF5	max (0, MEDWDTH - 54)	0.0180	0.0025	<.0001
BF6	max (0, 54 - MEDWDTH)	0.2397	0.0220	<.0001
BF8	max (0, 3.4745 - LOGVMT) * BF6	-0.3121	0.0516	<.0001
BF16	max (0, LOGVMT - 3.46735)	59.7275	3.4404	<.0001
BF18	(LSHTYP in (1)) * BF16	-18.1680	1.8210	<.0001
BF20	(FACTYP in (1)) * BF16	-27.4586	3.3759	<.0001
BF23	max (0, 3.5081 - LOGADTT) * BF16	-11.666	1.4805	<.0001
	Goodness-of-fit (Calibration)	Prediction Assessment		
R^2	0.60	MAD	3.21	
AIC	3109.4	MSPE	23.27	
K	0.175	#of obs.	492	
#of obs.	1146			

(D) MARS model for truck crashes

BFs	BF function information	Estimates	SE	p-value
BF0	CONSTANT	5.9108	0.2379	<.0001
BF1	max (0, LOGVMT - 4.0917)		Not. Sig.	
BF2	max (0, 4.0917 - LOGVMT)	-4.4119	0.2848	<.0001
BF3	max (0, BRGCOUNT - 1)		Not. Sig.	
BF15	max (0, LOGVMT - 2.64156) * BF3	5.4500	0.5851	<.0001
BF18	max (0, WRSH - 2) * BF1	7.8044	0.4344	<.0001
BF19	max (0, TPER - 0.574776)		Not. Sig.	
BF21	max (0, LOGVMT - 3.47731) * BF19	8.6516	0.1122	<.0001
	Goodness-of-fit	Prediction Validation		
R^2	0.50	MAD	2.03	
AIC	3559.7	MSPE	10.14	
K	0.201	#of obs.	492	
#of obs.	1146			

Crash Modification Factors for VSL

The developed CMFs for total, F+I, PDO, and truck crashes of the VSL for the rural mountainous freeways is given in Table 4.5. Standard errors, upper and lower confidence interval limits (CI) were calculated for 95 percent significance level to identify the reliability of the calculated CMFs. The developed CMFs indicated a significant reduction on all the investigated crash types at 95 percent confidence level when VSL exists on the freeway. This was expected as the VSL harmonizes the speed within the corridor and reduces the speed variability among motorists [41], [71], [106]. Furthermore, it provides the adequate safe operating speed that corresponds the real-time weather conditions. The VSL showed its ultimate effectiveness on reducing truck crashes. The safety effectiveness attained using NB and MARS for truck crash models were 29 percent and 34 percent, respectively. For total and F+I crashes, the VSL showed a reduction of 22 percent and 28 percent using NB and MARS. Moreover, VSL showed involvement in reducing PDO crashes, however, the effectiveness was low compared to the other crashes. The calculated CMFs for PDO crashes were 15 percent using NB model and 13 percent using the MARS model. It could be noted from Table 4.5 that all the calculated Standard Errors (SE) for the developed CMFs using the MARS models were lower than the SE calculated using NB models. This shows that the CMFs developed using the MARS model are more reliable than the ones developed using NB, given the lower SE values.

Table 4.5 Developed CMFs for VSL using NB and MARS

	CMFs using NB				CMFs using MARS			
	Tcrash	F+I	PDO	Truck	Tcrash	F+I	PDO	Truck
CMF	0.7832	0.7844	0.8549	0.7134	0.7194	0.7204	0.8752	0.6622
SE (CMF)	0.0097	0.0092	0.0121	0.0130	0.0088	0.0085	0.0093	0.0099
Min. 95% CI	0.7642	0.7664	0.8312	0.6879	0.7022	0.7037	0.8570	0.6428
Max. 95% CI	0.8022	0.8024	0.8786	0.7389	0.7366	0.7371	0.8934	0.6816
Safety Effectiveness	21.68%	21.56%	14.51%	28.66%	28.06%	27.96%	12.48%	33.78%

Conclusions and Discussions

Interstate 80 is one of the busiest freight corridors in Wyoming, which is characterized by challenging roadway geometry and adverse weather conditions. The primary focus of this study was to investigate the safety efficacy of weather-based VSL system on a vital corridor, I-80, in Wyoming, using a before-after study with the EB method. Parametric and non-parametric approaches were utilized in this study to develop CMFs for the VSL. Due to several transferability issues of the HSM SPFs to other states, developing site-specific SPFs were preferred. Great controversy exists in the traffic safety literature about the preference of using regular parametric approaches over nonparametric approaches to develop SPFs and CMFs. Each of which has its own advantages and disadvantages. Parametric models are considered practitioner-friendly approach to develop CMFs in order to assess the safety effectiveness of countermeasures. In addition, the obtained results are easier to interpret. However, simple approaches, such as NB models, might suffer from critical limitations. NB models are among the Generalized Linear Models (GLM), in which a linear relationship between the predictors and the response is assumed. For crash data, this linear relationship might not exist with several predictors. This would affect the results and the accuracy of the developed models and CMFs. This particular issue is considered one of the main advantages of the nonparametric models, such as MARS. MARS models have no prior assumptions about the underlying functional relationships between response and predictor variables. A flexible model is developed by connecting splines, smoothly, in which it can handle both linear and nonlinear relationships. This would provide more accurate prediction of crashes and a more precise CMFs compared to NB models. To decide which approach should be selected to develop CMFs of a certain countermeasure, the overall purpose and application should be clearly identified. Three main purposes could drive researchers to develop CMFs; 1) evaluating the safety benefits of a new countermeasure that was not previously investigated, 2) comparing the usefulness of multiple countermeasures, and/or 3) utilizing CMFs to develop a cost-benefit analysis. Additionally, the application of CMF might vary based on the study objectives and goals. They might be used to determine the benefits of a certain severity levels, total crashes, or certain crash types. Based on the required level of accuracy and validity of assumptions the statistical approach should be determined. This could also be reflected in the developed SPFs, whether they target crash prediction or crash causality [105]. The results showed the SPFs developed using MARS provide better model prediction given the lower Akaike Information Criterion (AIC) values compared to the ones obtained from the NB model. Additionally, the MARS models accounted for the non-linear relationship between the independent and the dependent variable, in which several variables were involved in multiple BFs. The SPFs developed using the nonparametric MARS model resulted in better CMFs with lower standard errors. While it was proven in this study that nonparametric models are generally superior to parametric approaches, parametric approaches could be adequate for transportation agencies to conduct computationally inexpensive safety/cost-benefit analyses.

SNOW FENCES

Introduction

Wyoming experiences some of the most severe weather conditions in the US; blowing snow conditions, specifically, cause the most problems throughout the state. Snow Fences are a countermeasure that WYDOT has been using to help control the amount of blowing snow across highways and interstates. Originally used to protect railroads, Wyoming has been using snow fences for almost 150 years. Snow fences are used to divert wind patterns and cause the winds to dump their snow on the leeward side of the snow fences rather than continuously carry snow. This technique of snow mitigation targets drifting snow, snow build-up, and maintenance cost reduction. Because of this, the design and placement of snow fences can directly affect the amount of snow collected. There have been correlations found between the amount of vehicle crashes occurring during a blizzard and the percentage of roads protected by snow fences. This information indicated a negative correlation meaning that the amount of crashes occurring during a blizzard reduces as the percentage of snow fence protection increases. In addition, a reduction in the severity of vehicle crashes was found when comparing the crash data for the before the installation of snow fences and the crash data for the after the installation of snow fences.

Literature Review

No one likes to drive in adverse weather conditions; it can be difficult to see road markings and signs and roads might become icy or snow packed. In Wyoming, the majority of traffic uses interstate roads and the highway roads, given the remote nature of the state [107]. This intensifies the need to keep the roadways safe and clear for people to travel, especially in the winter seasons. According to WYDOT’s 2016 Fact Sheet, the majority of crashes that occurred in 2016, in Wyoming, occurred in November, which is at the beginning of the winter season [108]. In relation to this, 70 percent of injuries from vehicle crashes are related to ice and snow every year in Wyoming [109]. According to Figure 4.2 there is a positive linear relationship when relating the number of crashes during a blizzard to the number of crashes associated with slush and ice from 1970 to 1985. This means that as blizzard conditions intensify, the amount of crashes related to ice and slush will increase as well.

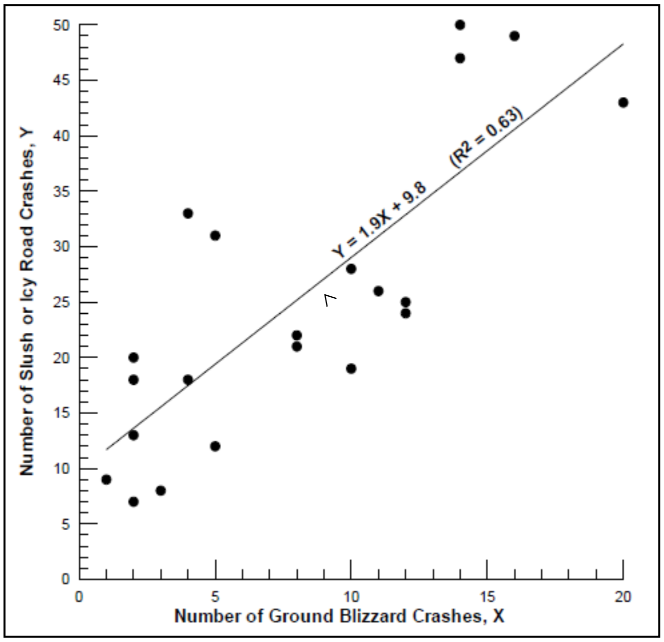


Figure 4.2 The relationship for blizzard caused crashes against slush/icy caused crashes from 1970 to 1985 [110]

In a study conducted in 1980, snow fences were responsible for preventing 54 crashes and 35 injuries; in 2001, the study was repeated and snow fences were responsible for preventing 78 crashes and 36 injuries. It is worth mentioning that these studies used a naïve before-after analysis which is not very reliable, and does not account for the Regression-to-the-Mean (RTM) bias and confounding factors. Figure 4.3 shows the number of crashes has a negative linear relationship with the percentage of roads that were protected by snow fences from 1970 to 1985. This means that as the percentage of snow fence protected roadways increased there was a noticable decrease in crashes due to adverse weather conditions [110]. Because of the positive outcome, interest in the use of snow fences continues.

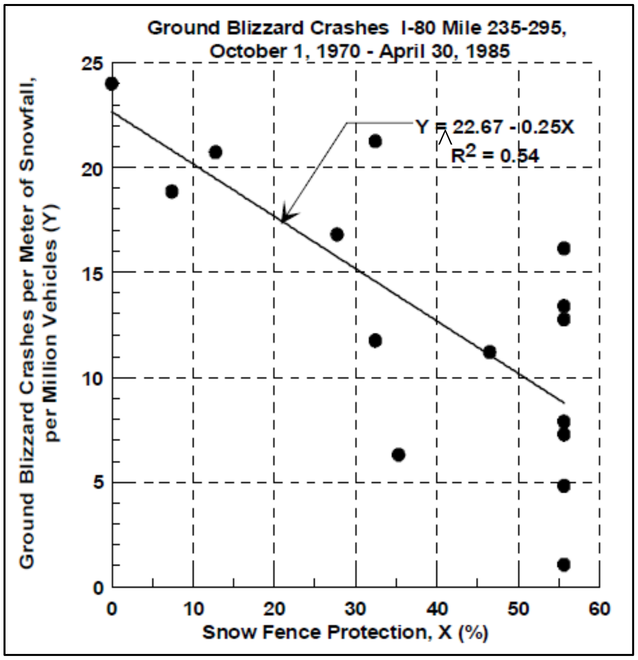


Figure 4.3 The Relationship of Blizzard Caused Crashes Against the Percentage of Snow Fence Protection from 1970 to 1985 [110]

The research regarding snow fences that is to follow in this report is expected to be a continuation and expansion of the Phase 1 study on Snow Fences [38] and [9]. The study looked at a concentrated area of snow fences that spanned 19 miles of I-80, in Wyoming; this section of roadway had an unusually large number of snow fences in a rural mountainous location. To begin with, in Phase 1 a naïve before-after analysis was conducted to see if there was a crash pattern associated with the winter seasons. As shown in Table 4.6, it was determined that there is an unusually high number of crashes that occurred during adverse weather conditions when compared to the total number of crashes. Of the 949 crashes that occurred in the winter seasons, 749 crashes occurred during adverse weather conditions, that is 79 percent of the crashes that occurred during the winter seasons [111]. As shown in Table 4.7, this information was specifically analyzed during adverse weather conditions, and it shows that before snow fences were installed in this area 34 percent of crashes were F+I crashes but after snow fences were installed the percentage of crashes decreased to 24 percent for F+I crashes. The total amount of crashes was reduced by 56 crashes and the percentage of F+I crashes reduced by 43 percent [9]. Figure 4.4 shows the effects of snow fence implementation by mapping the crashes along the 19-mile segment of I-80 by using a heat map where there are 4 years in the before period and 4 years in the after period. On the left, the crashes that occurred before snow fence implementation are shown; in the center, the snow fence locations on I-80 segment are shown in relation to where the roadway falls; on the right, the crashes that occurred after snow fence implementation are shown. There is an obvious decrease in crash frequency along the roadway that is observed between the before and after periods. Figure 4.4 illustrates the crash frequencies on a 19-mile (mileposts 325 to 344) on I-80 in Wyoming before and after the implementation of snow fences [9], [112].

Table 4.6 Crash Distribution by Severity Level (2003-2011 Winter Seasons) [112]

Crash Type	Frequency	Percentage
PDO Crashes	685	72%
F+I Crashes	264	28%
Total Crashes	**949**	100%
PDO Adverse Weather Crashes	545	73%
F+I Adverse Weather Crashes	204	27%
Total Adverse Weather Crashes	**749**	100%
*Note: Total Crashes = (PDO Crashes) + (F+I Crashes)		

Table 4.7 Adverse Weather-Related Crash Breakdown by Winter Weather Season

Winter Season	Total Crashes	F+I Crashes	PDO Crashes	%F+I
2003-2004	28	6	22	21%
2004-2005	36	14	22	39%
2005-2006	27	13	14	48%
2006-2007	37	10	27	27%
Before Total	**128**	**43**	**85**	**34%**
2007-2008	20	2	18	10%
2008-2009	12	1	11	8%
2009-2010	21	7	14	33%
2010-2011	19	7	12	37%
After Total	**72**	**17**	**55**	**24%**

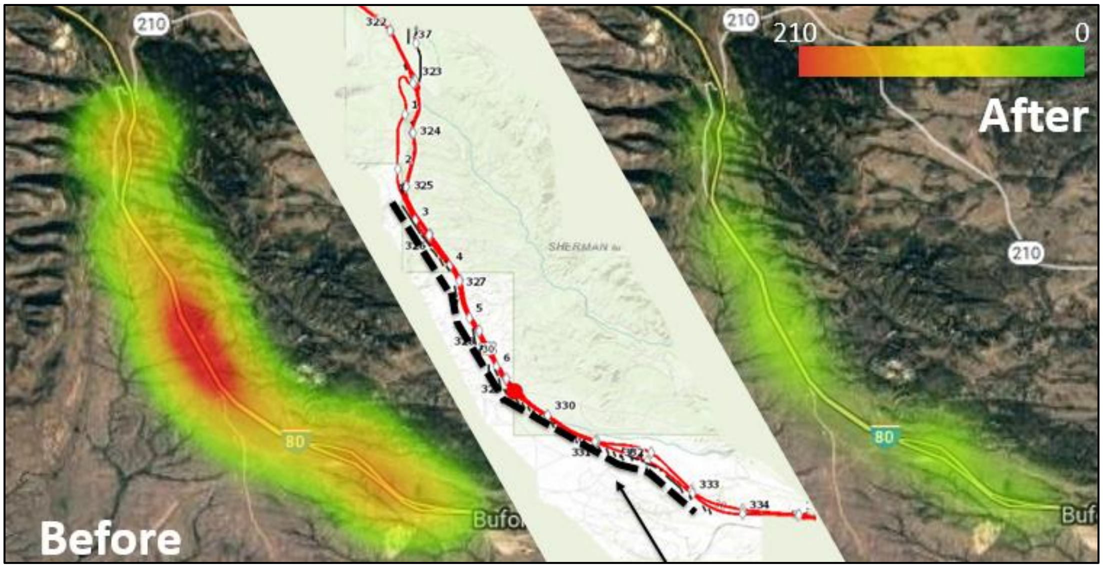
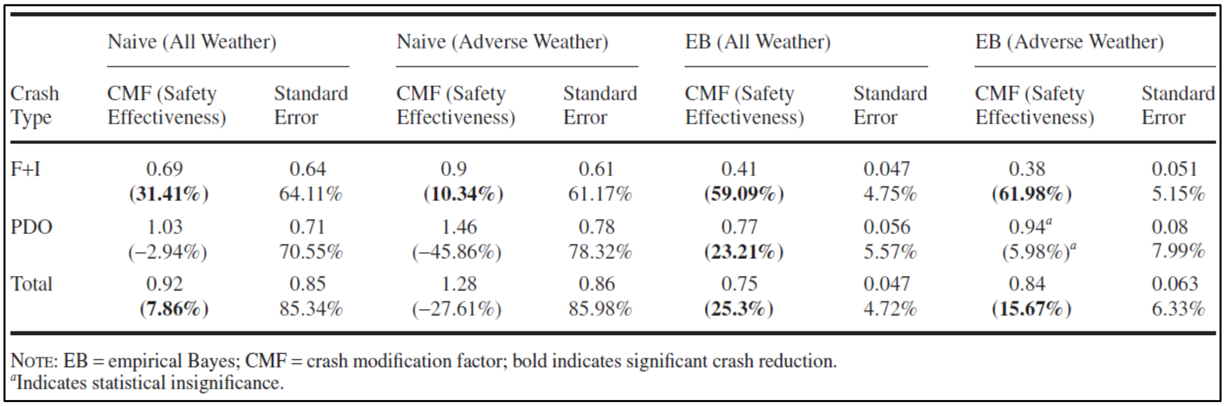


Figure 4.4 Crash Mapping of 19 Mile Segment of I-80 [112]

In Table 4.6 and Table 4.7, the information states that adverse weather is the main cause of winter crashes and the installation of snow fences helped reduce the amount of crashes that occurred. In Table 4.8, the CMFs were calculated using two methods: naïve analysis and the EB analysis. By doing this, the safety effectiveness and corresponding statistical significance was determined based on type of crash for all weather conditions and for adverse weather conditions. Table 4.8 shows that there was a positive effect on the frequency for all four tests for F+I crashes; there was a significant decrease in crashes for F+I crashes. However, for PDO crashes, the only test that showed any positive statistical significance was the EB test for all weather conditions; this means that the other three tests did not have enough of a positive effect to be statistically significant, or there was a decrease in the safety effectiveness. For the total crashes, the only test that did not show a positive statistical significance was the naïve test for adverse weather; this means that the other three tests had enough of a positive effect that is statistically significant and increased the safety effectiveness. Peel et al. (2017) concluded that there was a significant increase in safety effectiveness of F+I crashes once snow fences were installed [9]. This means that snow fences decreased the severity of the crashes that were occurred, but it did not reduce the amount of PDO crashes and the naïve tests stated that there was a negative effect associated with the installation in regards to PDO crashes [9], [38].

Table 4.8 - Before-After Analysis Results [9], [38]



	Naive (All Weather)		Naive (Adverse Weather)		EB (All Weather)		EB (Adverse Weather)	
Crash Type	CMF (Safety Effectiveness)	Standard Error	CMF (Safety Effectiveness)	Standard Error	CMF (Safety Effectiveness)	Standard Error	CMF (Safety Effectiveness)	Standard Error
F+I	0.69 **(31.41%)**	0.64 64.11%	0.9 **(10.34%)**	0.61 61.17%	0.41 **(59.09%)**	0.047 4.75%	0.38 **(61.98%)**	0.051 5.15%
PDO	1.03 (–2.94%)	0.71 70.55%	1.46 (–45.86%)	0.78 78.32%	0.77 **(23.21%)**	0.056 5.57%	0.94[a] (5.98%)[a]	0.08 7.99%
Total	0.92 **(7.86%)**	0.85 85.34%	1.28 (–27.61%)	0.86 85.98%	0.75 **(25.3%)**	0.047 4.72%	0.84 **(15.67%)**	0.063 6.33%

NOTE: EB = empirical Bayes; CMF = crash modification factor; bold indicates significant crash reduction.
[a]Indicates statistical insignificance.

Data Sources and Preparation

Snow Fence Data

Because this study models the before-after effects of snow fences, snow fence data needed to be acquired in order to determine where the snow fence influence areas are, and which types of snow fences are where along I-80. The snow fence data, including locations, fence types, lengths, materials, and various secondary characteristics (porosity, inclination angle, bottom gap, etc.), were obtained from the Winter Research Department of WYDOT. For this safety analysis, the primary concerns were the type, location, length, and associated influence area of the snow fences along the I-80 corridor in Wyoming.

Four separate analyses were conducted based on snow fence types: lath, Wyoming, upright/vertical, and combined/all types. Lath snow fences are similar to property line fences, do not exceed 4 feet in height, and tend to be made of wooden vertical slats or woven wire. These snow fences are primarily used to help mitigate the effects of blowing near snow; near snow is the snow that is between the snow fence structure and the roadway. An example of lath snow fences along I-80 in Wyoming is shown in Figure 4.5; this picture was taken on the Summit between Laramie and Cheyenne on March 21, 2019. Wyoming snow fences are 6 to 12 feet tall and set at an angle, which varies based on the location. An example of Wyoming snow fences along I-80 in Wyoming is shown in Figure 4.6; this picture was taken on the Summit between Laramie and Cheyenne on March 21, 2019. Upright/vertical snow fences are 6 to 12 feet tall and set vertically. An example of upright/vertical snow fences along I-80 in Wyoming is shown in Figure 4.7; this picture was taken on the Summit between Laramie and Cheyenne on March 21,

2019. Wyoming and upright/vertical snow fences are typically made of wood, metal, and/or polymer rail; these fences are known to collect and store large amounts of blowing snow [11]. Many segments of I-80 tend to have multiple types of snow fences in the same area, hence, a combined snow fence analysis was also conducted. Through this, it is possible to see and understand how multiple types of snow fences work in unison. Lath fences protect 148 miles of I-80, Wyoming fences protect 81 miles, and upright/vertical fences protect 55 miles; combined, the three types (i.e., all types) protect a total of 278 miles of I-80. The sections of I-80 that are characterized with snow fences are between: milepost (MP) 9 and MP 39, MP 49 and MP 67, MP 81 and MP 85, MP 90 and MP 94, MP 99 and MP 127, MP 131 and MP 176, MP 181 to MP 221, MP 233 and MP 292, MP 302 and MP 311, and MP 318 and MP 359.

Figure 4.5 - Example of Lath Snow Fences on I-80 (Taken: 2019)

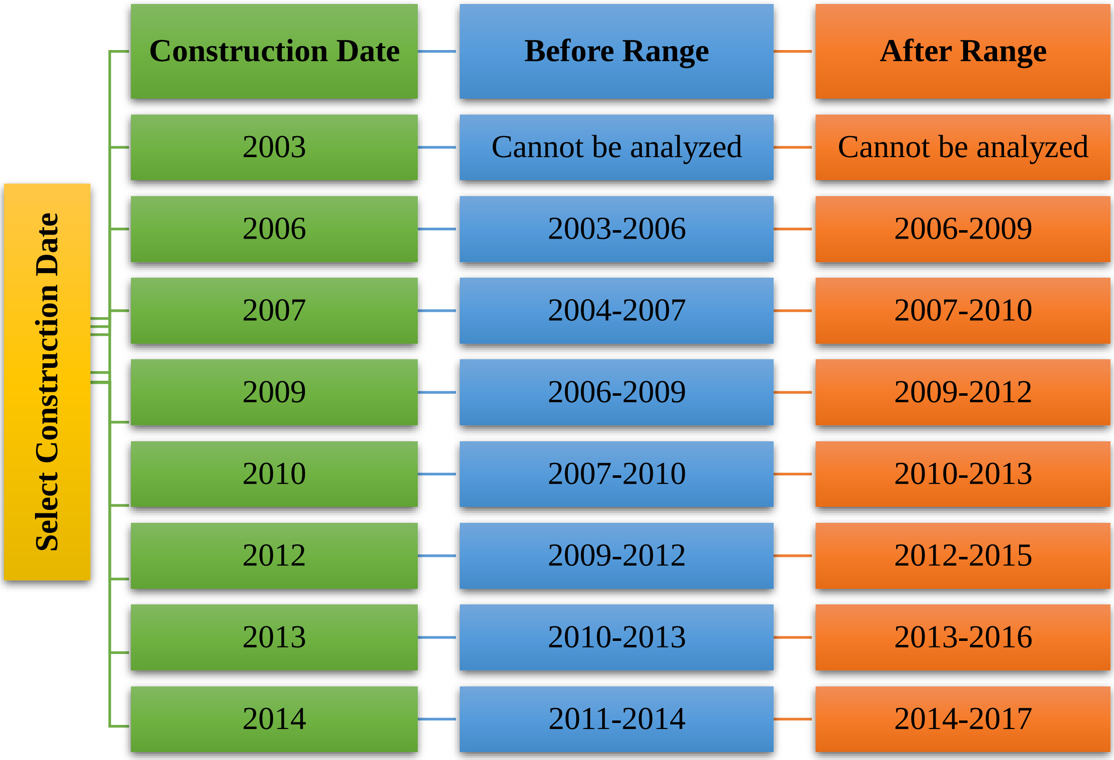
Figure 4.6 Examples of Wyoming Snow Fences on I-80 (Taken: 2019)

Figure 4.7 Examples of Upright/Vertical Snow Fences on I-80 (Taken: 2019)

Crash Data

Detailed and accurate crash data are extremely significant for the development of accurate and reliable SPFs. The primary source of crash data comes from the CARE, which is a crash reporting software provided and distributed by WYDOT [113]. WYDOT began using CARE in 1994, and continues to update the system each year with crash data from the previous calendar year. For this study, the dataset from 2003 to 2017 was made available. CARE was used exclusively as the sole source of crash data, which is common in many road safety studies in Wyoming [21], [38].

For the analysis period, crash data was collected on a 'winter weather season' basis. To provide a consistent and defined winter season for each year; each season was limited to October 15th through the following April 15th [9], [41]. For this study, the overall analysis range is from October 15th, 2003 to April 15th, 2017; however, each segment is assigned an analysis period of six full winter seasons worth of crash data depending on the snow fence's construction dates, as shown in Figure 4.8. For example, if the snow fences for a segment were constructed in 2009, this segments before analysis period spans from October 2006 to April 2009, and the after-analysis period spans from October 2009 to April 2012. This provides data for three years before the snow fence installation and three years after the snow fence installation, which meets the duration recommendation established by the HSM [12]. Figure 4.8 shows how the analysis periods were assigned based on the snow fence's construction date. It is worth mentioning that any snow fence implemented in 2003 could not be analyzed because the crash dataset was not available to create an adequate before period. In Figure 4.8, 2004, 2005, and 2008 are not included as construction dates because of the existing snow fences, none were recorded to be constructed in 2004, 2005, and 2008, along I-80. Common practice requires that the first six months of crash dataset following the implementation of a countermeasure be eliminated from the study to account for the drivers adjusting to the new countermeasure. However, this adjustment is not needed for snow fences since they are not a behavioral-based countermeasure.



Select Construction Date

Construction Date	**Before Range**	**After Range**
2003	Cannot be analyzed	Cannot be analyzed
2006	2003-2006	2006-2009
2007	2004-2007	2007-2010
2009	2006-2009	2009-2012
2010	2007-2010	2010-2013
2012	2009-2012	2012-2015
2013	2010-2013	2013-2016
2014	2011-2014	2014-2017

Figure 4.8 Selected years for the before-after analysis based on the construction dates of the snow fences

For this study, the investigation areas were characterized through homogeneous segmentation process; this means that the I-80 corridor was divided into small roadway segments based on geometric characteristics to help evaluate common contributing factors to crashes. The study areas were selected based on snow fence locations; therefore, even though this study looked at the entire I-80 corridor in its data range, only a total of 278 miles were used for this investigation. The process outlined throughout the equations provided in this section, combined with the associated crash, traffic, and facility data, and their associated segmentation, allowed for the safety effectiveness to be determined for each crash type during the overall winter season as well as during adverse winter weather conditions.

In addition to crash frequencies, developing various models for different levels of crash severity was also desired; especially when considering an adverse weather-related countermeasure, such as snow fences, where a high portion of crashes of higher severity levels are expected during severe weather and surface conditions [114]. Typically, within safety studies, crashes are simplified into three severity levels, 1) total crashes, which represents all crashes that occur on the investigated sections, 2) PDO crashes, which indicate a minimum cost of $1,000, and no reported injuries crashes, and 3) F+I crashes, which indicate the crash events associated with some type of injury (non-incapacitating or incapacitating) or fatality [9], [21], [38], [110], [115]–[119].

Terrain Type Data

In addition to investigating the before-after effects of each snow fence type, this study analyzes the before-after effects of snow fences on different terrain types. When driving, people tend not to think too much into how the terrain is affecting their driving behaviors or how it may be affecting their vehicle's performance. When road designers are using general design manuals, most of the manuals are designed for level roadway conditions. What many do not realize is that changes in terrain conditions tend to increase the likelihood of a vehicle crash.

According to AASHTO's Green Book, there are three classifications for terrain: flat/level terrain, rolling terrain, and mountainous terrain. Flat/level terrain is defined where the sight distance of the driver is unobstructed for a great distance; if the sight distance is compromised and can be removed with minimal construction expenses, this section of roadway is also classified as flat/level terrain. Rolling terrain is defined as sections of roadway that have "natural slopes consistently rising above and falling below the road grade" [120]. These sections can also have steep slopes dispersed amongst the gentle grade changes, but rolling terrain is primarily when there is "some restriction to the normal horizontal and vertical roadway alignment" [120]. Mountainous terrain is defined as roadways that undergo abrupt "longitudinal and transverse changes in the elevation" [120]; this type of terrain tends to cause the most difficulty for drivers to navigate. In the HSM, terrain is not discussed as much as grade change is; the HSM is another manual that is typically referenced by practitioners. As shown in Table 4.9, an association between grade and CMF was found where the steeper the slope the more likely a crash is to occur [12].

Table 4.9 CMFs for Grade of Roadway Segment [12]

Approximate Grade (%)		
Level Grade (-3% ≤ grade ≤ 3%)	Moderate Terrain (-3% < grade ≤ -6% and 3% < grade ≤ 6%)	Steep Terrain (grade < -6% and grade > 6%)
1.00	1.10	1.16

This leads to the belief that mountainous terrains have a higher likelihood, when compared to flat/level terrain and rolling terrain, of creating crashes. Because of this, one of the objectives of this study was developed to investigate which type of terrain snow fences can help reduce the largest number of crashes. Because this study is investigating I-80 in Wyoming, data regarding terrain type for I-80 needed to be acquired in order to develop SPFs and CMFs that isolate the effects of snow fences on each terrain type. Due to the extreme effects of steeper grades found in the HSM, flat/level terrains and rolling terrains were paired together to be compared against mountainous terrain. The sections of I-80 in Wyoming that were classified as mountainous terrain are between MP 12 and MP 26.5, MP 260 and MP 272, and MP 318 and MP 342 [43]. The other sections of I-80 in Wyoming were classified as flat/level and rolling terrain.

Facility Data

In order to properly develop simple and full SPFs to predict crash frequencies, various roadway characteristics were required for the investigation areas. In SPF development, it is desirable to include as many predictor variables as possible to optimally account for the effects of various confounding factors on the observed crashes. Therefore, predictor variables, such as roadway geometry, traffic, and countermeasure characteristics, were included. Roadway (geometric) data that is combined with traffic data, as well as countermeasure data, is commonly referred to as facility data. Traffic data, such as VMT, is typically included into simple and full SPFs calculations due to correlations between traffic volumes and crash frequencies. When pairing the traffic data with roadway data and countermeasure data, the full SPF analyses developed are more accurate at predicting the contributing factors of crashes [105], [122]. The inclusion of countermeasure data is crucial to this study because it helps to isolate the effectiveness of snow fences. Ideally, this will garner the truest possible understanding of the isolated safety effect of snow fences. The roadway, traffic, and countermeasure data were provided by WYDOT.

Data Description

Table 4.10 displays the crash frequencies for the crashes that occurred in non-adverse winter weather conditions and in adverse winter weather conditions, for I-80 in Wyoming. This investigation area analyzes 278 miles of I-80 that are characterized with snow fences that have been implemented between 2006 and 2014. In order to understand the full effect of snow fence installation on crash frequencies, winter weather condition, snow fence type, and crash severity level were taken into consideration. For these analyses, adverse winter weather conditions were characterized by crashes that were reported in CARE to have taken place in “Blowing Snow”, “Snowing”, “Blizzard”, or “Sleet/Hail/Freezing Rain” weather conditions; all other weather conditions were considered to be non-adverse winter weather conditions. Three different snow fence types (lath, Wyoming, and upright/vertical snow fences) were assigned to crashes, if the crash reported from CARE fell within the designated time frame based on the snow fence construction date and investigation area. In addition to this, a combined snow fence analysis was conducted to determine the overall effect of snow fence implementation. Each condition (snow fence type and winter weather condition) was investigated by crash severity level as well to understand the dangers associated with the driving conditions. Additionally, the portion of crashes that were categorized as PDO and F+I are provided, as it has been found that a larger proportion of higher severity crashes typically occur during winter events [123].

Table 4.10 Descriptive Analysis for the Before-After Crash Frequencies along I-80

Non-Adverse Winter Weather Condition Crashes							
	Type of Snow Fence	**Length (miles)**	**Total Crashes**	**PDO**	**% PDO**	**F+I**	**% F+I**
Before	Lath	148	712	558	78%	154	22%
	Wyoming	81	654	473	72%	181	28%
	Upright/Vertical	55	277	206	74%	71	26%
	Combined/All Types	**278**	**1515**	**1119**	**74%**	**396**	**26%**
After	Lath	148	602	488	81%	114	19%
	Wyoming	81	511	408	80%	103	20%
	Upright/Vertical	55	258	211	82%	47	18%
	Combined/All Types	**278**	**1301**	**1020**	**78%**	**281**	**22%**
Adverse Winter Weather Condition Crashes							
	Type of Snow Fence	**Length (miles)**	**Total Crashes**	**PDO**	**% PDO**	**F+I**	**%F+I**
Before	Lath	148	731	563	77%	168	23%
	Wyoming	81	595	447	75%	148	25%
	Upright/Vertical	55	453	361	80%	92	20%
	Combined/All Types	**278**	**1578**	**1219**	**77%**	**359**	**23%**
After	Lath	148	537	436	81%	101	19%
	Wyoming	81	522	401	77%	121	23%
	Upright/Vertical	55	410	342	83%	68	17%
	Combined/All Types	**278**	**1399**	**1126**	**80%**	**273**	**20%**

From Table 4.10, it was found that for non-adverse winter weather condition crashes, as well as adverse winter weather condition crashes, that there was a reduction in crashes in the after period for almost all severity levels and snow fence types, after the installment of snow fences along I-80 in Wyoming. The only instance in which there was an increase in crashes between the before and the after periods was for PDO crashes at locations with upright/vertical snow fences during non-adverse winter weather conditions. This is not a concerning result from the descriptive statistics because there is a large decrease in F+I crashes, as well as the overall decrease in crashes between the before and after period for upright/vertical snow fences, during non-adverse winter weather conditions. In addition to this, results from the simple and full CMFs show that there are decreases in crashes associated with PDO, crashes occurring at sections with upright/vertical snow fences.

Crashes that occurred during adverse winter weather conditions are expected to be more representative of the safety effect of snow fence implementations. When analyzing the proportion of F+I crashes, a reduction was observed between the before and the after crash frequencies for all snow fence types during adverse winter weather condition crashes. This suggests a potential safety trend that may be attributed to snow fence implementations. However, the proportion of PDO crashes were found to increase as the proportion of F+I crashes were found to decrease. This indicates that for crashes occurring after snow fence implementation, both during adverse winter weather conditions and non-adverse winter weather conditions, are being reduced in severity.

Results and Discussion

Naïve before-after Analysis (Snow Fence Types)

CMFs that were developed from the naïve analysis were based off the proportions between the before and after crash frequencies; these CMFs are shown in Table 4.11. Table 4.11 shows the CMF, safety effectiveness (or percent effective), and SE for each snow fence type at each crash severity level during non-adverse winter weather conditions and adverse winter weather conditions. This is found by dividing the after crash counts by the before crash counts. If there is a reduction in crashes, the CMF is less than one; if there is an increase in crashes, the CMF is greater than one. When calculated, as seen in Table 4.11, almost all the CMFs resulted in a value less than one. The only instance that was found to produce a CMF greater than one, indicating an increase in crashes, was for PDO crashes at locations with upright/vertical snow fences during non-adverse winter weather conditions. As it was determined in the previous subsection, although this indicated a decrease in safety, this is not concerning because there are decreases associated with F+I crashes and total crashes at locations with upright/vertical snow fences. This is later supported by results found through producing the CMFs using EB method.

Table 4.11 Naïve CMFs for Snow Fence Types

Non-Adverse Winter Weather Condition									
Type of Snow Fence	**Total**			**PDO**			**F+I**		
	CMF	% Effective	SE	CMF	% Effective	SE	CMF	% Effective	SE
Lath	0.84	15.75%	0.047	0.87	13.08%	0.054	0.72	28.67%	0.087
Wyoming	0.78	22.24%	0.046	0.86	14.41%	0.058	0.56	44.42%	0.068
Upright/Vertical	0.95	5.82%	0.081	1.04	-3.06%	0.101	0.65	35.72%	0.12
Combined/All Types	**0.85**	**14.64%**	**0.032**	**0.91**	**9.51%**	**0.039**	**0.70**	**30.13%**	**0.054**

Adverse Winter Weather Condition									
Type of Snow Fence	**Total**			**PDO**			**F+I**		
	CMF	% Effective	SE	CMF	% Effective	SE	CMF	% Effective	SE
Lath	0.73	26.77%	0.042	0.77	23.02%	0.049	0.59	41.78	0.073
Wyoming	0.87	12.76%	0.052	0.89	11.06%	0.061	0.80	20.67%	0.096
Upright/Vertical	0.92	7.97%	0.063	0.96	3.89%	0.072	0.74	27.20%	0.115
Combined/All Types	**0.88**	**11.85%**	**0.032**	**0.92**	**8.25%**	**0.038**	**0.75**	**25.02%**	**0.060**

Naïve before-after Analysis (Terrain Type)

Table 4.12 shows the CMFs that were developed from the naïve analysis, as well as their safety effectiveness (or percent effective), and SE for each terrain type at each crash severity level during non-adverse and adverse winter weather conditions. All of the CMFs resulted in a value less than one which indicates that snow fences placed on any terrain type will reduce vehicle crashes; this also indicates that developing the simple and full SPFs and their associated are worthwhile to calculate. CMFs are discussed more in a later subsection.

Table 4.12 Naïve CMFs for Terrain Types

Non-Adverse Winter Weather Crashes									
Type of Terrain	**Total**			**PDO**			**F+I**		
	CMF	% Effective	SE	CMF	% Effective	SE	CMF	% Effective	SE
Flat/Level and Rolling	0.89	11.15%	0.038	0.93	7.05%	0.046	0.75	24.77%	0.067
Mountainous	0.75	25.47%	0.058	0.82	18.01%	0.074	0.54	46.55%	0.085
All-Terrain Types	**0.85**	**14.64%**	**0.032**	**0.91**	**9.51%**	**0.039**	**0.70**	**30.13%**	**0.054**

Adverse Winter Weather Crashes									
Type of Terrain	**Total**			**PDO**			**F+I**		
	CMF	% Effective	SE	CMF	% Effective	SE	CMF	% Effective	SE
Flat/Level and Rolling	0.92	8.39%	0.041	0.96	4.54%	0.048	0.76	24.69%	0.076
Mountainous	0.82	18.56%	0.052	0.84	16.10%	0.061	0.73	27.79%	0.093
All-Terrain Types	**0.88**	**11.85%**	**0.032**	**0.92**	**8.25%**	**0.038**	**0.75**	**25.02%**	**0.060**

Safety Performance Functions (Snow Fence Types)

Wyoming-specific SPFs were developed for interstate freeway conditions to predict the conditions leading to crashes on I-80, in Wyoming. Full SPFs have the ability to accurately predict crashes compared to simple SPFs, as it accounts for multiple confounding factors. Full SPFs attempt to predict crash frequencies utilizing the following variables in conjunction with traffic volumes (logarithmic transformation of VMT): total segment length, vertical grade, deflection angle (delta), radius, degree of curvature, horizontal condition, median type, median width, left shoulder type, lane type, right shoulder type, number of lanes, total width of roadway, left shoulder width, right shoulder width, intersecting road functional classification, presence of climbing lanes, presence of rumble strips, presence of VSL signs, facility type, and number of bridges per segment. From this initial list of predictors, based on a significance level of 0.05 and correlations between predictors, the predictors were narrowed down to the most significant contributing factors: logarithmic transformation of VMT, deflection angle (delta), curved horizontal condition, intersecting roadway type (interstate), lane type (asphalt or concrete), depressed median type, median width, number of bridges per segment, presence of rumble strips, presence of VSL signs, right shoulder width, and VG (-2 percent < VG < 0 percent). For the horizontal conditions, median types, intersecting roadway types, lane types, and vertical grades, these predictors were created into categorical variables where each condition was split up and analyzed in terms of presence. Similar to the previous analysis, results were obtained from the crash severity levels for the combined/all type model in both non-adverse and adverse winter weather conditions. For this analysis, six full SPFs were developed where each model corresponds to a different set of contributing factors. Each combination of crash severity and winter weather condition for the combined/all type model were found not to be identical to each other. Table 4.13 displays the developed crash prediction models for each crash severity type during non-adverse winter weather conditions.

Table 4.14 displays the developed crash prediction models for each crash severity type during adverse winter weather conditions. All of the full SPF models were developed using NB. The full SPFs were calibrated using the data from the before period to identify the contributing factors to the crashes that occurred without the influence of the investigated countermeasure. All the provided variable estimates were significant at the 95th percentile significance level. From

Table 4.13 and Table 4.14, it becomes possible to see the factors that increase and reduce the likelihood of a crash occurring before snow fences were implemented along I-80 in Wyoming.

Table 4.13 NB Full SPFs for I-80 in Wyoming

Non-Adverse Winter Weather Crashes							
	Crash Severity:	**Total**		**PDO**		**F+I**	
Parameter:	Category:	Estimate	P-Value	Estimate	P-Value	Estimate	P-Value
Intercept		-4.5093	<.0001	-4.8737	<.0001	-7.2308	<.0001
Delta (degrees)		0.0082	0.0024	…	…	0.0117	0.0024
Horizontal Condition	Curve	-0.3387	0.0016	…	…	-0.6699	<.0001
Log(VMT)		1.8559	<.0001	1.9024	<.0001	1.8365	<.0001
Median Type	Depressed	-0.4028	<.0001	-0.3394	0.0002	-0.5495	<.0001
Number of Bridges per Segment		0.4404	<.0001	0.4481	<.0001	0.3495	0.0015
Presence of Rumble Strips		-0.3375	<.0001	-0.3727	<.0001	…	…
Presence of VSL		…	…	…	…	0.3343	0.0088
Right Shoulder Width		-0.1318	<.0001	-0.1469	<.0001	…	…
Dispersion (k):		0.5742		0.578		0.4471	

Table 4.14 NB Full SPFs for I-80 in Wyoming

Adverse Winter Weather Crashes							
	Crash Severity:	**Total**		**PDO**		**F+I**	
Parameter:	Category:	Estimate	P-Value	Estimate	P-Value	Estimate	P-Value
Intercept		-5.6923	<.0001	-6.1525	<.0001	-8.734	<.0001
Delta (degrees)		…	…	…	…	0.0105	0.0236
Intersecting Roadway Type	Interstate	…	…	1.9415	0.025	…	…
Lane Type	Asphalt	…	…	-0.2858	0.0016	0.9065	0.0056
	Concrete	…	…	…	…	0.903	0.0058
Log(VMT)		1.9634	<.0001	1.9889	<.0001	2.0215	<.0001
Median Width		0.0011	0.0134	0.0011	0.0151	0.0014	0.0155
Number of Bridges per Segment		0.391	<.0001	0.3956	<.0001	0.3506	0.0084
Presence of Rumble Strips		-0.2778	0.0038	…	…	…	…
Presence of VSL		0.6724	<.0001	0.6466	<.0001	0.8838	<.0001
Right Shoulder Width		-0.1193	0.0005	-0.1123	0.0016	-0.1103	0.0313
Vertical Grade	-2% < VG < 0%	-0.2232	0.0138	-0.2517	0.0084	-0.3762	0.05
Dispersion (k):		0.8914		0.8035		0.8698	

Safety Performance Functions (Terrain Type)

Table 4.15 illustrates the full SPFs for each crash type during non-adverse winter weather conditions on flat/level and rolling terrains, while Table 4.16 shows the full SPFs for the same conditions but during adverse winter weather.

Table 4.17 exhibits the full SPFs for each crash type during non-adverse winter weather conditions on mountainous terrains, while Table 4.18 illustrates the same conditions but during adverse winter weather conditions. All of the full SPF models were developed using NB. The full SPFs were calibrated using the data from the before period to identify the contributing factors to the crashes that occurred without the influence of the investigated countermeasure. All the provided variable estimates were significant at the 95th percentile significance level. From Table 4.15, Table 4.16, Table 4.17, and Table 4.18, it becomes possible to see the factors that increase and reduce the likelihood of a crash occurring before snow fences were implemented along I-80, in Wyoming.

Table 4.15 NB Full SPFs for Flat/Level and Rolling Terrains

Non-Adverse Winter Weather Crashes							
	Crash Severity:	**Total**		**PDO**		**F+I**	
Parameter:	Category:	Estimate	P-Value	Estimate	P-Value	Estimate	P-Value
Intercept		-4.6052	<.0001	-4.5835	<.0001	-7.3138	<.0001
Delta (degrees)		0.0079	0.0496	…	…	…	…
Horizontal Condition	Straight	0.3289	0.037	…	…	…	…
Log(VMT)		1.7935	<.0001	1.8552	<.0001	1.831	<.0001
Median Width		-0.0022	0.025	-0.0024	0.0234	…	…
Number of Bridges per Segment		0.5051	<.0001	0.4844	<.0001	0.5376	<.0001
Presence of Rumble Strips		-0.5371	<.0001	-0.5085	<.0001	-0.6715	<.0001
Presence of VSL		…	…	…	…	0.3058	0.0287
Right Shoulder Width		-0.1344	<.0001	-0.1584	<.0001	…	…
Dispersion (k):		0.6194		0.6356		0.4868	

Table 4.16 NB Full SPFs for Flat/Level and Rolling Terrains

Adverse Winter Weather Crashes							
	Crash Severity:	**Total**		**PDO**		**F+I**	
Parameter:	Category:	Estimate	P-Value	Estimate	P-Value	Estimate	P-Value
Intercept		-5.3424	<.0001	-4.9335	<.0001	-9.1406	<.0001
Lane Type	Asphalt	…	…	-0.2991	0.0065	…	…
Log(VMT)		1.8791	<.0001	1.8108	<.0001	2.01	<.0001
Median Type	Depressed	0.6469	<.0001	0.6023	0.0001	0.481	0.0422
Number of Bridges per Segment		0.4865	<.0001	0.5115	<.0001	0.3675	0.0169
Presence of Climbing Lane		-0.8741	0.0405	…	…	…	…
Presence of Rumble Strips		-0.5026	<.0001	-0.4029	0.0015	…	…
Presence of VSL		0.5151	<.0001	0.456	<.0001	0.6301	0.0002
Right Shoulder Width		-0.1591	0.0002	-0.1552	0.0006	…	…
Vertical Grade	VG < -2%	…	…	-0.4508	0.0337	…	…
	-2% < VG < 0%	-0.242	0.0253	-0.5912	0.0011	…	…
	0% < VG < 2%	…	…	-0.3907	0.0275	…	…
Dispersion (k):		0.9777		0.9117		0.8791	

Table 4.17 NB Full SPFs for Mountainous Terrains

Non-Adverse Winter Weather Crashes							
Crash Severity:		**Total**		**PDO**		**F+I**	
Parameter:	Category:	Estimate	P-Value	Estimate	P-Value	Estimate	P-Value
Intercept		-7.1352	<.0001	-7.6228	<.0001	-11.9221	<.0001
Delta (degrees)		0.0137	0.0021	…	…	0.0419	0.0001
Horizontal Condition	Straight	…	…	…	…	1.428	0.001
	Curved	-0.455	0.0086	…	…	…	…
Lane Type	Asphalt	0.3351	0.0187	…	…	1.2605	0.002
	Concrete	…	…	…	…	2.1419	<.0001
Log(VMT)		2.2151	<.0001	2.3155	<.0001	1.9799	<.0001
Median Type	Depressed	-0.4619	0.0022	-0.5082	0.0022	…	…
Presence of Rumble Strips		…	…	…	…	1.3867	0.0001
Vertical Grade	-2% < VG < 0%	…	…	…	…	0.7575	0.026
	0% < VG < 2%	…	…	…	…	0.9117	0.0066
Dispersion (k):		0.2684		0.3244		0	

Table 4.18 NB Full SPFs for Mountainous Terrains

Adverse Winter Weather Crashes							
Crash Severity:		**Total**		**PDO**		**F+I**	
Parameter:	Category:	Estimate	P-Value	Estimate	P-Value	Estimate	P-Value
Intercept		-7.7749	<.0001	-8.1895	<.0001	-11.0259	<.0001
Delta (degrees)		0.0079	0.0283	0.0088	0.015	…	…
Left Shoulder Width		…	…	…	…	-0.3933	0.0075
Log(VMT)		2.5274	<.0001	2.4857	<.0001	2.4783	<.0001
Median Type	Depressed	-0.4621	0.001	-0.2876	0.04	-1.0029	0.0001
Presence of Climbing Lane		…	…	…	…	-1.5842	0.0025
Total Roadway Width		…	…	…	…	0.098	0.0048
Vertical Grade	VG < -2%	…	…	0.3394	0.0383	…	…
	0% < VG < 2%	…	…	0.3747	0.0143	…	…
Dispersion		0.419		0.2922		0.493	

For non-adverse winter weather conditions on flat/level and rolling terrains, Table 4.15, common trends that were found from the full SPFs are that the traffic volumes and number of number of bridges per segment increases the likelihood of a crash occurring; whereas, the presence of rumble strips causes the results to decrease. For total and PDO crashes, median widths and right shoulder widths resulted in a decrease of likelihood of a crash occurring, yet, proved not to be a significant factor for F+I crashes. For only total crashes, deflection angle and straight horizontal conditions showed an increase in the likelihood of a crash occurring. For only F+I crashes, the presence of VSL signs appeared to increase the likelihood of a crash occurring.

For adverse winter weather conditions on flat/level and rolling terrains, Table 4.16, common trends that were found from the full SPFs are that the traffic volumes, depressed median types, number of bridges per segment, and presence of VSL signs increased the likelihood of a crash occurring. For PDO crashes only, decrease in the likelihood were found due to asphalt lane types and VG (VG < -2 percent or 0 percent <VG < 2 percent). For total crashes only, a decrease in likelihood were found due to presence of climbing lanes. For total and PDO crashes, decreases were attributed to presence of rumble strips, right shoulder width, and VG (-2 percent <VG < 0 Percent).

For non-adverse winter weather conditions on mountainous terrains,

Table 4.17, the only common trend that was found is that traffic volumes increase the likelihood of a crashes occurring. For only F+I crashes, increases were found due to straight horizontal conditions, concrete lane types, presence of rumble strips, and VG (-2 percent < VG < 0 percent or 0 percent <VG < 2 percent); for only total crashes increases were found to be related to curved horizontal conditions. The deflection angle and asphalt lane types caused an increase in the likelihood for total and F+I crashes; whereas, total and PDO crashes have a decrease in the likelihood associated with depressed median type.

For adverse winter weather conditions on mountainous terrains, Table 4.18, common trends that were found from the full SPFs are that the traffic volumes increase the likelihood of a crash occurring; whereas, the depressed median types resulted in a decrease. Total and PDO crashes had an increase in the likelihood due to the deflection angle. For F+I crashes only, an increase was found due to total roadway widths, but a decrease was found to be attributed to left shoulder widths and the presence of climbing lanes. For PDO crashes only, increases were found to be related to VGs (VG < -2 percent or 0 percent <VG < 2 percent).

From these contributing factors, VSL signs and number of bridges per segment showed similar trends that were found previously. Because these factors were discussed in the previous section, other contributing factors will be focused on in this section.

Lane type (pavement types) appeared as a contributing factor in a few adverse winter weather condition full SPF analyses. There are two types of lane type conditions that are implemented along I-80 asphalt and concrete. For the most part, asphalt pavement types were found to decrease the likelihood of a vehicle crash; whereas, concrete pavement types increased the likelihood. When thinking of their properties, concrete is smoother than asphalt; asphalt has coarser aggregates on the surface of the pavement. Because of this, asphalt will have a higher friction factor associated with it than concrete does. When conditions begin to worse on roadways, vehicles will be more likely to slip on concrete pavements than asphalt pavements because they will not have as much friction between the pavement and the tires of the vehicle. VG has appeared in multiple full SPFs as a significant contributing factor. However, the results on whether they increase or decrease the likelihood of a crash occurring varied. For the overall, flat/level, and rolling terrains, in adverse winter weather conditions, all associated VGs (VG < -2 percent, -2 percent < VG < 0 percent, and 0 percent < VG < 2 percent) were found to decrease the likelihood of a crash occurring. These VGs are reasonable because, at flatter slopes in adverse conditions, drivers tend to have more control over their vehicles. For the result where there is a larger decrease in slope, this is also reasonable because drivers tend to travel down slopes more cautiously. This may be because drivers are not sure of the driving conditions that are below them on the roadway, and it is more difficult to stop a vehicle when it is traveling down a slope. On mountainous terrains, increases in the likelihood of a crash occurring for both non-adverse and adverse conditions was found. During non-adverse conditions, the contributing factors of VG were found on flatter slopes; this could be a result of drivers not adjusting the pressure they are applying to the brake or gas petal as the slopes are flattening out. During adverse winter weather conditions, the likelihood of a crash occurring increased on decreasing slopes; this indicates that drivers may have been driving too fast on these sections and/or lost control of their vehicle.

Crash Modification Factors (Snow Fence Types)

Table 4.19 displays the CMFs that were produced from the full SPF models, as well as their associated safety effectiveness, and SE for each crash type and snow fence type in both non-adverse and adverse winter weather conditions. Usually, CMFs produced from full SPF models are considered to be more reliable since they take the most predictor variables into consideration when predicting crashes [37].

Table 4.19 CMFs produced from the full SPF based on Snow Fence Types

Crash Type	Winter Weather Condition	Snow Fence Types	CMF	Safety Effectiveness	SE
Total	Non-Adverse	Combined/All Types	0.64	36.49%	0.022
		Lath	0.60	39.76%	0.030
		Wyoming	0.65	35.48%	0.036
		Upright/Vertical	0.71	29.55%	0.055
	Adverse	Combined/All Types	0.72	27.62%	0.025
		Lath	0.58	41.74%	0.031
		Wyoming	0.75	24.71%	0.043
		Upright/Vertical	0.80	19.65%	0.052
PDO	Non-Adverse	Combined/All Types	0.63	36.78%	0.024
		Lath	0.60	40.44%	0.033
		Wyoming	0.68	32.35%	0.042
		Upright/Vertical	0.73	27.31%	0.062
	Adverse	Combined/All Types	0.71	29.17%	0.027
		Lath	0.57	42.76%	0.033
		Wyoming	0.73	26.96%	0.047
		Upright/Vertical	0.81	19.61%	0.057
F+I	Non-Adverse	Combined/All Types	0.36	64.22%	0.023
		Lath	0.30	69.83%	0.030
		Wyoming	0.36	64.12%	0.039
		Upright/Vertical	0.32	67.66%	0.051
	Adverse	Combined/All Types	0.45	55.12%	0.031
		Lath	0.33	66.66%	0.037
		Wyoming	0.55	45.60%	0.058
		Upright/Vertical	0.49	51.36%	0.068

From the full CMFs presented in Table 4.19, all of the CMFs show that snow fences implementation does help reduce vehicle crashes along I-80, in Wyoming, as mentioned earlier. Based on crash severities, total crashes were reduced between 20percent to 42 percent, PDO crashes decreased by 20 percentto 43 percent, and F+I crashes were reduced between 46 percent to 70 percent during both adverse and non-adverse winter weather conditions, respectively. Based on snow fence types, significant reductions in crashes at locations with lath snow fences ranged from 40 percent to 70 percent, locations with Wyoming snow fences ranged from 25 percent to 64 percent, and locations with upright/vertical snow fences ranged from 20 percent to 68 percent was obtained during non-adverse winter weather conditions, as well as during adverse winter weather conditions, respectively. These results were in accordance with Colwill et at.

2015, where snow fences helped in reducing total, PDO, and F+I crashes, as well as reducing the severity of the crashes occurring [119].

Multiple sections of I-80 in Wyoming are charaterized by multiple types of snow fences. For example, lath snow fences are usually implemented to isolate the effects of near blowing snow; whereas, Wyoming and upright/vertical snow fences are used to stop blowing snow from outside of the right of way of the roadway. Usually, lath snow fences are used in conjunction with Wyoming and upright/vertical snow fences. For these analyses related to snow fence types, the effects of each snow fence type were isolated. This was done by finding the location of each snow fence on I-80 and cateloging their type and location. The overall model looks at each snow fence that is placed on I-80; whereas, each snow fence type model looks at the sections of I-80 that have a snow fence constructed on. Because most segments of I-80 are characterized by multiple types of snow fences, it is practical to conclude that the combined models are the most practical results that respect to the effects of snow fences.

It was found that all of the CMFs calculated indicated that all snow fence types aid in reducing crashes at all crash severity levels in all winter weather conditions. When looking at the safety effectivenesses, lath snow fences, for every crash type in both adverse and non-adverse winter weather conditions, reduce the most amount of crashes. However, because lath snow fences are installed to mitigate the effects of near snow, Wyoming and upright/vertical snow fences are battling a different type of blowing snow condition. When investigating the effectiveness of Wyoming snow fences, and comparing them to the effectiveness of upright/vertical snow fences, Wyoming snow fences indicate having a greater reduction associated with total and PDO crashes in all winter weather conditions. The ultimate goal of countermeasure installation is to reduce the most F+I crashes from occurring; by these definitions, upright/vertical snow fences reduce the most F+I crashes and should be implemented more frequently than Wyoming snow fences. However, upright/vertical snow fences tend to have higher installation costs associated with them when compared to Wyoming snow fences.

Crash Modification Factors (Terrain Type)

Table 4.20 exhibits the CMFs that were produced from the full SPF models, as well as their associated safety effectiveness, SE for each crash type, and terrain type in both non-adverse and adverse winter weather conditions.

Table 4.20 CMFs Produced from the Full SPF Based on Terrain Types

Crash Type	Winter Weather Condition	Terrain Type	CMF	Safety Effectiveness	SE
Total	Non-Adverse	All Types	0.64	36.49%	0.022
		Flat/Level & Rolling	0.67	33.14%	0.027
		Mountainous	0.50	50.36%	0.034
	Adverse	All Types	0.72	27.62%	0.025
		Flat/Level & Rolling	0.74	26.49%	0.030
		Mountainous	0.64	35.85%	0.038
PDO	Non-Adverse	All Types	0.63	36.78%	0.024
		Flat/Level & Rolling	0.67	33.02%	0.030
		Mountainous	0.53	47.31%	0.041
	Adverse	All Types	0.71	29.17%	0.027
		Flat/Level & Rolling	0.72	27.84%	0.032
		Mountainous	0.58	42.07%	0.038
F+I	Non-Adverse	All Types	0.36	64.22%	0.023
		Flat/Level & Rolling	0.32	68.00%	0.026
		Mountainous	0.18	81.95%	0.023
	Adverse	All Types	0.45	55.12%	0.031
		Flat/Level & Rolling	0.50	50.54%	0.038
		Mountainous	0.45	54.94%	0.051

Snow fence implementation does help reduce vehicle crashes along I-80 in Wyoming based on the presented CMFs. When investigating the safety effectivenesses at each severity level based on terrain type, it was discovered that snow fences are more effective than what was found in Chapter 5. Total crashes encountered a reduction between 26 and 50 percent (an 8 percent increase); PDO crashes show a reduction of between 28 to 47 percent (a 4 percent increase); F+I crashes are found to reduce between 51 and 82 percent (a 12 percent increase). This could be attributed to an isolation of each driving conditions being experience by the drivers. Mountainous terrains are expected to experience more crashes, which results in higher reductions in crashes. Based on surrounding terrain during both non-adverse and adverse winter weather conditions, snow fences were found to have significant reductions in crashes on flat/level and rolling terrains between 26to 68 percent and on mountainous terrains by 36to 82 percent. When further investigating the specific terrain types in which snow fences were and still are being installed, trends begin to appear with respect to high safety effectiveness values. Both terrain types can create blowing snow issues for drivers due to their different environments.

Flat/level and rolling terrains do not have a lot of obstructions around the roadway to break the blowing snow (except for snow fences), so winds can pick up speed fairly quickly and maintain the high speeds. In mountainous terrain, these areas can be on the side of a hill or within a valley; these conditions create hazardous conditions for drivers because if something was to occur, there is little area to do to maneuver around the event. According to the CMFs calculated and presented in Table 4.20, snow fences are most effective for flat/level and rolling terrain during non-adverse winter weather conditions at preventing/reducing F+I crashes. At a safety effectiveness of 68 percent for F+I crashes in non-adverse winter weather conditions, this model produces the most statistically significant results in comparison to the other flat/level and rolling terrain models. For mountainous terrain, at a safety effectiveness of 82 percent, snow fences are also most effective during non-adverse winter weather conditions at preventing F+I crashes. From these results, it has become extremely obvious that snow fences are not just helping during adverse winter weather conditions.

Comparisons between Surrounding Terrain and Snow Fence Type

Higher safety effectivenesses have been found to be associated with different terrain types when compared to snow fence types. Each snow fence type, as well as each terrain type, behave/react differently in comparison to the other types. Terrain plays a huge factor in the success of snow fence installation, since the terrain directly affects the storage of the snow fences. Table 4.21 and Table 4.22 show the safety effectivenesses of each type of snow fence, the number of miles each type of snow fence covers of each terrain type, and the safety effectivenesses of each terrain type by crash type; Table 4.21 shows the results for non-adverse winter weather conditions and Table 4.22 displays the results for adverse winter weather conditions. General trends that are noticed between both tables is lath snow fences cover the most area of I-80 in Wyoming, and flat/level and rolling terrains are the majority of the terrain for the investigated areas.

Table 4.21 Safety effectiveness of snow fences by types and surrounding terrain in non-adverse winter weather conditions

Crash Types	Snow Fence Type	Safety % based on Snow Fence Type	Flat/Level and Rolling Terrain (Total: 225 miles)		Mountainous Terrain (Total: 53 miles)	
			Miles of Terrain per Snow Fence Type (% of Terrain)	Safety % based on Terrain	Miles of Terrain per Snow Fence Type (% of Terrain)	Safety % based on Terrain
Total	Lath (148 miles)	39.76%	125.9 (56%)	33.14%	22.1 (42%)	50.36%
	Wyoming (81 miles)	35.84%	64.6 (29%)		16.4 (31%)	
	Upright/Vertical (55 miles)	29.55%	49.5 (22%)		5.5 (10%)	
PDO	Lath	40.44%	125.9 (56%)	33.02%	22.1 (42%)	47.31%
	Wyoming	32.35%	64.6 (29%)		16.4 (31%)	
	Upright/Vertical	27.31%	49.5 (22%)		5.5 (10%)	
F+I	Lath	69.83%	125.9 (56%)	68%	22.1 (42%)	81.95%
	Wyoming	64.12%	64.6 (29%)		16.4 (31%)	
	Upright/Vertical	67.66%	49.5 (22%)		5.5 (10%)	

Table 4.22 Safety effectiveness of snow fences by type and surrounding terrain in adverse winter weather conditions

Crash Types	Snow Fence Type	Safety % based on Snow Fence Type	Flat/Level and Rolling Terrain (Total: 225 miles)		Mountainous Terrain (Total: 53 miles)	
			Miles of Terrain per Snow Fence Type (% of Terrain)	Safety % based on Terrain	Miles of Terrain per Snow Fence Type (% of Terrain)	Safety % based on Terrain
Total	Lath (148 miles)	41.74%	125.9 (56%)	26.49%	22.1 (42%)	35.85%
	Wyoming (81 miles)	24.71%	64.6 (29%)		16.4 (31%)	
	Upright/Vertical (55 miles)	19.56%	49.5 (22%)		5.5 (10%)	
PDO	Lath	42.76%	125.9 (56%)	27.84%	22.1 (42%)	42.07%
	Wyoming	26.96%	64.6 (29%)		16.4 (31%)	
	Upright/Vertical	19.61%	49.5 (22%)		5.5 (10%)	
F+I	Lath	66.66%	125.9 (56%)	50.54%	22.1 (42%)	54.94%
	Wyoming	45.60%	64.6 (29%)		16.4 (31%)	
	Upright/Vertical	51.36%	49.5 (22%)		5.5 (10%)	

From Table 4.21 and Table 4.22, it is noticed that the highest crash reductions associated with all snow fence types and terrain types are for F+I crashes; this confirms that, in general, snow fences have the greatest effect on reducing F+I crashes. It is also observed that safety effectivenesses that were found for non-adverse winter weather conditions is higher than the ones found for adverse winter weather conditions, expect for lath snow fences for total and PDO crashes. This indicates that snow fences are not only effective in adverse winter weather conditions, that they are also effective when there is no one their to report the conditions. This shows that blowing snow conditions may not only be occurring in adverse weather conditions and that blowing snow conditions are not being recorded with vehicle crashes accurately. In addition to this, this shows that snow fences are able to control blowing snow conditions more in non-adverse conditions because, during adverse winter weather conditions, not all of the falling snow is able to be collected by the snow fences.

Another observation is that the safety effectivenesses of snow fences was found to be higher on mountainous terrains compared to flat/level and rolling terrain. This shows that snow fences performs differently according to the terrain type. This could be interpreted as the direction and strenght of wind differes according to the terrain types, which create additional natural snow fence effect.

The snow fence types analyses do not take into account the different terrain types; and the terrain types analyses do not take into account the different snow fence types. Because of this, and the trend found in Table 4.21 and Table 4.22, queries have been raised as to whether there is a specific snow fence type that works the best for a specific terrain type. Terrain plays a huge factor into what type of snow fence should be used. Upright/vertical snow fences are better to be placed in sections where it is not difficult to embed large posts; mountainous terrains would be anticipated to have difficulty installing these snow fences. For this study, there was not enough resources to conduct and compile results for this specific analysis; this is an idea for investigation for potential expansions of this research.

CHAPTER 5-ROADWAY CORRIDORS

This chapter presents the studies carried out on five-lane arterials corridors with center left-turn lanes and urban/suburban four-leg signalized intersections. Although CMFs were not developed for these facilities, the study is comprised of important findings and recommendations that could be useful for WYDOT.

LITERATURE REVIEW

Many studies have calibrated and developed SPFs for roadway segments and intersections. Variable selection is a primary step in the process of developing SPFs and requires picking certain contributing factors to be included in the model. Mayora and Rubio (2003) found that there are over 50 various roadway conditions that could affect crash rates in some way [124]. On the other hand, selection of an excessive number of variables in a crash prediction model may lead to an over-fitting of the predictor variable in the database. In addition to over-fitting issue, it becomes a challenge for agencies to find resources and time to collect all variables to fit a model. Eventually, the best practical model is expected to have a balance between goodness of fit and simplicity. Investigating the contributing factors affecting crashes on arterials and intersections from other studies would provide a baseline for the variable selection procedure for this study. The literature shows that there is a positive association between traffic volumes and crashes on urban roadways [37], [125]–[128]. Kim et al. (2015) found that there is a positive relation between AADT and accidents on urban and suburban five lane roadways (5T) with center two-way-left-turn-lane (TWLTL) [129]. An increase in crashes on urban arterials was linked to density of stop-controlled intersections [125], [126] . In addition to the driveway density, pedestrian crosswalk density, and type of land use were also found to be positively associated with crashes [126]. Sawalha and Sayed (2001) concluded in their study that geometric characteristics such as length, and number of lanes significantly affected crashes on urban arterials [126]. They also found that undivided arterials were less safe than arterials with a raised curb median. Alarifi (2014) found that the conversion of TWLTLs to raised medians on urban roads decreased total crashes by at least 34 percent, and fatal and injury crashes by at least 16 percent [130]. In general, urban arterials were found to be less safe than other urban road types expect for frontage roads with diamond interchanges [127].

Increase in crashes at intersections have often been associated with total entering traffic volumes [131]–[137]. A study by Giuffrè et al., (2011) concluded that major AADT was the only traffic volume that significantly affect crashes at four-leg signalized intersections (4SG) [138]. Traffic signals at 4SG intersections could also contribute to intersection crashes. Some studies found positive effects of signal phases on crashes [136], [139]. Xie et al. (2013) also found the same positive relationships and explained that the openings that are caused by frequent switching signal phases triggered more crashes [140]. Roess et al. (2004) attributed rear-end crashes at intersections to multitude of phases of traffic signals [141]. Signal Phasing and Timing (SPaT) had significant effect on crashes of signalized intersections [142]. The geometric design of intersections plays a significant role in the number of crashes at intersections. It was found in a study that an increase in the ratio of turning lanes to the total lanes contributes to increase in crashes [140]. Giuffrè et al. (2011) found that number of permitted lanes on major road and width of minor road positively affected crashes on urban 4SG intersections [138]. Intersection crashes increased with the presence of right-turn lanes [143]. However, Bauer and Harwood (1996) found eight features of geometric design that affected crashes at signalized intersections [142]. Among these features, minor road right turn channelization was linked with reduction in crashes. Lyon et al. (2005) found that the number of approaches with left-turn lane on major-road and minor-road had fewer PDO, and fatal and injury crashes on urban 4SG intersections [144].

Assigning crashes to be intersection-related crashes could pose some difficulties because crash reports may lack a consistent way to determine whether crashes belong to an intersection or a roadway segment. Intersection-related crashes tend to be identified by either collision types or an influence area of the intersection. In the influence area method, a standard influence area of 250 feet circle around the center of the intersection has been commonly considered in the literature [143], [145]–[151].

The typical practice of crash prediction in the literature has been to estimate crashes for intersections and segments separately. Such an approach evaluates the safety of network or corridor based on summing up the prediction models of the two entities. Under the assumption that roadway segments and intersections are independent, and their crashes are also independent of each other. Thus, network connectivity and traffic interactions are not considered. This highlights the need and importance to evaluate the safety performance on corridors or networks as a whole [131]. It may be more reasonable to estimate crashes for an entire facility. In a study about urban transportation networks in transportation planning environment, Lord and Persaud (2004) highlighted the importance of investigating segment-intersection (corridor) SPF models [152]. The subject of developing crash prediction models for corridors or combined segment-intersection entities in the research is quite sparse. Prediction models for segment-intersection crashes that are defined by involved vehicles movement were developed using GIS land use inventories as exposure with the major road AADT [153]. Crashes at successive signalized intersections along corridors were analyzed via Generalized Estimating Equations (GEEs) considering spatial effect. Patterns of crashes were found to be spatially correlated [132]. Xie et al. (2013) used Bayesian hierarchical models to assess the safety of signalized intersections at corridor-level [140]. In another study, the effect of corridor was evaluated by clustering segments into corridors using Poisson-lognormal (PLN) models with random parameters [154]. Similar to this study, work was done by Das et al. (2009). Lord and Persaud (2004) developed SPFs for urban transportation networks in transportation planning environment [152]. Another study in the aspect of safety of access management considered the corridor totality concluded a positive relationship between access density, and number of crashes and their severity [156]. Understanding automobile crashes leads to better decision making. The precision of the HSM model prediction remarkably depends on the calibration factor. A significant disadvantage of using calibration factor is that it does not account accurately for local conditions. Crash reporting procedures and thresholds, terrain, weather, wildlife, and driver populations are some of the local conditions that usually differ from one state to another. That may result in significant differences between predicted crashes and observed crash proportions. Several studies have found the calibrated HSM SPFs either over-estimated or under-estimated the prediction of total or proportional crashes in comparison to state-specific SPFs [157]–[159]. The criteria in the HSM for calibration sites that should have at least 100 crashes per year might not apply to several facilities and crash severity levels. In addition, the data acquisition that are required to obtain calibration factors is time consuming. The time and effort should be devoted to the development of state-specific SPFs.

DATA PREPARATION AND DESCRIPTION

Three types of roadway facilities were considered for this study: 1) urban and suburban five-lane arterials with a center two-way left-turn lane (TWLTL) (5T) segments, 2) urban and suburban arterial signalized four-leg intersections (4SG), and 3) urban and suburban corridors that are combined roadways segments and intersections. Data sources used to collect and prepare the dataset for analysis included WYDOT maintenance maps, WYDOT roadway characteristics inventory (RCI), Google Earth Pro®, WYDOT traffic data, WYDOT crash database, and Geographic Information System (ArcGIS®).

The first step in the data preparation procedure was to select urban and suburban 5T routes across Wyoming. Secondly, geometric design features and characteristics were collected for 5T segments, 4SG intersections and 5T/4SG corridors. Then, AADTs and crashes were assigned to the selected sites in the facilities. Crash records from the years 2003 to 2012 were used for the analysis in this study. The SPFs in the HSM for urban and suburban 5T roadways are valid with AADT ranging from 0 to 53,800 vehicles per day. The HSM SPFs for urban and suburban arterial 4SG intersection are applicable for the following range of AADT: major AADT between 0 and 67,700 vehicles per day, and minor AADT between 0 and 33,400 vehicles per day. The 5T segments and 4SG intersections that did not meet this criterion were removed. It should be mentioned that signalized interchanges were not considered as intersections since interchanges are grade-separated junctions and function as separating point between corridors. The final dataset consisted of 6,130 crashes from eight different urban and suburban routes in Wyoming with a total length of 32.6 miles. Out of the 6,130 crashes, 2,396 crashes (39 percent) were on 5T arterials and 3,734 crashes (61 percent) were on intersections. Summary statistics of the variables used for the Wyoming-specific SPFs are presented in Table 5.1 and Table 5.2.

Table 5.1 Summary statistics of variables used for Wyoming-specific SPFs (5T segments)

Variables			N	Mean	SD	Min.	Max.
Traffic	Ln(AADT)		670	9.475	0.383	8.223	10.403
Roadway Geometry	Segment Length		670	0.409	0.447	0.040	2.413
	Number of 3ST		670	2.299	2.712	0	11
	Number of 4ST		670	0.910	1.592	0	8
	Number of Major Driveway		670	0.239	0.601	0	3
	Number of Minor Driveway		670	10.433	9.672	0	41
	Number of Signalized Pedestrian and Railroad Crossings		670	0.090	0.334	0	2
	Posted Speed Limit		670	34.948	7.318	20	65
			Percentage in each category				
	Street Lighting	Yes	200 (29.9%)				
		No	470 (70.1%)				
	On-Street Parking	No Parking	620 (92.5%)				
		Partially	20 (3%)				
		Full	30 (4.5%)				
	Type of Segment	Urban	530 (79.1%)				
		Suburban	140 (20.9%)				

Table 5.2 Summary statistics of variables used for Wyoming-specific SPFs (4SG intersections and 5T/4SG corridors

4SG Intersection SPFs							
Variables			N	Mean	SD	Min.	Max.
Traffic	Natural log of Major AADT		540	9.468	0.452	7.065	10.403
	Natural log of Minor AADT		540	8.451	0.951	6.444	9.948
Geometric Design Elements	# Major Right Turn		540	0.537	0.739	0	2
	# Minor Right Turn		540	0.593	0.759	0	2
	# Major Left Turn		540	2.019	0.360	1	4
	# Minor Left Turn		540	1.333	0.944	0	4
	Posted Speed Limit		540	33.056	5.732	20	45
			Percentage in each category				
Traffic Control Features	Major L-turn Signal	Permissive	270 (50%)				
		Protected-Permissive	220 (40.7%)				
		Protected-Permissive one approach	40 (7.4%)				
		Protected	10(1.9%)				
	Minor L-turn Signal	Permissive	430 (79.6%)				
		Protected-Permissive	80 (14.8%)				
		Protected-Permissive one approach	30 (5.6%)				
5T/4SG Corridor SPFs							
Traffic	Natural log of Avg. Major AADT		220	9.380	0.406	8.223	10.170
	Natural log of Avg. Minor AADT		220	7.094	3.403	0	9.751
Roadway Geometry	Length of Corridor		220	1.450	1.217	0.040	4.191
	Number of 3ST		220	7	6.067	0	20
	Number of 4ST		220	2.773	3.309	0	10
	Number of 4SG		220	2.409	2.646	0	9
	Number of Signalized Pedestrian and Railroad Crossings		220	0.273	0.539	0	2
	Avg. Posted Speed Limit		220	35.297	6.754	25	55
	Number of Major Driveway		220	0.727	1.138	0	4
	Number of Minor Driveway		220	32.227	33.013	0	113
			Percentage in each category				
	Street Lighting	No Lighting	60 (27.3%)				
		Partially	30 (13.6%)				
		Full	130 (59.1%)				
	On-Street Parking	No Parking	200 (90.9%)				
		Partially	20 (9.1%)				

RESULTS AND DISCUSSION

HSM SPF Model Calibration

The HSM provides the following SPFs, as shown in Equation 5-1 and Equation 5-2, to predict crashes on urban and suburban 5T segments including TWLTL and 4SG intersections, respectively for base conditions.

$$\begin{aligned} N_{spfrs} = {} & \exp(-9.70 + 1.17 \times In(AADT) + In(L)) + \exp(-4.82 + 0.54 \\ & \times In(AADT) + In(L)) + \sum_{\substack{all \\ driveway \\ types}} n_j \times N_j \times \left[\frac{AADT}{15{,}000}\right]^{(1.172)} \end{aligned} \qquad \text{Equation 5-1}$$

Where, N_{spfrs} is the predicted average crash frequency of an individual roadway segment for base conditions, $AADT$ is the average annual daily traffic volume (vehicles/day) on roadway segment, L is the length of roadway segment in miles, N_j is the number of driveway-related collisions per driveway per year for driveway type j, and n_j = number of driveways within roadway segment of driveway type j including all driveways on both sides of the road.

$$\begin{aligned} N_{spfint} = {} & \exp(-10.99 + 1.07 \times In\left(AADT_{maj}\right) + 0.23 \times In(AADT_{min})) \\ & + \exp(-10.21 + 0.68 \times In\left(AADT_{maj}\right) + 0.27 \\ & \times In(AADT_{min})) \end{aligned} \qquad \text{Equation 5-2}$$

Where, N_{spfint} is the predicted total average crash frequency of intersection-related crashes for base conditions, $AADT_{maj}$ is the average daily traffic volume (vehicles/day) for major approach (both directions of travel combined), and $AADT_{min}$ is the average daily traffic volume (vehicles/day) for minor approach (both directions of travel combined).

To determine the calibration factor, crash counts from 2010 to 2012 were used. There were 551 reported crashes on the 61 5T segments during that time period. Using the SPF from the HSM it was predicted that 715 total crashes would occur for these 3 years using all applicable crash adjustment factors. Using Equation (2), the calibration factor was calculated to be 0.763. Similarly, 231 crashes were reported on 36 arterial 4SG intersections during 2010 to 2012, and using the HSM SPF it was predicted that 239 total crashes would occur on urban and suburban 4SG intersections during the same time period using all applicable crash adjustment factors for this facility. The calibration factor was found to be 0.967. The values of the calibration factors were less than 1 for both facility types. The calibration factor for 5T segments was 0.76 indicating that the HSM SPF over-estimated the total crashes for urban and suburban 5T arterials in Wyoming. The calibration factor of 0.97 for urban and suburban 4SG intersections indicating that the HSM SPF slightly over-estimated total crashes. These differences between predicted total crashes from nationally derived SPFs and locally observed crashes can be attributed to many factors. Some studies attributed these differences to crash reporting practice, especially to PDOs thresholds [160], the distribution of crash severity, and crash type (an example of that is collision with animal in single-vehicle crashes), and terrain type [161]. In general, the differences between sites where HSM SPFs applied and sites where original HSM SPFs were developed are associated with over/underestimation of crashes. Notably, Wyoming differs from the nation, especially in weather, terrain, and driver populations. This warrants the need for developing Wyoming-specific SPFs.

Wyoming-specific SPFs

Wyoming-specific SPFs were developed for 3 levels of crash severity (Total crashes, PDO, and F+I). The significant variables (p-value < 0.05) associated with number of crashes of 5T segments and 4SG intersections are presented in Table 5.3.

For the 5T segments model the regression coefficients of the variables are found to be positive, which indicated that the AADT, number of three legs controlled and four legs-controlled intersections, and number of major and minor driveways within a segment contribute to growth in crashes. The results are consistent with other studies in the literature [125], [126], [129]. Presence of lighting was found to increase expected total and PDO crashes but was not found to be significant for F+I crashes. This finding might be counter intuitive but similar results have been reported in another study [145]. One of the reasons for this could be that presence of lighting indicates the segment experiences higher traffic volumes due to land-use pattern, such as downtown activities. Partial on-street parking was found to be associated with an increase in expected F+I crashes only. This association could be explained by the nature of the surrounding environment. Segments with on-street parking have different characteristics, such as different speed limits and land use patterns, compared to those without parking. That could make the segments with partial on-street parking more hazardous than others.

Table 5.3 Wyoming-specific SPFs for urban and suburban arterial segment and 4SG intersection

Urban and suburban arterial segment							
		Total Crashes		PDO Crashes		F+I Crashes	
Parameter		Estimate	*p*-value	Estimate	*p*-value	Estimate	*p*-value
Intercept		-4.4489	<.0001	-4.4338	0.0002	-5.2673	<.0001
Natural log of AADT		0.4931	<.0001	0.4517	0.0004	0.4829	0.0004
Number of 3ST		0.1012	<.0001	0.0987	<.0001	-	-
Number of 4ST		0.1124	<.0001	0.1020	<.0001	0.1005	0.0004
Number of Major Driveway		0.3845	<.0001	0.3780	<.0001	0.4202	<.0001
Number of Minor Driveway		0.0211	<.0001	0.0216	<.0001	0.0290	<.0001
Lighting	No	-	-	-	-	-	-
	Yes	0.3239	0.0028	0.4030	0.0007	-	-
On-Street Parking	No	-	-	-	-	-	-
	Partially	-	-	-	-	0.7999	0.0010
	Full	-	-	-	-	-0.0159	0.9516
Dispersion		0.5769	-	0.6013	-	0.5058	-
BIC		3049	-	2692	-	1768	-
Urban and suburban arterial 4SG intersection							
Intercept		-5.1746	<.0001	-5.6722	<.0001	-6.4414	<.0001
Natural log of major AADT		0.5472	<.0001	0.5843	<.0001	0.5710	<.0001
Natural log of minor AADT		0.0821	0.0235	0.0949	0.0105	-	-
# Major Right Turn		-0.1028	0.0254	-0.0962	0.0402	-	-
# Minor Right Turn		0.1520	0.0016	0.1424	0.0043	0.2122	0.0016
# Major Left Turn		0.3596	0.0093	0.2771	0.0443	0.3640	0.0495
# Minor Left Turn		0.1009	0.0289	-	-	0.2986	<.0001
Major L-turn Signal	Permissive	-	-	-	-	-	-
	Protected-Permissive	0.2820	0.0002	0.3472	<.0001	0.2361	0.0273
	Protected-Permissive one approach	-	-	-	-	0.3871	0.0376
	Protected	-	-	0.9137	0.0067	-	-
Minor L-turn Signal	Permissive	-	-	-	-	-	-
	Protected-Permissive	0.4037	<.0001	0.4206	<.0001	0.3407	0.0041
	Protected-Permissive one approach	0.5225	0.0019	0.5674	0.0008	-	-
Dispersion		0.2714	-	0.2599	-	0.2884	-
BIC		3023	-	2734	-	1857	-

In the intersection models, there is an increase in total, PDO, and F+I crashes with the increase in major entering AADTs. However, minor entering AADTs are only linked with an increase in total and PDO crashes. This finding of the positive relationship between AADTs and crashes at intersections is well-established in many studies [131], [132], [134]. The presence of a protected-permissive phase in left-turn signal on major roads and minor roads of an intersection are associated with an increase in total, PDO, and F+I crashes. The presence of a protected-permissive phase in one approach of intersection on minor roads are only linked with an increase in total and PDO crashes. The presence of a protected phase in the left turn signal of the major road is associated with an increase in PDO crashes only. Protected-permissive phase are one approach of a minor left-turn signal that has only significant impact on F+I crashes that indicates a rise in F+I crashes when this phase is present. This finding of the effect of traffic signal phases on crashes at intersections is consistent with other studies [136], [139]. Investigation of the number of dedicated turning lanes reveal that an increase in the number of dedicated lanes of any minor right-turn or major left-turn is accompanied with an overall increase in all expected crashes (total, PDO, F+I crashes). Having dedicated left-turn lanes on minor roads promotes the likelihood of total and F+I crashes. On the other hand, total and F+I crashes are expected to decrease with an increase in the number of dedicated right-turn lanes on major roads at an intersection. It can be concluded that expected increases in crash frequency is generally associated with the geometric design of intersection with respect to the number of turning lanes. The study of Xie et al. (2013) had similar findings where more turning lanes as total number led to more crashes [140].

Table 5.4 shows the results from the corridor model developed by combining the segments and intersections into corridors at three levels of crash severity. There is an increase in all crashes (total, PDO, and F+I crashes) in all 5T/4SG corridor SPFs when there is an increase in any of the average major AADT or the average entering minor AADT. Similarly, the presence of partially street lighting is linked with a rise in all crashes. The full street lighting parameter has a positive relationship with only total and PDO crashes. The number of 4SG intersections along the corridor are associated with a rise in overall expected crashes. Total and PDO crashes have positive correlations with the average posted speed limits along the corridor.

Table 5.4 Wyoming-specific SPFs for urban arterial corridor

		Total Crashes		PDO Crashes		F+I Crashes	
Parameter		Estimate	P-Value	Estimate	P-Value	Estimate	P-Value
Intercept		-9.8688	<.0001	-10.3347	<.0001	-9.9496	<.0001
Ln(Avg. Major AADT)		0.6942	<.0001	0.6500	<.0001	0.8543	<.0001
Ln(Avg. Minor AADT)		0.4345	<.0001	0.5015	<.0001	0.3291	0.0008
Number of 4ST		0.0258	0.0098	-	-	0.0472	0.0004
Lighting	No	-	-	-	-	-	-
	Partially	0.6231	<.0001	0.6968	<.0001	0.4531	0.0076
	Full	0.5350	<.0001	0.6620	<.0001	0.0205	0.8975
Number of 4SG		0.2386	<.0001	0.2503	<.0001	0.2036	<.0001
Avg. Speed Limit		0.0425	<.0001	0.0410	<.0001	-	-
Dispersion		0.1082	-	0. 1186	-	0.1258	-
BIC		1341	-	1252	-	966	-

Model Validation

To examine the prediction capability of the calibrated HSM SPFs and the developed Wyoming-specific models, a validation procedure was performed using new dataset. The new dataset was prepared using a new site for the years between 2003 and 2012. Even though the validation data and the modeling data were collected for the same period, the two sets of data are completely different as they were collected for two different locations. The selected site was an urban arterial consisted of five 5T segments and four 4SG intersections forming a corridor. The AADTs and observed crashes were extracted from 2003 to 2012. Table 5.5 summarizes the results of crash prediction using calibrated and Wyoming-specific models compared side by side with the observed crashes.

Table 5.5 Validation of the models for Urban Arterial Facilities

Total Crashes								
	Segments			Intersections			Corridors	
Year	Obs.	Calibrated HSM SPF	Wyoming-specific SPF	Obs.	Calibrated HSM SPF	Wyoming-specific SPF	Obs.	Wyoming-specific SPF
2003	27	11 (-59.3%)	14 (-48.1%)	27	14 (-48.1%)	38 (40.7%)	54	49 (-9.3%)
2004	23	12 (-47.8%)	14 (-39.1%)	33	14 (-57.6%)	38 (15.2%)	56	50 (-10.7%)
2005	22	10 (-54.5%)	13 (-40.9%)	20	13 (-35%)	37 (85%)	42	48 (14.3%)
2006	20	10 (-50%)	12 (-40%)	24	12 (-50%)	36 (50%)	44	48 (9.1%)
2007	19	10 (-47.4%)	12 (-36.8%)	19	11 (-42.1%)	36 (89.5%)	38	47 (23.7%)
2008	13	10 (-23.1%)	13 (0%)	30	12 (-60%)	37 (23.3%)	43	47 (9.3%)
2009	17	11 (-35.3%)	14 (-17.6%)	32	13 (-59.4%)	38 (18.8%)	49	49 (0%)
2010	13	11 (-15.4%)	13 (0%)	32	13 (-59.4%)	37 (15.6%)	45	48 (6.7%)
2011	9	10 (11.1%)	12 (33.3%)	25	11 (-56%)	36 (44%)	34	47 (38.2%)
2012	15	9 (-40%)	12 (-20%)	19	12 (-36.8%)	36 (89.5%)	34	45 (32.4%)
Total	178	104 (-41.6%)	129 (-27.5%)	261	125 (-52.1%)	369 (41.4%)	439	478 (8.9%)
Avg.	17.8	10.4 (-41.6%)	12.9 (-27.5%)	26.1	12.5 (-52.1%)	36.9 (41.4%)	43.9	47.8 (8.9%)

The Wyoming-specific model performed better than the calibrated model in estimating the total crashes during the ten-year period. While the calibrated segment HSM SPF underestimated the observed total crashes by 41.6 percent, the Wyoming-specific segment model underestimated the observed total crashes by 27.5 percent. For the 4SG intersections, the calibrated model underestimated crashes by 52.1 percent. However, the Wyoming-specific models overestimated the observed crashes by at most 41.4 percent. The observed crashes for the corridors were obtained by combining the crash counts of segments and intersections. Comparison of the observed crash frequency and predicted crash frequency using Wyoming-specific SPF for corridors showed that the predicted crashes are overestimated by 8.9 percent, only.

CHAPTER 6-NON-CONVENTIONAL INTERSECTIONS/INTERCHANGES

This chapter presents the preliminary analysis conducted on roundabouts and the diverging diamond interchange (DDI) in Wyoming as non-conventional intersections. Due to the limitations of small sample size and few observations, crash modification factors were not developed for roundabouts and DDIs.

LITERATURE REVIEW

Diverging Diamond Interchange

DDIs are commonly proposed to replace traditional diamond interchanges. They feature a significantly less number of conflict points and have the ability to accommodate high traffic volumes of left turns [162]. Since the first DDI was put into operation in Springfield, Missouri, in 2009, there have been a few studies evaluated the safety performance of DDIs using real-world crash data.

Edara et al., (2015) conducted a safety evaluation of DDIs using three types of before–after evaluation methods: naïve, empirical Bayes, and comparison group [163]. All three methods showed that DDIs replacing a conventional diamond decreased crash frequency for all severities. The highest crash reduction (59.3 percent to 63.2 percent) was observed for fatal and injury crashes, respectively. Crashes involving property damage only were reduced by between 33.9 percent to 44.8 percent. Total crash frequency also decreased by anywhere from 40.8 percent to 47.9 percent. Hummer et al., (2016) analyzed seven of the earliest DDIs in the US, developed CMFs for the conversion of a conventional diamond to a DDI [164]. The results showed that in general, a CMF of 0.67 was estimated for DDIs, which meant that installation of a DDI to replace a conventional diamond should reduce all crashes by 33 percent. Afterward, Claros et al., (2017) developed crash prediction models for DDI ramp terminals for different crash severities based on historical crash data from DDI sites in Missouri [165]. The Empirical Bayes (EB) method was employed to analyze the safety benefits of DDIs; it was found that the DDI ramp terminals experienced 55 percent fewer fatal and injury crashes, 31.4 percent fewer property damage only crashes, and 37.5 percent fewer total crashes. Another study performed by Claros et al., (2017) investigated the safety effect of DDIs on adjacent roadway facilities, such as adjacent intersections and speed-change lanes (SCLs) at freeway entrances and exits [166]. Similarly, EB method was used to estimate the safety effect of the DDI on adjacent facilities. It was summarized that no evidence showed that the DDI design had any positive or negative effect, on the crashes that occurred at the entrance or exit SCLs. In comparison, a 6.5 percent decrease in fatalities and injuries, which was not statistically significant, was found for signalized intersections next to the DDI ramp terminals. Nevertheless, after DDI implementation, it was found that a 19.5 percent increase in PDO and a 12 percent increase in total crashes at adjacent intersections. Walls et al., (2018) conducted a project-level safety evaluation for two DDIs in Minnesota using Naïve and EB before-after approaches to determine the safety savings of converting the signalized intersections into DDIs [167]. The results indicated that the average CMF was 0.48 for the Naïve method and 0.42 for the EB method, which proved that the DDI design is a valid and reliable safety countermeasure.

Although the positive safety effectiveness for DDIs proven by several studies, from a motorist stand point, it has a complicated and a non-conventional operation. Introducing a new DDI for unfamiliar drivers might provide contradicting effect. In the presence of harsh weather and high truck traffic, navigating a DDI might be even more complicated. In the following sections, a preliminary analysis is presented for the College Ave DDI, in Cheyenne, from a traffic safety stand point.

Roundabouts

Recent studies in the US suggest that roundabouts are safer than signalized and stop controlled intersections [12], [168]–[172]. Roundabouts mainly eliminate or alter conflict types that would help in reducing crash severities, and in some cases, frequencies as well. The geometry of roundabouts influences motorists to reduce approach speeds. Roundabouts are popular in many countries, including Europe and the Middle East. However, in the US roundabouts are starting to be recognized as an alternative intersection design. Studies on roundabout safety in the US showed an average reduction of 37 percent, 51 percent, and 29 percent for total, injury, and PDO crashes, respectively. Recent studies showed various safety benefits of roundabouts compared to other types of intersections. A study, in 2012, conducted before-after analysis using negative binomial model for crashes obtained from 19 rural intersections that were converted to roundabouts [173]. These 19 intersections were selected from different states in the US and Canada. The results showed a reduction of 63 percent for total crashes, and 88 percent in injury crashes after the implementation. The study also showed a reduction of 91 percent for angle crashes. It is worth mentioning that the characteristics of the select roundabouts were not consistent. Given that the roundabouts are located in different regions in the US and Canada, this indicate that the driver population and behavior is significantly different. Additionally, different roundabouts types were used to develop the SPFs (i.e. single lane roundabout and multilane roundabouts). Additionally, regulations, enforcement, and crash reporting thresholds are different across the selected sites. These limitations might hinder the generalization of the findings obtained from the study. A recent study conducted in 2019, concluded that the overall safety would be enhanced by gaining experience navigating roundabouts [174]. The results of the study showed a significant reduction of 32 percent in the odds of injury crashes and a 9 percent reduction in total crashes. Additionally, an 11 percent reduction was obtained for right-of-way crashes, as well as 19 percent reduction in speeding-related crashes.

To conduct reliable safety effectiveness of roundabouts, sample size and limited observations will be the controlling factors. Roundabouts have several types that needs to be investigated separately to evaluate the safety effectiveness of each type. For example, mini-roundabout cannot be combined with regular roundabouts, or roundabouts intersecting arterial roads cannot be investigated with roundabouts intersecting collector or local roads. Sufficient sample size and crash observations in the before period and the after period of implementation should be met to conduct a traditional traffic safety analysis on roundabouts. Accordingly, a major roundabout in Cheyenne was selected to conduct a preliminary crash analysis for roundabout in Wyoming.

COLLEGE AVE DIVERGING DIAMOND INTERCHANGE (DDI)

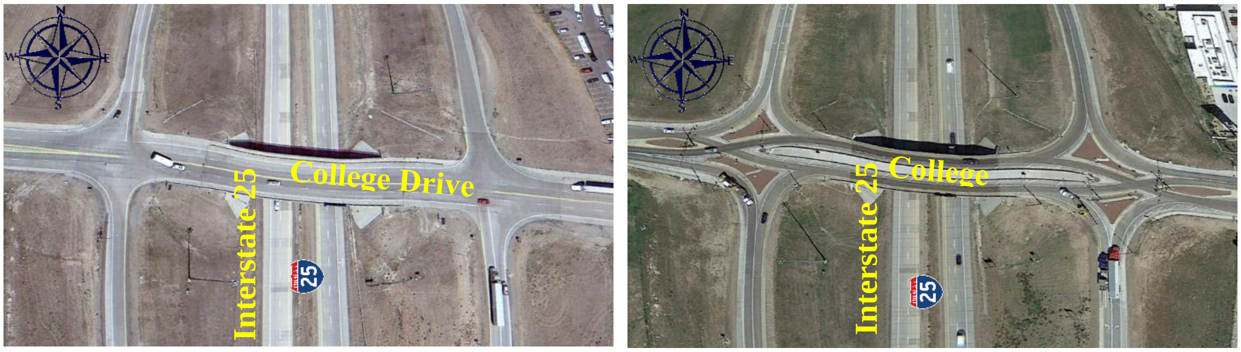
The College Drive/Interstate Freeway 25 (I-25) interchange has been considered by WYDOT) as the southerly gateway to the city of Cheyenne [175]. It is located approximately one mile south of the I-80/I-25 full cloverleaf interchange. In 2013, WYDOT converted the interchange at this location signalized four-lane conventional Diamond Interchange (DI) to a signalized Diverging Diamond Interchange (DDI), which is the only DDI in Wyoming, as shown in Figure 6.1. Since the overall traffic volume was not significant, WYDOT decided to use a two-lane DDI instead of a typical four-lane DDI, even though the existing bridge could accommodate a four-lane DDI [175]. Through a naïve before-after comparison (three years and nine months and after the re-construction, respectively), it was found that after converting the traditional DI to DDI, there is an increase in number of crashes in both property damage only (PDO) crashes (29 vs. 33), and fatal and injury (F+I) crashes (6 vs. 8). Particularly, during the winter season, total crashes increased from 21 to 27 from the before to the after period.

In terms of the causes of crashes, it was concluded that driving behavior and traffic control related factors, such as speeding, lane keeping/recognizing, and improper turn or lack of traffic signals, are the key factors that contributed to the increase in crashes. In general, the crash modification factor (CMF) for the College Drive DDI was determined as 1.17 [(33+8) / (26/6)], which means that total crashes increased by 17 percent after converting the traditional DI to DDI. This is significantly higher than the other DDIs deployed in the US. For instance, Hummer et al. [164] developed CMFs for seven of the earliest DDIs in the US. The results showed that in general, a CMF of 0.67 was applied for DDIs that meant that installation of a DDI to replace a DI should reduce all crashes by 33 percent.

Table 6.1 shows the frequencies for the crashes occurred in the before and after periods of DDI construction year.

Table 6.1 Before-After crash statistics for the DDI

Number of Crashes		Before Period (Apr. 2009 to Dec. 2012)	"After" Period (Apr. 2014 to Dec. 2017)
Total Number of Crashes	PDO	29	**33**
	F+I	6	**8**
Crash Frequencies by Season	Winter	21	**27**
	Summer	14	14
Type of Crash	Angled – Same Direction	12	10
	Angled – Opposite Direction	3	1
	Backing	1	n/a
	Hit Fixed Object	13	**19**
	Rear-End	5	**8**
	Sideswipe	1	**4**
Cause of Crash	Speeding	10	**13**
	Failed to Yield ROW	10	5
	Following too close	6	6
	Run off road	5	4
	Failed to keep proper lane	2	**5**
	Improper turn or no signal	1	**3**
	Other	5	**8**



(a) Previous un-signalized diamond interchange configuration (Date of photo: August 18, 2012)

(b) Existing signalized diverging diamond interchange configuration (Date of photo: September 12, 2018)

Figure 6.1 College Ave. Diverging Diamond Interchange

Safety Improvement Suggestions for the DDI

According to the preliminary analysis, four treatment alternatives are suggested for further investigation:

- Do nothing
  - Conduct an education campaign on driving rules of DDIs and different traffic movements.
- Signal timing optimization
  - Optimize signal control schemes to reduce queuing within the interchange and the number of conflict points
- Replace the off-ramp left-turn yield sign to a signal
  - Using traffic signal to mitigate the potential conflicts between off-ramp left-turn traffic and arterial through traffic
- Geometric improvements
  - Changing exiting two lane interchange to four lanes to mitigate the potential conflicts between off-ramp left-turn traffic and arterial through traffic

NINETEENTH/PERSHING/CONVERSE ROUNDABOUT

Roundabouts are considered a new intersection design in Wyoming. It is implemented in few locations across Wyoming. The city of Cheyenne has multiple roundabouts, yet they are considered as a very small sample size to conduct any statistical analysis. The intersection of 19th/Pershing/Converse was selected to conduct a preliminary investigation on roundabouts performance. It is considered one of the major intersections in the city of Cheyenne as it accommodates more than 41,000 vehicles on daily bases. It is located near the center of the City of Cheyenne. This roundabout connects a principle arterial road (Pershing Boulevard) with the two minor arterial roads (19th Street and Converse Avenue). In 2018, Traffic volumes reaches over 16,000 vehicle per day (vpd) on the east bound of Pershing Boulevard, 15,300 vpd for the westbound of Pershing Boulevard, 13,500 vpd for the northbound of Converse Ave., 8,400 vpd for the southbound Converse Ave., and nearly 6,900 vpd for the 19th Street. It was converted from a complex signalized intersection to a two-lane five-leg roundabout as shown in Figure 6.2.

(a) Previous three grade intersections (Prior to April 2013)

(b) Existing upgraded roundabout Design (After May 2014)

Figure 6.2 Intersection of Converse Avenue/East 19th Street/ East Pershing Boulevard (Source: Google Earth)

Roundabouts are not a common type of intersection in Wyoming. Although the safety tips and education that the City of Cheyenne has offered to drive through a roundabout, it might introduce confusions for motorists who encounter such intersections for the first time. However, the anticipated safety benefits of the roundabout, historical crash data indicated that this two lane roundabout performed worse when compared to national statistics. Moreover, through a before-after comparison for crash frequencies, it was found that crashes were significantly increased after the implementation, as shown in Table 6.2.

Table 6.2 Summary of the Number of Crashes at the 19th/Pershing/Converse Roundabout

Number of Crashes		Before Period (Apr. 2008 to Dec. 2012)	"After" Period (Apr. 2014 to Dec. 2017)
Total Number of Crashes	PDO	76	**239**
	F+I	17	**28**
Crash Frequencies by Season	Winter	57	**146**
	Summer	36	**121**
Type of Crash	Angled – Same Direction	8	**131**
	Angled – angles and Opposite Direction	50	**69**
	Rear-end	23	19
	Head-on	5	0
	Sideswipe Same Direction	4	**32**
	Other	3	**16**
Cause of Crash	Ran Red Light	25	0
	Failed to Yield ROW	20	**158**
	Following too Close	10	**11**
	Drove too Fast for Conditions	7	3
	Reckless/Careless/Aggressive	4	**11**
	Failed to Keep Proper Lane	2	**42**
	Disregarded Traffic Signs	3	**11**
	Other	22	**31**

Note: PDO = Property Damage Only; F+I = Fatal and Injury; ROW = Right of Way

According to the type and the main contributing factor of crashes, there were a statistically significant increase in angled and sideswipe crashes, as well as the failing to yield or keeping proper lane. Figure 6.3 shows that most of the crashes occur at the weaving sections in the roundabout when vehicles entering and exiting the roundabout share the same geographic location. This observed increase in crashes could be due to three main reasons: 1) insufficient weaving lengths that might indicate a geometric design deficiency, 2) lack of clear sight distance, and/or 3) motorists lack of knowledge/skills to drive through roundabouts. Urgent executable actions should be considered to enhance the traffic safety for this roundabout which could include determining a way to reducing the overall crashes to match the national roundabout crash trends.

Figure 6.3 Crash Locations within the Cheyenne 2-lane roundabout from 2014 to 2018 (Source: Google Fusion)

Safety Improvement Suggestions for the Roundabout

According to the preliminary analysis, five mitigation strategies are suggested for further investigation:

- Do nothing
    - Conduct an education campaign on driving rules of roundabouts and clarifying the different traffic movements.
- Improvements in signage and markings
    - More clear signs and pavement markings at roundabout entries and weaving sections
- Reduce the speed simits at the entries
    - Reduce the speed limit to 25 mph or less
- Signal control at high crash-risk locations
- Geometric improvements to reduce conflict points at high crash-risk locations

CONCLUSIONS

Traditional safety studies depend primarily on aggregate crash data that is reactive in nature, and cannot directly relay driver behavior prior to a crash nor provide detailed and accurate pre-crash information. Crashes are rare events when compared to other traffic events, nevertheless, they are complex events caused by accumulation and interaction of multiple factors and failures. In addition, exposure information, such as the frequency of behaviors in normal driving, as well as the larger context of contributing factors to crashes and near crashes cannot be obtained from crash reports. Additionally, having few investigated sites with few observations provide another layer or complication to the traditional safety analysis. To investigate the safety effectiveness of non-conventional intersections, innovative methodologies needs to be adopted.

Innovative safety techniques have the ability to assess driver behavior and performance interactions with roadway, environmental and vehicular factors, and their impact on collision risk. These evolving techniques could complement historical crash data and help proactively to identify hazardous locations with high probability of crashes and /or near-crash risks. This proactive approach utilized near crashes as surrogate measure of crashes to identify location with high crash risk prior to crash occurrence. They will help in recommending effective mitigation strategies in relatively shorter time compared to traditional safety analysis. Utilizing Surrogate Measures of Safety (SMoS) might provide an alternative approach to traditional safety studies. Conducting a traffic conflict analysis and/or microsimulation analysis could not only help in identifying potential solutions for non-conventional intersections, but also it could provide a timely interventional countermeasure. SMoS are factors that could be used to identify the cause of a near crash, which is a proactive approach of traffic safety analysis.

CHAPTER 7-CONCLUSIONS AND RECOMMENDATIONS

SUMMARY

Many transportation agencies assume that safety will be achieved solely by compliance to roadway design standards; known as nominal safety. Yet traffic crashes continue to increase or fluctuate from year to year, even on newly constructed roadways. In the US, tens of thousands lose their lives every year in traffic crashes. Contrasting fatalities in Wyoming to the national average revealed that Wyoming experiences higher fatality rates compared to all states in the US. Adhering only to standards will not address this issue. Shifting and moving to more substantive safety approach should be considered. This could be achieved by quantifying the safety performance of roadway facilities in Wyoming following a scientific-based approach. Moreover, to allocate limited resources more appropriately, evaluation of the safety effectiveness of various countermeasures is a crucial step. The focus of this study was to validate the applicability and transferability of the HSM to Wyoming-specific conditions. In addition, this study elucidated data limitations and challenges to conduct traffic safety analyses in Wyoming and alike states in the US. It proposes alternative solutions to overcome data limitations and challenges to implement a scientific-approach following the HSM.

Two main tasks were accomplished in this study, starting with developing SPF for Wyoming-specific conditions followed by calibrating CMFs for different countermeasures implemented in Wyoming's road network. Several limitations were encountered to calibrate SPFs and CMFs presented in the HSM. Data used to develop crash prediction models in the HSM were obtained from only a few states, states from the mountain plains region are not represented. The mountain plains region has different traffic characteristics and composition, roadway characteristics, and weather conditions, which make them unique in their nature.

To achieve the study goals, several tasks were undertaken. Identifying existing data, data imputation and validation, preliminary data analysis, advanced analysis, conducting comparisons with the HSM, and providing recommendations.

One major and arduously performed task was data preparation and validation. Several datasets were needed to conduct this study. Crash data, roadway characteristics, weather data, traffic volumes, and implementation dates and locations for treatments were all required. A number of data sources were utilized to prepare these various datasets. Many gaps and limitations were identified and discussed throughout the different chapters. Non-traditional data sources were used to overcome limitations and fill in the gaps.

The study focused on investigation of countermeasures on three groups of roadway facilities; 1) roadway segments/corridors, 2) ITS and special facilities, and 3) non-conventional intersections. Calibrating reliable CMFs required having reliable SPFs for the site-specific conditions. SPFs were developed, as they are considered an essential step in the analysis process. A number of statistical techniques were used to develop SPFs in this study. These techniques ranged from traditional statistics such as Negative Binomial models (NB) and Zero Inflated Negative Binomial models (ZINB), and non-parametric ones, such as MARS. Comparisons between the obtained models were performed to select the most accurate and reliable SPFs.

The HSM provides multiple statistical techniques to calibrate CMFs. observational before-after studies using Empirical Bayes (EB) method, and before-after studies using naïve method were the ones used to calibrate the crash modification factors. Obtained results for SPFs and CMFs for the various roadway facilities are located in their corresponding chapters.

CONCLUSIONS

Lane Departure Crash Countermeasures

Fatalities resulting from traffic crashes is a cause for concern in Wyoming. The crash fatality rate per 100 million vehicle miles traveled (MVMT) in Wyoming has always been higher than the national average. Wyoming has the highest vehicle miles traveled (VMT) per capita coupled with challenging roadway geometry and adverse weather conditions. This led to higher crash rate fatalities in Wyoming than the national average. Research and statistics on Wyoming data show that a significant number of fatal and serious injury crashes result from lane departure crashes. These crashes occur when a vehicle leaves the traveled path and moves to the shoulder, or crosses over to the opposite lane in a two-lane two-way roadway. Generally, lane departure crashes include angle, head-on, sideswipe, and run-off-road crashes. These types of crashes often lead to fatal and injury crashes on two-lane two-way roadways. In Wyoming, the percentage of fatalities from a lane departure crash is high compared to fatalities from other types of crashes. Lane departure crashes can be caused by factors such as driver fatigue and drowsiness, distracted driving, poor road surface condition, adverse weather, and challenging roadway geometry preventing passing maneuver. Some of these contributing factors could be mitigated by providing countermeasures that can alert drivers when they start drifting off the roadway. These countermeasures include rumble strips, adding passing lanes to provide opportunities to pass or overtake safely on a two-lane roadway, and dividing the roadway into a four-lane highway to prevent cross-over crashes. This study analyzes the safety effectiveness of the combined effect of shoulder and centerline rumble strips, centerline rumble strips only, and adding lane and divide. Furthermore, a case study on passing lanes feasibility on a rural two-lane two-way highway in Wyoming (WY-50) was investigated.

The CMFs developed from the analysis of the combined shoulder and centerline rumble strips using before-after EB method show that there is 33 percent expected reduction of total crashes, 25 percent expected reduction of PDO crashes, and 79 percent expected reduction in F+I crashes. The safety effectiveness of the centerline rumble strips was also analyzed in this study using before-after Naïve and before-after EB methods. The summary statistics as well as the developed CMFs show that there was no reduction in crashes, rather crashes were expected to increase on roadways with only centerline rumble strips implemented. There could be numerous reasons for these observation and findings including the limited sample size among others. More limitations for this study is further explained in the limitations section.

Analysis of the conversion to four-lane divided highway showed that there is expected reduction of 37 percent associated with total crashes and expected crash reduction of 64 percent linked to F+I crashes. The result were significant at the 95th percent confidence interval.

It can be concluded from this study that the combined effect of shoulder and centerline rumble strips, and conversion to a four-lane divided highway are effective in reducing crashes overall on rural two-lane two-way highways of Wyoming. This would help the agencies to devise effective strategies to reduce lane departure crashes on rural two-lane two-way highways of Wyoming. Often the agencies are limited in their resources in terms of funds allocation for necessary treatments on the roadway. This study could be used as a starting point by transportation agencies or safety analysts to carry out a benefit-cost analysis of multiple countermeasures and make decisions based on the safety needs, and available resources.

Snow Fences

The study on snow fences investigated snow fences based on their design, their safety effectiveness in relation to snow fence types, surrounding terrain types, and their economic significance. All of the CMFs calculated from the analysis of the snow fences indicated that all snow fence types aid in reducing crashes at all crash severity levels in all winter weather conditions. The ultimate goal of countermeasure installation is to reduce the most F+I crashes from occurring; by these definitions, upright/vertical snow fences reduce the most F+I crashes and should be implemented more frequently than Wyoming snow fences.

From the calibrated CMFs based on terrain type, total crashes are indicating to be reduced between 26 percent and 50percent; PDO crashes are showing a reduction of 28 percent to 47percent; and F+I crashes are found to be reduced by between 51 percent to 82percent. Both terrain types can create many blowing snow issues for drivers due to their different environments. Snow fences were found to be the most effective for flat/level and rolling terrain during non-adverse winter weather conditions at preventing/reducing F+I crashes. For flat/level and rolling terrains, a safety effectiveness of 68 percent for F+I crashes in non-adverse winter weather conditions was found. For mountainous terrain, at a safety effectiveness of 82 percent, snow fences are also the most effective during non-adverse winter weather conditions at preventing F+I crashes. From these results, it has become obvious that snow fences are not just helping during adverse winter weather conditions, but are also having an effect on crashes that are occurring in non-adverse conditions.

Variable Speed Limits (VSL)

CMFs developed from the study of VSL systems on I-80 for total crashes, fatal + injury, PDO, and truck crashes using MARS and Negative Binomial models provided comparable results. The safety effectiveness attained using NB and MARS for truck crash models were 29 percent and 34 percent, respectively. For total and F+I crashes, the VSL showed a reduction of 22 percent and 28 percent using NB and MARS.

Roadway Corridors

The objective of the study on urban and suburban five-lane arterial roadway corridors was to understand crash contributing factors on five-lane arterials with a center two-way left-turn lane (TWLTL) (5T), and urban and suburban arterial signalized four-leg intersections (4SG). This better understanding would help WYDOT to identify appropriate safety countermeasures for the urban and suburban arterials.

Examining the resulted calibration factors that were derived from the HSM SPFs, the values of the calibration factors were less than 1 for both facility types. This indicated that the HSM SPFs generally over-estimated total crashes for urban and suburban 5T arterials, and urban and suburban 4SG intersections in Wyoming. These differences between predicted total crashes from nationally derived SPFs and locally observed crashes can be attributed to many factors. Notably, Wyoming differs from the national average especially in weather, terrain, and driver and wildlife populations.

The newly developed Wyoming-specific SPFs for the segment facility showed that the AADT, number of four-leg controlled intersections, and number of driveways (major and minor) were strongly associated with an increase in expected crashes (Total, PDO, and F+I). Models developed to estimate the number of crashes for the 4SG intersections showed a strong association between AADT, left-turn signal phasing, and right/left turning lane with the expected increase in crashes. Wyoming-specific SPFs were developed to predict corridor crashes. A positive relationship was found between number of crashes and AADTs, speed limit, and number of signalized and controlled intersections along the corridor.

To examine the prediction capability of the calibrated HSM SPFs and the developed Wyoming-specific models, a validation procedure was performed using new dataset. The comparison between the calibrated HSM SPFs and developed models was done for segments and intersections. In general, the developed models performed better than the calibrated model in estimating the total crashes during the ten-year period. The findings of this study will help WYDOT in evaluating the safety of urban arterial roadways, intersections, and corridors in Wyoming.

Non-conventional Intersection/Interchange

DDIs and roundabouts are considered non-conventional in the US. In addition, they are newly introduced to the road networks in Wyoming. Due to the small number of locations that these types of interactions /interchanges are deployed, as well as the few observed crash years, new innovative methodologies are needed to provide accurate traffic safety assessment. The observed increase in crash frequencies in the two investigated locations might be due to driver behaviors factors that is related to unfamiliarity with the operation concept of these unconventional intersection/interchange designs. The traditional traffic safety evaluation methods might not be suitable to evaluate safety performance of the DDI and roundabouts, in Wyoming, due to the mentioned limitations. It is suggested that WYDOT should utilize site-based observations of SMoS and microsimulation evaluation as proactive methodologies instead of traditional reactive approaches. Conflict analysis and microsimulation has proven to be effective innovative approaches to evaluate the safety performance of special roadway facilities. Additionally, conflict analysis using machine vision and machine learning techniques is considered more superior than traditional methodologies as it collects video footage that near misses could be analyzed by using traffic operational factors in space and time as well as driver behaviors.

LIMITATIONS AND RECOMMENDATIONS

Several limitations and challenges have been discussed in previous sections and were overcome by various techniques. Even though many of the issues that were encountered throughout the study were able to be resolved, there are still multiple areas that can be addressed in future work.

Low sample mean and low crash count observations

Most of the countermeasures considered for analysis in this study were implemented on rural two-lane, two-way highways in Wyoming. The rural two-lane, two-way highways in Wyoming are characterized with low traffic volumes. This resulted in low sample mean and observations with too many zero counts per segment. Consequently, this leaded to poor statistical model fit when the traditional models, such as negative binomial and zero-inflated models, were used. Furthermore, the problems are aggravated when the countermeasures were implemented only on a short roadway segment and the segmented dataset provided only a few observations that fit into the model. Due to this reason, some of the countermeasures, such as the wildlife-vehicle crash countermeasures, could not be analyzed. However, there are on-going research efforts to tackle these issues. One of the potential solutions could include using Bayesian models that are highly efficient in fitting data with low sample mean and low observations. Non-parametric models have been used in this study with success for one of the countermeasures. Such models could also be useful in analyzing other countermeasures. Further investigation in this regard could potentially provide more solutions. Issues related to roadway segmentation is discussed below.

Segmentation

Roadway segmentation is one of the most crucial steps in developing SPFs. As discussed earlier in previous chapters, the accuracy of the developed SPFs largely depends on the segmentation process. There is not a single method that applies to all types of data and roadway classifications. Both fixed length segmentation and homogeneous segmentation were adopted in this project to develop accurate SPFs. Fixed length segmentation is easier to adopt; however, homogeneous segmentation is more reliable and accurate but could be time consuming. Fixed length segmentation considers a constant length of the roadway no matter the variation throughout the developed segments. On the other hand, homogenous segmentation takes into consideration the variation in cross sectional elements, vertical alignment, horizontal alignment, and average daily traffic. Time and effort should be invested in this regard to determine the impact of different types of homogeneous segmentation procedures on the accuracy of SPFs and to determine which method would best suit the data needs of rural highways of Wyoming.

Data sources

Various non-traditional data sources were used for this study, such as the Pathway video logs, Google Street View®, and Google Earth Pro® to mainly identify construction dates. The non-traditional sources were helpful only up to an extent. For example, Pathway video logs consist of video feeds collected every other year, sometimes even longer, starting 2010, and not all of the routes are included for all the years. Google Street View® only shows the latest street view. Historical images of Google Earth Pro® are often blurry and inconsistent, which was also pointed out in the Phase 1 final report. The only solution to overcome these issues would be to archive better data regarding construction dates, reconstruction and resurfacing, widening and overlay, etc. The archiving system could utilize an HTML GIS system and require contractors to log construction activities as part of their reporting and documentation of the projects.

Adjustment period after the implementation of the countermeasures

Ideally, for before-after EB study, 3-5 years of crash data in the before period and 3-5 years' crash data in the after period should be acquired to develop CMFs. Furthermore, after the implementation of a countermeasure, one to two years should be provided as an adjustment period so that drivers can gain familiarity with the changes. This was limited for some of the countermeasures assessed in this study. For example, due to unavailability of crash data in the after period, three years of crash data immediately after the implementation of the centerline rumble strips, conversion to the four-lane divided highway were used to develop the CMFs. A more reliable before-after EB study should be carried out when three years or more of crash data become available after accounting for an appropriate adjustment period.

Another solution would be to use cross-sectional analysis. It can be utilized when calibrating CMFs for certain countermeasures to overcome missing implementation dates and missing data in the before period. However, it has its disadvantages as well. Cross-sectional analysis does not account for the Regression-to-the-Mean (RTM) bias. Therefore, cross-sectional analysis may overestimate or underestimate the safety effectiveness of the treatment.

Weather

Weather is considered a critical component contributing to crashes in Wyoming. Weather station information obtained from the National Oceanic and Atmospheric Administration (NOAA) was utilized for the study locations for some of the analysis in this study. However, for most of the roadway segments, it was not possible either to find a weather station nearby the segments or the weather stations close to the segments did not have archived weather information (number of rainy, snowy, windy days) for the analysis period. Forecasted historical weather and real-time weather could be used in future work to potentially determine the impact of weather conditions on the crashes.

The weather condition information used in the snow fence analysis was provided at the scene of each crash and was found to be inconsistant. This is because crash reports are filled out by different police officers/first reponders, and the weather condition is based on personal, subjective judgements. In conjunction to inconsistencies in weather reporting, additional levels should be created to cataloging the weather conditions. For example, snowy conditions can occur in non-adverse winter weather conditions; if it is snowing in non-adverse winter weather conditions, this tends to be light snow conditions and are associated with the wrong winter weather conditions. For future studies, these limitations will not be present due to the developments in Road Weather Information Systems (RWIS) and updated archived weather data. The advancements in these technologies in Wyoming potentially will create consistant systems for tracking weather and roadway conditions.

Traffic Volume Data

The study on snow fences utilized aggregate levels of data to investigate the safety efficacy of snow fences, as well as the safety preformance of the I-80 corridor. The traffic volumes that were used are based of the VMT volumes, therefore, this study was not able to analyze the performance of snow fence with the exact traffic volumes at the moment that the crashes occurred (real-time traffic data). In the winter, people tend to plan their trips more carefully around weather conditions. Even though factors for time and day were used in conjuction with the VMTs, the factors were not able to take into consideration random storm events, closures, and trip cancellations. Some of the CMFs were close in range when comparing winter season crashes to advserse winter condition crashes because the traffic volumes were not able to account for the lower exposure volumes during adverse winter conditions. Overcoming these limitations and obtaining more accurate traffic volume information could lead to more accurate and reliable assessment.

Combined Countermeasures

Various safety improvements would usually be implemented at the same time and location. Hence, assessing individual efficacy of individual countermeasure could be infeasble. As mentioned earlier, many snow fence types were implemented at the same location and time frame. For example, lath snow fences are usually implemented to isolate the effects of blowing near snow, whereas, Wyoming and upright/vertical snow fences are used to stop blowing snow from outside of the right of way of the roadway. This effect limited the snow fence types analysed when investigating the locations and assigning crash counts based on the construction dates of the snow fences. This is also a contributing reason as to why an analysis was conducted that analyzed the effects of all snow fence types together. However, lath snow fences are usually used to control blowing near snow, which are different conditions than what Wyoming and upright/vertical snow fences are designed for. Another example presented in this study was combined shoulder and centerline rumble strips. In many cases, assessing their individual effetiveness in reducing lane departure crashes would be infeasible.

Driver Behaviour and Human Factors

Driver behavior is one of the most important factors that influence nearly all traffic crashes. Nevertheless, traditional safety studies depend primarily on aggregate crash data that is reactive in nature and cannot directly relay driver behavior prior to a crash nor provide detailed and accurate pre-crash information. Crashes are fortunately quite rare events when compared to other traffic events, nevertheless, they are complex events caused by accumulation and interaction of multiple factors and failures. In addition, exposure information, such as the frequency of behaviors in normal driving, as well as the larger context of contributing factors to crashes and near crashes cannot be obtained from crash reports. On the other hand, innovative safety techniques have the ability to assess driver behavior and performance interactions with roadway, environmental and vehicular factors, and their impact on collision risk. These evolving techniques could complement historical crash data and help proactively to identify hazardous locations with high probability of crashes and /or near-crash risks prior to when they occur and recommend effective mitigation strategies in relatively shorter time. This raises an ethical issue that transportation agencies must wait until a sufficient number of crashes, including fatalities and injuries, to happen before hazardous locations could be identified and mitigated. Proactive safety evaluation methodologies could provide a potential solution for these aforementioned issues. Proactive safety methodologies would include evaluation of SMoS using conflict analysis and microsimulation models utilizing SSAM.

FUTURE WORK

Currently, several additional countermeasures are recommended for future consideration. These countermeasures include, but are not limited to, roadway widening and overlay, climbing lanes, adding lane(s) undivided, roadway diet, cable median barriers, resurfacing, restoration and rehabilitation. The analyses of these various countermeasures in the future will not only aid the understanding of the safety effectiveness of various Wyoming roadway treatments, but some of them have a particular strong association to some of the emerging intelligent transportation systems related countermeasures including connected vehicles and the future work within this field that will take place on Wyoming roadways and intersections.

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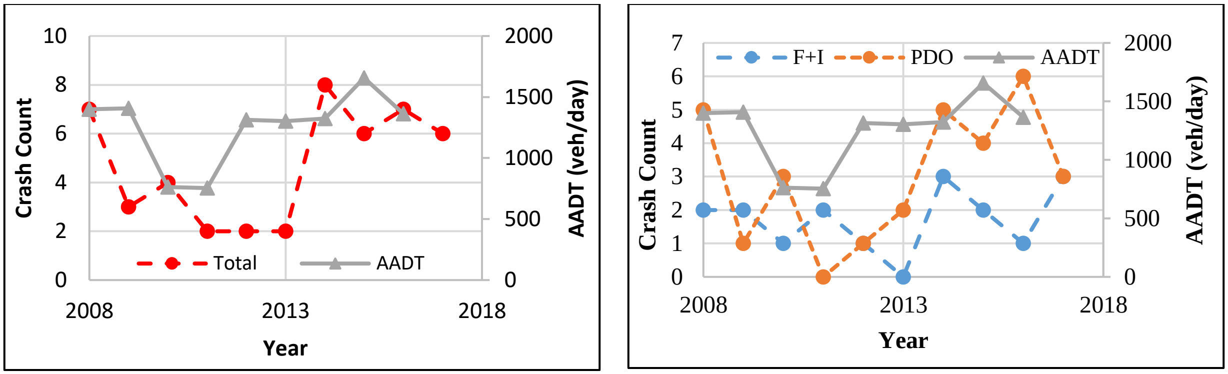
APPENDIX A.

FEASIBILITY OF INSTALLING PASSING LANES ON WY-50

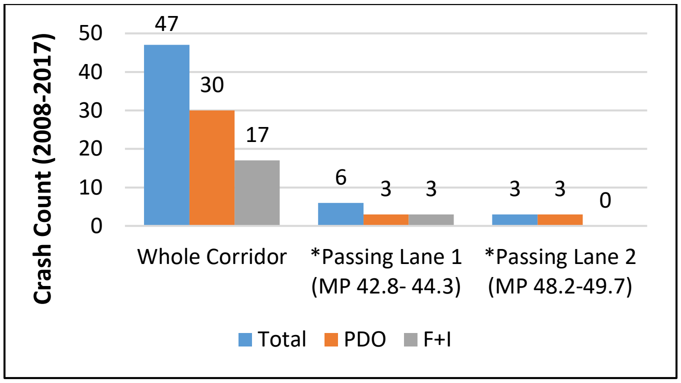
WY-50 Crash Data Analysis: 2008-2017

Crash data used in this study were collected from WYDOT for the period between 2008 and 2017 (10 years of crash data). The yearly variation in AADT was consistent throughout the corridor. The total length of the corridor is 17.34 miles starting from milepost (MP) 35.328 and ending at MP 52.67, on Wyoming Highway 50 (WY-50). The proposed locations for construction of passing lanes are MP 42.8 to 44.3, and MP 48.2 to 49.7, both 1.5 miles in length. To analyze the need to install passing lanes, it is necessary to separate the target crashes occurring only due to the lack of passing opportunities, such as head on, run off road, sideswipe collisions. From the dataset provided, it was not possible to extract crashes occurring at access points, turning movement related crashes, crashes due to drivers falling asleep, drivers being emotionally distressed, depressed, angry, fatigued, ill or sick, and crashes related to fire or explosion. Only crashes involving animals could be removed from the analysis, and the resulting crash trends and charts are shown in Figure A.1. The crash trends that include lane departure crashes along with other types of collisions are shown alongside annual average daily traffic (AADT). Traffic volumes on a roadway is an indication of the exposure to potential crashes, the more the number of vehicles using the roadway per day, the higher the probability of crashes. The crash counts throughout the years are very few and the fluctuations are not alarming at all, rather it can be attributed to the regression-to-the-mean bias (RTM) [12]. Regression-to-the-mean is a well-known statistical phenomenon that high number of motor vehicle crashes on a roadway facility in a particular period are likely to decrease during the following period. Crashes are rare stochastic events that expected to fluctuate around their mean. Figure A.1c show crash counts by severity; total, Fatal and Injury (F+I), and Property Damage Only (PDO) crashes. Fatal and injury crashes are the most severe types of crashes and the number of crashes in this category between years 2008 and 2017 was quite low. It is worth mentioning that there were two crashes that led to fatalities on WY-50. One took place in the year 2008 and another in 2016, both crashes were related to overtaking or passing.



a) Total Crashes vs. AADT

b) F+I and PDO Crashes vs. AADT



c) Crash Count Comparison. *Proposed passing lanes

Figure A.1 WY-50 Yearly Crash Trends, Total; F+I = Fatal + Injury; PDO = Property Damage Only

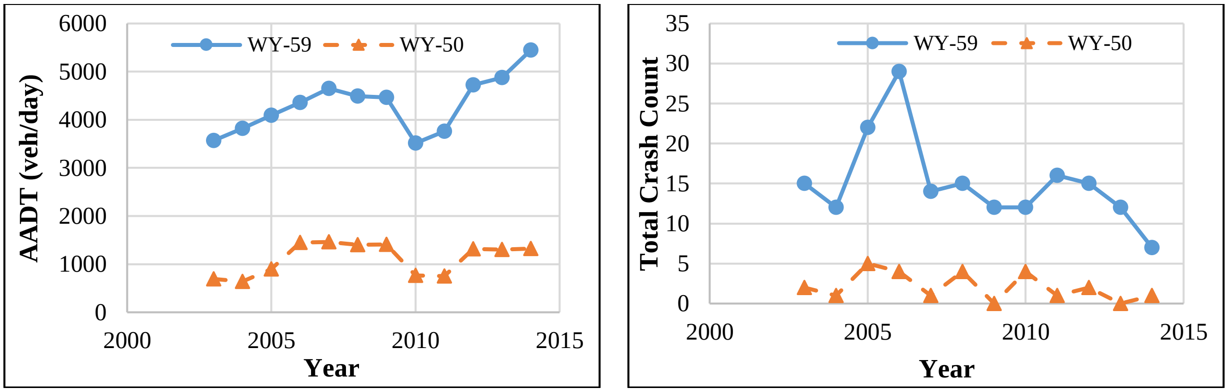
WY-50 and WY-59 Crash Data Analysis: 2003-2014

In 2006, passing lanes were implemented in WY-59, which has similar roadway characteristics (rural two-lane highway) with WY-50. The crash data analysis before and after the implementation of passing lanes on WY-59 provides a basis for comparison and analysis of the need for passing lanes on WY-50. Detailed reports from CARE package were used to extract crash data of both roadways (WY-50 and WY-59) for the years 2003-2014. The study conducted by Schumaker et al., (2017) evaluated the safety effectiveness of passing lanes utilizing crash data, which had crashes involving intersections, driver impairment (alcohol/drug involvement, fatigued or emotionally distressed), and animals-related crashes removed [35]. Such crashes that are not directly relevant in evaluating passing lane effectiveness were also removed from this analysis. A summary of the data extracted from the CARE package is provided in Table A.1.

Table A.1 Summary of data extracted (WY-59 and WY-50)

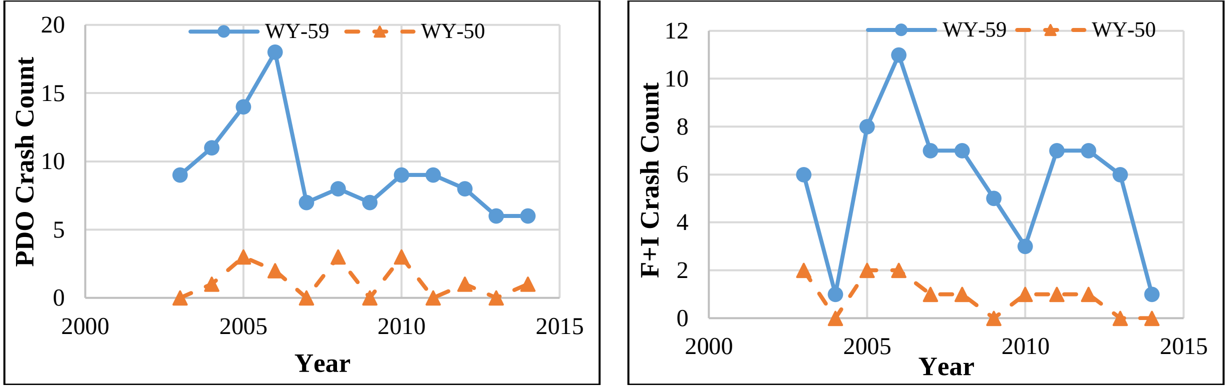
		WY-59	WY-50
Total Length (mile)	Whole Corridor	26	17.34
	Passing Lanes	10.03	3.00
Crash count per mile	Total	7	1.44
	PDO	4.31	0.81
	F+I	2.69	0.63
Average of AADT (veh/day)		4314	1117

Figure A.2 shows the comparison of yearly trends between WY-59 and WY-50. AADT, Total Crash Count, F+I and PDO crash counts at WY-59 are all significantly higher than WY-50, even after the implementation of passing lanes in the year 2006.



a) AADT Yearly Trend

b) Total Crash



c) Property Damage Only Crash

d) Fatal + Injury Crash

Figure A.2 AADT and Crash Count Comparison between WY-59 and WY-50

A closer look at the yearly trends of AADT and Total Crash counts show that for WY-59, although there is an increase in AADT, the crash count is decreasing. This can be attributed to the implementation of passing lanes on the corridor [35]. AADT and Total Crash count for WY-

50 are still much lower for any kind of decision to be made regarding the implementation of passing lanes in the corridor.

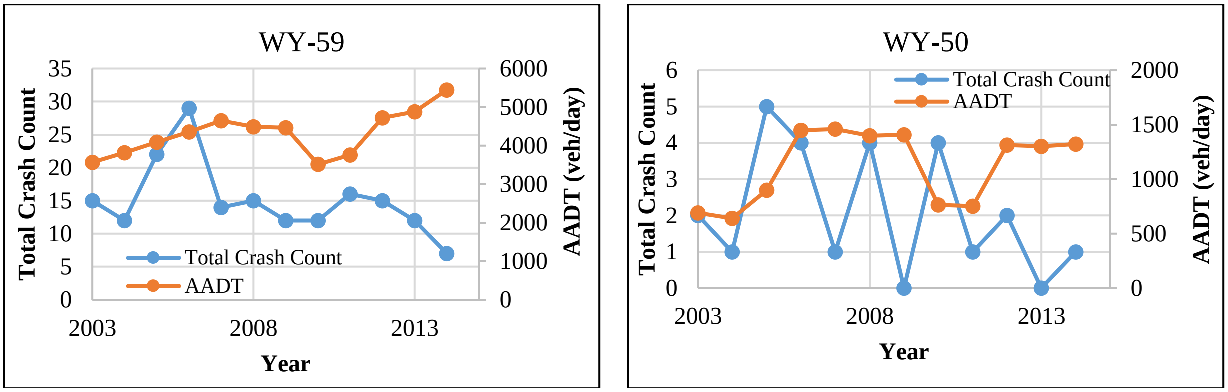


Figure A.3 Yearly Trend of Total Crash Count vs. AADT for WY-50 and WY-59

Table A.2 provides a crash rate comparison between WY-59 and WY-50. The average total crash rate per year per million vehicle miles traveled (MVMT) for WY-50 is 0.29 (total) and 0.13 (F+I) for the whole corridor. The crash rate for WY-50 is lower than the crash rate for WY-59 before the implementation of passing lanes.

Table A.2 Crash Rate Comparison

	WY-59		WY-50
	Before*	After (2007-20014)	Before (2003-2014)
Average crash rate per year per MVMT	0.42	0.18	0.29

*Before crash rate obtained from Schumaker and Ahmed et al. (2017)

A closer look at the different types of collisions is provided in Table A.3 and Figure A.4. Other than overturn or rollover crashes, the only type of target crashes (lane departure crashes) that occurred on WY-50 between 2003 and 2014 is sideswipe same direction crashes (count of 2 in 12 years). In comparison WY-59 encountered different types of lane departure crashes that warranted the need for passing lanes.

Table A.3 Collision Type Comparison between WY-59 and WY-50 (2003-2014)

WY-59						WY-50					
Collision Type	Total		Weather Related Crashes			Collision Type	Total		Weather Related Crashes		
	Count	%	Weather	Count	%		Count	%	Weather	Count	%
Overturn/Rollover	48	26%	Adverse	25	52%	Overturn/Rollover	17	68%	Adverse	8	47%
			Clear	23	48%				Clear	9	53%
SS same direction	7	4%	Adverse	4	57%	SS same direction	2	8%	Adverse	0	0%
			Clear	3	43%				Clear	2	100%
Others/Unknown	82	45%	Adverse	34	41%	Others/Unknown	6	24%	Adverse	2	33%
			Clear	48	59%				Clear	4	67%
Rear end	14	8%	Adverse	3	21%						
			Clear	11	79%						
SS opposite direction	9	5%	Adverse	2	22%						
			Clear	7	78%						
Head on	9	5%	Adverse	4	44%						
			Clear	5	56%						
Angle (direction not specified)	5	3%	Adverse	2	40%						
			Clear	3	60%						
Angle (front to side)	4	2%	Advance	1	25%						
			Clear	3	75%						
Angle right (front to side)	2	1%	Advance	1	50%						
			Clear	1	50%						
Angle same direction	2	1%	Advance	0	0%						
			Clear	2	100%						

Figure A.4 Collision type comparison between WY-59 and WY-50

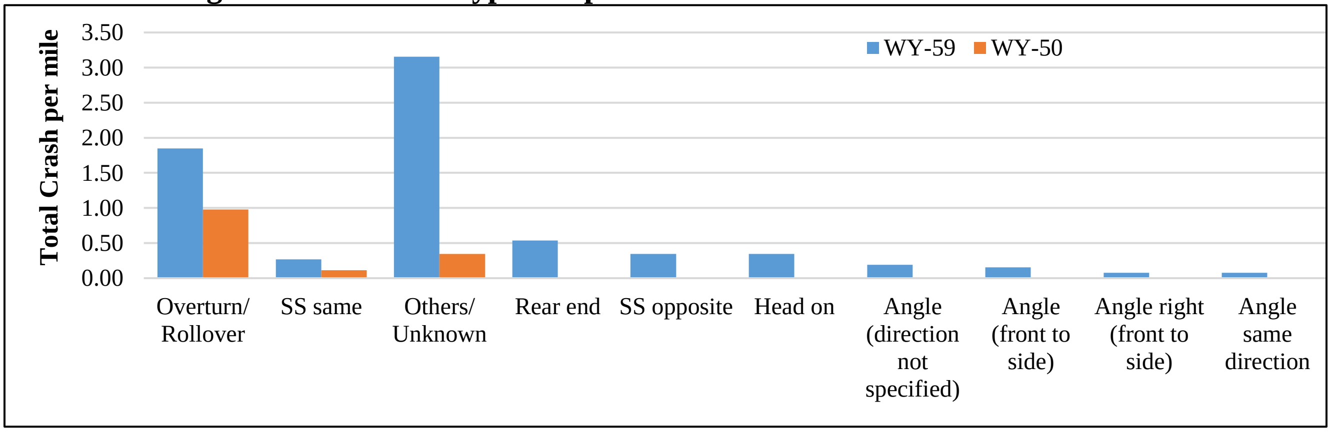


Table A.4 Wyoming Specific SPFs for rural flat and rolling two-lane roads

Crash Severity	Intercept Estimate	Log (AADT) Estimate	Dispersion (k)
Total	-6.4633	0.8220	0.2242
F+I	-7.3609	0.7700	0.2235

Using the Wyoming-specific safety performance functions (SPFs) as provided in Table A.4, the expected number of total and F+I crashes for WY-50 corridor was calculated. It is expected to have 0.35 total crash/ mile/ year and 0.12 F+I crash/ mile/ year), considering the AADT remains same as that for the year 2016. Using the CMFs of 0.68 (Total) and 0.80 (F+I), the expected number of crashes in the whole corridor after the implementation of passing lanes is also calculated and shown in Table A.5.

Table A.5 Expected Number of Crashes in WY-50 for the year 2016

	Total	**F+I**
Expected Number of Crashes	0.35	0.12
Expected Number of Crashes (after passing lane implementation)	0.24	0.096
Crash Reduction	32%	20%

Cost-Benefit Analysis

The monetary impacts of crashes or economic costs, known also as human capital costs include goods and services related to the crash response, property damage, and medical costs. These economic costs have direct and indirect expenses to individuals and society from decline in general health or quality of life of crash victims. The following Table A.6 provides the severity-weighted Fatal Injury (K)/ Disabling (A), Evident Injury (B)/ Possible Injury (C), and No Apparent Injury (O) crash unit cost values used by WYDOT. These values are based on 2012 USDOT costs [5]. The costs provided in Table A.6 must be adjusted to reflect present or future year costs by multiplying the values by a factor of 1.0107^N, where N is the number of years after 2012.

Table A.6 Wyoming DOT Comprehensive Crash Unit Costs (2013 dollars)

Severity	**Comprehensive Crash Unit Cost**
Fatal (K)/ Disabling (A)	$ 2,237,000
Evident (B)/ Possible (C)	$ 98,000
No Injury (O)	$ 39,000

Table A.7 Comprehensive Crash Cost Estimate for WY-50 (2003-2014)

Severity	Cost[1] (2014 dollars)	Count (2003-2014)	Cost
Fatal (K)	$ 2,285,128	0	$ 0
Disabling (A)	$ 2,285,128	2	$ 4,570,256
Evident (B)	$ 100,108	7	$ 700,759
Possible (C)	$ 100,108	2	$ 200,217
No Injury (O)	$ 39,839	14	$ 557,747
Total		**25**	**$ 6,028,979**
Crash Cost per year			**$ 502,415**

1 Adjusted for inflation by multiplying the costs by a factor of 1.0107^N where N is the number of years after 2012.

Using the updated comprehensive crash cost [5], the estimated crash cost for the crashes that might be influenced by lane changing maneuvers is calculated to be approximately $6 million for the years 2003-2014, or $500,000 per year (Table A.7). Considering the possible total and F+I crash reduction of 32 percent and 20 percent (Table A.5), crash cost reduction expected after proposed passing lane implementation is calculated and shown in
Table A.8.

Table A.8 Breakdown of benefit calculation in terms of crash cost reduction

	Crash Count (2003-2014)	Reduction in crash count (expected in 2014)[1]	Reduction in crash cost (expected in 2014)[2]	
Fatal (K)	0	0	$	-
Disabling (A)	2	0.4	$	894,800
Evident (B)	7	1.4	$	137,200
Possible (C)	2	0.4	$	39,200
No Injury (O)	14	1.68	$	65,520
Total Crash Cost Reduction			**$**	**1,136,720**
Crash Cost Reduction per year (Benefit)			**$**	**94,727**

1 Using CMF of 32% and 12% for F+I crash and PDO crashes respectively
2 Using the comprehensive crash costs provided in Table 7.

Furthermore, considering the passing lane construction costs of WY-59 ($585,000 per mile) it would have cost approximately $1.7 million to construct the 1.5-mile each, a total of 3-mile passing lane in WY-50 in the year 2005-2006. Projecting the costs to 2018 with an inflation rate of 3 percent the present-day cost of adding 3-miles of passing lanes would cost approximately $2.5 million ($834,000 per mile). For example, given that a two-year period for the construction and drivers gaining familiarity with the added passing lanes, the benefits, in terms of comprehensive crash cost reduction, would start to be realized by 2020. Nevertheless, the return from the investment in implementing passing lanes is almost negligible. As it can be seen in Table A.9, the benefits in terms of crash cost reduction do not overcome the costs of constructing the passing lanes in the foreseeable future (2050). The projected reduction in crash costs (benefits) are calculated using the factor 1.0107^N [176]. It is worth mentioning that maintenance/ resurfacing costs and other unforeseeable costs were not included.

Table A.9 Cost-Benefit Analysis

Year	Benefits*	Costs
2020	$ 105,365	$ 2,500,000
2021	$ 106,492	$ 2,500,000
2022	$ 107,631	$ 2,500,000
.	.	.
.	.	.
2050	$ 144,998	$ 2,500,000

***(Benefits = reduction in comprehensive crash cost)**

Conclusion

The reasons for implementing passing lanes have been analyzed in this study and the outcomes from the analysis provided in Table A.10. Analyzing the crash severities, it was found that between 2008 and 2017 there have been only three fatal crashes on WY-50, one of which was due to overtaking or passing maneuver. However, there's not enough information regarding whether that one overtaking-related crash was due to DUI, fatigue, etc. Comparing this to crashes on WY-59 in the before period of installing passing lanes (1997-2004), there were eight fatal crashes resulting from possible passing maneuvers. Although the AADT on WY-59 is much higher than WY-50, the trend in AADT over the years does not suggest any significant cause for concerns of drastic increase in crash counts on WY-50 in the next few years. One of the reasons for implementing passing lanes on WY-59 was the occurrence of different types of lane departure collisions or collisions resulting from passing maneuvers. However, only few such collisions were observed on WY-50 during the years 2003-2014. The crash cost-benefit analysis conducted suggests that it is not possible for the benefits of the passing lanes to overcome the construction costs in the near future, if only comprehensive crash cost reduction is considered as benefits. Therefore, from the results of all the analysis conducted, it can be concluded that passing lanes on WY-50 are not quite needed in the near future.

Table A.10 Outcomes of Feasibility Analysis of Installing Passing Lanes on WY-50

Is the crash count significant to warrant passing lanes?	NO
Does the trend in crash count and severities suggest the need for passing lanes?	NO
Is the AADT increasing significantly over the years?	NO
Compared to WY59 (similar roadway classification), is there a significant trend in crashes?	NO
Are there enough lane departure crashes to suggest the need for passing lanes?	NO
Are there significant benefits to adding passing lanes in terms of comprehensive crash cost reduction?	NO