FINAL REPORT WY-17/04F

State of Wyoming Department of Transportation

# CALIBRATING CRASH MODIFICATION FACTORS FOR WYOMING-SPECIFIC CONDITIONS: <br> APPLICATION OF THE HIGHWAY SAFETY MANUAL - PART D 

Final Report<br>April 2017<br>Principal Investigator<br>Mohamed M. Ahmed, Ph.D., PE<br>Assistant Professor<br>Department of Civil and Architectural Engineering, University of Wyoming

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## FOREWORD

This report presents first steps to validate the applicability of the Highway Safety Manual to Wyoming conditions. The study developed Safety Performance Functions and Crash Modification Factors for Wyoming Department of Transportation (WYDOT) to assess the safety performance of various roadway facilities as well as evaluating the safety effectiveness of different countermeasures.

This report will be useful to WYDOT, the Safety Management System Committee, and the Mountain-Plain Region states to mitigate data limitation as well as to adopt the Highway Safety Manual. The methods used in this study to impute data and overcome different challenges will be helpful for researchers. This report will be available online.

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## METRIC CONVERSION FACTORS

| SI* (MODERN METRIC) CONVERSION FACTORS |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: |
| APPROXIMATE CONVERSIONS TO SI UNITS |  |  |  |  |
| Symbol | When You Know | Multiply By | To Find | Symbol |
| LENGTH |  |  |  |  |
| in | inches | 25.4 | milimeters | mm |
| ft | feet | 0.305 | meters | m |
| yd | yards | 0.914 | meters | m |
| mi | miles | 1.61 | kilometers | km |
| AREA |  |  |  |  |
| $\mathrm{in}^{2}$ | square inches | 645.2 | square millimeters | $\mathrm{mm}^{2}$ |
| $\mathrm{ft}^{2}$ | square feet | 0.093 | square meters | $\mathrm{m}^{2}$ |
| $\mathrm{yd}^{2}$ | square yard | 0.836 | square meters | $\mathrm{m}^{2}$ |
| $\mathrm{ac}^{\text {mi }}$ | acres | 0.405 259 | hectares | ha |
| VOLUME |  |  |  |  |
| fl oz | fluid ounces | 29.57 | milliters | mL |
| gal | gallons | 3.785 | liters | L |
| $\mathrm{ft}^{3}$ | cubic feet | 0.028 | cubic meters | $\mathrm{m}^{3}$ |
| $y d^{4}$ | cubic yards NOTE: volur | 0.765 <br> reater than 1000 | cubic meters | $\mathrm{m}^{3}$ |
| NOTE: volumes greater than 1000 L shall be shown in $\mathrm{m}^{3}$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 ( $\mathrm{or}^{\prime 2} \mathrm{t}$ ") |
| ${ }^{\circ} \mathrm{F}$ TEMPERATURE (exact degrees) ${ }^{\circ} \mathrm{C}$ |  |  |  |  |
| ${ }^{0} \mathrm{~F}$ | Fahrenheit | 5 (F-32) 19 or (F-32)/1.8 | Celsius | ${ }^{\circ} \mathrm{C}$ |
| ILLUMINATION |  |  |  |  |
| $\mathrm{fc}$ | foot-candles foot-Lamberts | $\begin{gathered} 10.76 \\ 3.426 \end{gathered}$ | lux candela/m ${ }^{2}$ | $\begin{aligned} & \mathrm{lx} \\ & \mathrm{~cd} / \mathrm{m}^{2} \end{aligned}$ |
| FORCE and PRESSURE or STRESS |  |  |  |  |
| lbf | poundforce | 4.45 | newtons | N |
| $\mathrm{lbf} / \mathrm{in}^{2}$ | 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 |  |  |  |
| AREA |  |  |  |  |
|  | square millimeters | 0.0016 |  |  |
| $\mathrm{m}_{2}^{2}$ | square meters | 10.764 | square feet | $\mathrm{ft}^{2}$ |
| $\mathrm{m}^{2}$ | square meters | 1.195 | square yards | $\mathrm{yd}^{2}$ |
| $\mathrm{ha}_{2}$ | hectares | 2.47 | acres | $\mathrm{ac}_{-2}$ |
| $\mathrm{km}^{2}$ | square kilometers | 0.386 | square miles | $m i^{2}$ |
| VOLUME |  |  |  |  |
| mL | milliliters | 0.034 | fluid ounces | fil oz |
| $\mathrm{L}^{3}$ | liters | 0.264 | gallons | gal |
| $\mathrm{m}^{9}$ | cubic meters | 35.314 | cubic feet | $\mathrm{ft}^{3}$ |
| $\mathrm{m}^{3}$ | cubic meters | 1.307 | cubic yards | $y d d^{3}$ |
| MASS |  |  |  |  |
|  | grams | 0.035 | ounces | oz |
| $\mathrm{kg}$ | kilograms | 2.202 | pounds | 1 b |
| Mg (or "t") | megagrams (or "metric ton") | 1.103 | short tons (2000 lb) | T |
| TEMPERATURE (exact degrees) |  |  |  |  |
| ${ }^{\circ} \mathrm{C}$ | Celsius | $1.8 C+32$ | Fahrenheit | ${ }^{\circ} \mathrm{F}$ |
| ILLUMINATION |  |  |  |  |
| lx $\mathrm{cd} / \mathrm{m}^{2}$ | lux candela/m ${ }^{2}$ | $\begin{aligned} & 0.0929 \\ & 0.2919 \end{aligned}$ | foot-candles foot-Lamberts | $\begin{aligned} & \mathrm{fc} \\ & \mathrm{fl} \end{aligned}$ |
| FORCE and PRESSURE or STRESS |  |  |  |  |
| N | newtons | 0.225 | poundforce | lbf |
| kPa | kilopascals | 0.145 | poundforce per square inch | $\mathrm{lbf} / \mathrm{in}^{2}$ |

${ }^{*}$ 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)

## EXECUTIVE SUMMARY

This study is considered a first step towards validating the applicability of the Highway Safety Manual (HSM) Part D to Wyoming conditions. The HSM Part D provides a quantitative measure of safety of various countermeasures known as Crash Modification Factors (CMF). These 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., highwayrail crossing), and road networks. CMFs provided in the HSM Part D 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. The objectives of this study were:

1. To validate the applicability of the HSM Part D to Wyoming conditions.
2. To calibrate CMFs for various countermeasures in Wyoming.
3. 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 methodologies in case of missing key data.

In this study, massive data collection efforts have been made to develop crash modification factors. Various data sets were obtained from WYDOT, these data included construction dates, crash data acquired from the Critical Analysis Reporting Environment (CARE) software, and road geometric and traffic characteristics. Other manual data collection techniques utilizing nontraditional data sources were also developed. Pathway video logs as well as satellite imagery from Google Earth Pro ${ }^{\circledR}$ and Google Maps were manually reduced to substitute missing construction dates, and to obtain accurate roadway geometric characteristics.

Depending on collected and imputed data, various observational before-after and cross-sectional techniques were adopted. In this study, CMFs for six countermeasures applied to roadway segments, intersections, and special facilities were calibrated. The observational before-after technique included naïve before-after, and before-after with Empirical Bayesian (EB) were utilized. Other techniques such as odds ratio and the ratio of odds ratio were also developed. Wyoming-specific simple and full Safety Performance Functions (SPFs) were calibrated as part of the CMFs development process. Variation in energy related activities between different counties was also taken into consideration while developing Wyoming-specific SPFs. Several roadways in Wyoming encounter high truck traffic because of oil and gas industries. SPFs were developed for oil counties and non-oil counties based on oil and gas developments and productions in the state, in addition to calibrating CMFs of the selected countermeasures for the two groups of counties.

The countermeasures considered in this study were; 1) passing lanes, 2) shoulder rumble strips, 3) regulatory headlight signs, 4) adding left-turn lane(s) at signalized intersections, 5) adding right-turn lane(s) at signalized intersections, and 6) snow fences on rural mountainous freeways.

This study provided a set of methodologies to collect and impute data required for the application of the HSM Part D. 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 severity.

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## LIST OF ACRONYMS/ABBREVIATIONS

| Acronym | Description |
| :---: | :---: |
| 3D | Three Dimensions |
| 4SG | four-leg signalized Intersections |
| AADT | Average Annual Daily Traffic |
| AASHTO | American Association of State Highway and Transportation Officials |
| AIC | Akaike Information Criterion |
| C | Calibration Factor |
| CARE | Critical Analysis Reporting Environment |
| CG | Comparison Group |
| CI | Confidence Interval |
| CMFs | Crash Modification Factors |
| CMVSS | Canada Motor Vehicle Safety Standard |
| DOC | Degree of Curvature |
| DOT | Department of Transportation |
| DUI | Driving under Influence |
| DRLs | Daytime Running Lights |
| EB | Empirical Bayes |
| EUD | European Union Directive |
| exp | Exponential |
| F+I | Fatal and Injury |
| FARS | Fatality Analysis Reporting System |
| FHWA | Federal Highway Administration |
| FMVSS | Federal Motor Vehicle Safety Standard |
| GES | General Estimate System |
| GIS | Geographic Information System |
| GM | General Motors |
| HSIS | Highway Safety Information System |
| HSM | Highway Safety Manual |
| KDE | Kernel Density Estimation |
| KDE | Kernel Density Estimation |
| LN | Log-Normal Model |
| MADIS | Meteorological Assimilation Data Ingest System |
| MUTCD | Manual on Uniform Traffic Control Devices |
| MVMT | Million Vehicle Miles Traveled |
| NB | Negative Binomial |
| NCEI | National Centers for Environmental Information |


| Acronym | Description |
| :--- | :--- |
| NCEP | National Centers for Environmental Prediction |
| NCHRP | National Cooperative Highway Research Program |
| NHTSA | National Highway Traffic Safety Administration |
| NOAA | National Oceanic and Atmospheric Administration |
| OR | Odds Ratio |
| PDO | Property Damage Only |
| PL | Passing Lanes |
| RHR | Roadside Hazard Rating |
| ROR | Ratio of Odds Ratio |
| RTM | regression to the mean |
| RTM | Regression to the Mean biasness |
| SE | Standard Error |
| SHSP | Wyoming Strategic Highway Safety Plan |
| SPFs | Safety Performance Functions |
| SRS | Shoulder Rumble Strips |
| SVROR | Single Vehicle Run-Off Road |
| SW | Shoulder Width |
| TEVs | Total Entering Vehicles |
| TRB | Transportation Research Board |
| VG | Vertical Grade |
| VMT | vehicle miles traveled |
| vpd | vehicle per day |
| WSDOT | Washington State Department of Transportation |
| WSI | Weighted Severity Index |
| WY | Wyoming |
| WYDOT | Wyoming Department of Transportation |
| ZINB | Zero Inflated Negative Binomial |
| ZIP | Zero Inflated Poisson |

## CHAPTER 1-INTRODUCTION

The Highway Safety Manual (HSM) is a result of extensive work led by the Transportation Research Board (TRB) committee on highway safety performance. After more than two decades of research, the first edition of the HSM has been published in 2010 by the American Association of State Highway and Transportation Officials (AASHTO). The HSM is considered as the sole national source to scientifically quantifying the safety performance of roadway facilities and evaluate the safety effectiveness of countermeasures. While the HSM is based on sophisticated and advanced statistical methodologies, it has a distinct goal of bridging the gap between research and practice. The HSM has the potential to produce efficient safety analyses that can be adopted by highway agencies and safety practitioners.

The National Cooperative Highway Research Program (NCHRP 17-50) conducted the "Lead State Initiative for Implementing the Highway Safety Manual" project. The goal of this initiative 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 1.


Figure 1: Lead States and Support States in the "NCHRP 17-50 HSM Lead State Initiative Project".

The HSM should also be integrated into the different highway project development process. In 2012, the Federal Highway Administration (FHWA) provided a guide 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. States DOTs and researchers are keen to work on simplifying the process of the application of the HSM. Florida [3], [4], and [5], Utah [6], Kansas [7], and Oregon [8], have already worked on calibrations and modifications of the Safety Performance Functions (SPFs) in the HSM on their own roadways. Although other states have calibrated their own SPFs and Crash Modification Factors (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.

## HIGHWAY SAFETY MANUAL ORGANIZATION

The HSM is organized into the following four parts: 1) Part A - Introduction, Human Factors, and Fundamentals of Safety, 2) Part B - Roadway Safety Management Process, 3) Part C Predictive Methods; and, and 4) Part D - Crash Modification Factors.

The HSM Parts C and D provide acts to predict the frequency and severity of different crash types, and to quantify the safety impact of particular countermeasures. The methodologies provided in HSM parts C and D enable transportation agencies to compare predicted and expected number of crashes for a certain roadway treatment. They also quantify the change in predicted crashes as a result of different treatments implementation, which allows comparing the safety benefits for different countermeasures.

The HSM part C predicts crash frequencies utilizing safety performance functions (SPFs) [9]. SPFs provided in the HSM are crash prediction models relating crash frequencies to site characteristics (e.g. AADT, vertical grades, the rate of curvature, lane width, shoulder width, weather conditions etc.). Historical crash data in a certain jurisdiction or regions with similar roadway and traffic characteristics, driver population, and weather condition are used to develop the SPFs.

The HSM Part D provides Crash Modification Factors or Functions (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 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 with Empirical Bayes (EB) is considered the most common and reliable approach to quantify the safety effectiveness of a countermeasure. The EB method can overcome the 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 Wyoming Department of Transportation (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 effects 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.


## TRANSFERABILITY AND LIMITATIONS OF THE HSM

The extreme weather conditions, challenging roadway geometry, and the rural nature of Wyoming may result in a large number of crashes and frequent closures. According to the National Highway Traffic Safety Administration (NHTSA), despite the steady reduction in fatality rates at the national level, Wyoming fatality rates are typically higher than the national level. In recent years, Wyoming fatalities have spiked to a significant rates [10]. Figure 2 shows difference between fatality rates in Wyoming and the national rates per 100 Million Vehicle Miles Traveled (MVMT). Figure 3 also shows that Wyoming has 72 percent increase in fatality rates in 2014, which is considered the greatest fatality rate surge in the last 10 years.


Source: Traffic Safety Facts 2006 to 2014
Figure 2: Fatality rates in Wyoming and U.S. from 2006 to 2014 [10].


Source: Traffic Safety Facts 2014
Figure 3: Percentage increase in fatality rates from 2013 to 2014 in the U.S. [10].

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 and mitigate crashes. However, the Simple Safety Performance Functions (SPF) presented in the HSM cannot be directly used as an accurate prediction, as it is not calibrated to Wyoming conditions.

Calibration of the SPFs presented in the HSM is necessary for full and accurate predictive capability. One of the main limitations within the first edition of the HSM is that the development of safety performance functions is based on data from few states shown in Figure 4 (California, Minnesota, Michigan, New York, Texas, and Washington State) that do not adequately represent the Rocky Mountains and Plain Regions, which has unique weather characteristics. Figure 5, shows the different climate regions, as defined by the National Oceanic and Atmospheric Administration (NOAA) [11].


Figure 4: HSM data collection states.


Source: National Centers for Environmental Information
Figure 5: U.S. Climate regions identified by NOAA.

Many factors contribute to crash occurrence. These factors may include driver behavior, traffic, geometric characteristics, weather conditions and interrelationships between these different factors. Unfortunately, the driver behavior factors are usually not available and hard to be incorporated with crash frequency analyses. Moreover, driver populations vary substantially from one location to another in age and gender distributions, driving experience, alcohol usage, cell phone usage (using hand-held mobile devices are permitted in some states and banned in others), seat belt usage, and many other behavioral factors.

Figure 6 shows a map of hand-held cell phone bans for all drivers; talking on a hand-held cell phone is banned in 14 states (Washington, Oregon, California, Hawaii, Nevada, Illinois, West Virginia, New York, Vermont, New Hampshire, Connecticut, New Jersey, Delaware, and Maryland) and the District of Columbia [12]. It is worth mentioning that the use of all cell phones by novice drivers is restricted in 37 states and the District of Columbia. Text messaging is banned for all drivers in 44 states and the District of Columbia as shown in Figure 7.


Source: Insurance Institute for Highway Safety
Figure 6: Map of hand-held cell phone bans (all drivers).


Source: Insurance Institute for Highway Safety
Figure 7: Map of texting bans.

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 in specific. 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.
- Each state of the abovementioned states has different crash reporting thresholds and using different reporting forms.
- Driving behavior and regulations in the mountain plains region are different from the aforementioned states.
- Adverse weather conditions within the region are not considered.
- The effect of specific activities in some areas (e.g., energy-related activities) are not addressed.

Resolving these issues will result in more accurate crash prediction by crash type and severity, which is crucial for the following reasons; 1) many crash modification factors (CMFs) in the HSM apply only to certain collision types or crashes at certain severity levels. Proper application of these CMFs requires accurate prediction of the number of crashes of the corresponding collision type and severity level. 2) The HSM safety management methodology includes
economic evaluation of the expected crash outcomes of road improvement scenarios. These evaluations apply standardized values of different crash severity levels to predicted crash count by severity level. Fully accounting for all the factors associated with crash severity will result in better prediction of crash counts by severity, and thus, more accurate economic evaluations.

## CHAPTER 2-LITERATURE REVIEW

This chapter provides a review of the literature on the development and application of the Safety Performance Functions (SPFs) and Crash Modification Factors (CMFs) studies in previous research. The chapter focuses on selected countermeasures implemented on roadway segments, intersections, and special facilities in Wyoming. These countermeasures included; 1) passing lanes, 2) shoulder rumble strips, 3) regulatory headlight signs, 4) adding left-turn lane(s) at signalized intersections, 5) adding right-turn lane(s) at signalized intersections, and 6) snow fences on rural mountainous freeways.

## ROADWAY SEGMENTS

## Safety Performance Functions for Roadway Segments

Safety Performance Functions (SPFs) are defined as mathematical models to predict average crash frequencies per year as a function of exposure and roadway characteristics. The Highway Safety Manual (HSM) Part C provides Safety Performance Functions (SPFs) for different roadway facilities and crash types [9]. SPFs in the HSM are developed to predict the number of crashes for a roadway segment or intersection as a function of exposure only. The exposure for roadway segments represented by the Annual Average Daily Traffic (AADT) and segment length. The SPFs presented in the HSM are developed for the base conditions (e.g., 12 ft typical lane width, 6 ft typical shoulder width, etc.). Calibration factors are used to adjust for variation from the base conditions. Another way to account for the variation from the base conditions is to use full SPFs calibrated for specific sites. The full SPFs include site-specific factors such as roadway geometry and weather conditions. As mentioned earlier, the HSM's SPFs were developed using data from a few states, which does not share the same weather or roadway characteristics as states located in the mountain plains region.

Wyoming has unique weather and road conditions compared to other states. The rural nature with relatively low traffic volumes in addition to severe adverse weather conditions may not allow for reliable and accurate transfer of the SPFs from the HSM to Wyoming-specific conditions.
Moreover, low traffic volumes in Wyoming may result in inaccurate crash prediction if simple SPFs were used. This raises the need to calibrate full SPFs to have a more reliable crash prediction models. Full SPFs could reflect and account for the effect of different geometric characteristics, traffic conditions, and weather conditions in estimating the crash frequencies.

Mehta et al. (2013) identified four different nonlinear models to predict crashes for rural twoway two-lane highways [13]. Annual Average Daily Traffic (AADT), segment length, speed limit, lane width, and shoulder width were considered as the explanatory variables in these models. Other variables such as number of access points, sight distance, and roadside hazards were also considered in other studies [14], [15], [16], [17], [18].

WYDOT developed Wyoming-specific simple SPFs where AADT is the only explanatory variable to predict crashes [19]. Chalise (2016) considered vertical, horizontal grades and truck percentages along with different weather conditions to predict crash frequency in rural two-way
two-lane highways in Wyoming for different terrains [20]. Degree of curvature, vertical grades, truck percentages, and average number of rainy and snowy days were the significant variables in the developed models. Negative Binomial (NB) Model was the statistical technique used in developing the Wyoming full SPFs obtained in the study. Garber et al. (2000) found speed limit was correlated with crash frequency and Bradford et al. (2012) found number of crashes increases with higher speed limit [21] and [6]. Hauer (1999) showed rural roads experience more crashes with wider lane widths [22]. Mayora et al. (2003) found a significant correlation between crash frequency and access density, proportion of no passing zones and sight distance [14]. In addition to the aforementioned variables, AADT, shoulder width and lane width were found to be significant in developed SPFs [6], [13], [14], [21], and [22]. Most of the aforementioned studies used Negative Binomial model. Other techniques utilized in the literature were univariate and multivariate linear regression models, Zero Inflated Poisson (ZIP), Zero Inflated Negative Binomial (ZINB), Lognormal, and full Bayesian. Calibration of site-specific full SPFs for roadway segments is of immense importance, as evidenced by growing literature and transportation initiatives.

## Countermeasure for Roadway Segments

## Shoulder Rumble Strips

Shoulder Rumble Strips (SRS) are defined as a series of raised or grooved strips or stripes along the sides of a roadway producing vibrotactile and audible warnings to inattentive drivers departing their lanes [23]. Shoulder rumble strips were first implemented in 1955 on 25 miles of New Jersey's Garden State Parkway [24]. Starting from 1960, different states implemented SRS in a variety of forms. At present, more than 85 percent of the states use shoulder rumble strips in their roads [25]. Wyoming Department of Transportation (WYDOT) started a SRS statewide practice of implementing starting 2002.

## Design and Application of Shoulder Rumble Strips

There are four common types of rumble strips; rolled in, milled in, formed, and raised rumble strips [26]. These different types of SRS vary in the method of installation, shapes, size, and the amount of produced vibrations and noise. Rolled in rumble strips were very common in the US and Canada until the milled in rumble strips replaced it due to their advantages. Rolled in rumble strips are implemented by pressing a series of steel pipes welded to rollers into hot asphalt during construction. This type of rumble strips is cheap to install but there are some issues with respect to maintenance and reconstruction [27]. Milled in rumble strips are simply grooves with specific measurements cut into the pavement by a milling machine. The FHWA prefers milled in rumble strips because of their easy installation on existing asphalt or concrete, efficiency in producing noise and vibration, and little effect on the integrity of the pavement structure [28]. Formed rumble strips are implemented at the same time of pavement construction similar to rolled in but have similar dimensions to milled in ones. This type of rumble strips lack consistency and have some installation limitations during operations of the pavement similar to milled rumble strips [26].

Raised rumble strips are usually rounded in shapes and used in warmer areas where snow removal is not required. Among all four types of rumble strips, milled in rumble strips are most widely used as they can be applied during or after the pavement construction and they are more effective [26]. WYDOT also prefers milled in type rumble strips. However, applying them on short roadway segments is not cost effective. Combining several segments together forming a significant miles of pavement sections that should receive rumble strips to provide a statewide contract would be a more cost effective application system.

Rolled in and formed rumble strips are rounded or V-shaped grooves with 1.2 inch deep in general and varying width from 1.57 inch to 2 feet. Raised rumble strips vary from 2 inch to 12 inch in width and 0.25 inch to 0.5 inch in height. Typical milled in rumble strips are 5 inch to 7 inch wide and 0.5 inch deep. Some states use 4 inch width but 6 inch width is more preferable. There is also 12 inch to 16 inch intermittent spacing provided to accommodate other road users [29].

Different states have their own practices to design and implement rumble strips. For example, SRS are installed on two-lane two-way highways in North Dakota, where the typical shoulder width is 4 feet, whereas Washington installed SRS where there is a minimum 4 feet offset between the SRS and the outside edge of the shoulder to accommodate bicyclists [29].

In Wyoming, SRS are implemented considering different factors such as lane departure crashes, shoulder width, guardrail, lateral clearance, etc. Ahmed et al. collected the preferences of WYDOT's engineers on the best way to accommodate all road users while implementing rumble strips utilizing a survey questionnaire. The survey answers were collected from 45 engineers at WYDOT. The analysis of the survey reflected that 4 feet clearance width is recommended for all types of roads except urban two-lane highways [29]. WYDOT also prefers different spacing, width and depth of the shoulder rumble strips depending on the road classification and existing geometric conditions. Continuous rumble strips was mostly preferred for interstates. On the other hand, intermittent SRS were favored for non-interstate highways to better accommodate bicyclists. For a shoulder width of 8 feet or more, 16 -inch wide rumble strips were specified. For shoulder width ranging between 6 feet to 8 feet wide shoulder width, 12 -inch wide rumble strips were recommended. WYDOT recommends 12 feet gap after 48 feet continuous rumble strips for intermittent types. SRS are more common compared to centerline rumble stripes, WYDOT installed centerline rumble strips recently in 2016. Rumble strips are, typically, 7 inches wide with 5 inches spacing in between unless specified otherwise. Depths are between $1 / 2$ inch to $5 / 8$ inch for interstates and $3 / 8$ inch to $1 / 2$ inch for non-interstate highways [26].

Crash Modification Factors for Shoulder Rumble Strips
The Highway Safety Manual (HSM) Part D and CMF Clearinghouse provide quantitative expression of the safety effectiveness of different countermeasures on various roadway facilities. The application of CMFs involves evaluating the expected average crash frequency with or without a particular treatment [9]. For example, shoulder rumble strips has a CMF of 0.84 for all crashes when installed in rural area but has a CMF of 0.99 when installed in urban area [30]. Shoulder rumble strips are installed primarily to reduce Single Vehicle Run-Off Road (SVROR) crashes. Several studies evaluated the safety efficacy of SRS in the US. Shoulder rumble strips
were found to reduce 36 percent of SVROR crashes on average as reported in the NCHRP 641 report [30]. The report also showed a reduction of total crashes by 21 percent. Kansas, Washington, Massachusetts, and Pennsylvania reported 3, 18, 42, and 60 percent reduction in SVROR crashes, respectively.

A recent study in 2013 from Washington State Department of Transportation (WSDOT) indicated that SRS resulted in 12, and 40 percent for lane departure, and SVROR crashes, respectively [31]. Another study reported that the safety effectiveness increases with the increase of shoulder width with shoulder rumble strips [32]. A study in California concluded 90 percent and 42 percent reduction in fatal, and total head-on crashes after installing SRS, respectively [33]. Different states have different CMFs for SRS ranging between 7 percent to 41 percent reduction in total crashes because of different traffic and geometric conditions [28]. A previous study in Wyoming showed that implementation of shoulder rumble strips can have an effect from no reduction to a reduction of total and $\mathrm{F}+\mathrm{I}$ crashes by 1 to 29 percent using Weighted Severity Index (WSI), based on simple before-after crash frequency only [24]. It is worth mentioning that this methodology may underestimate or overestimate the safety effectiveness of SRS due to the regression to the mean bias (RTM). Observational before-after with Empirical Bayes (EB) is recommended to provide more reliable assessment of the safety effectiveness of countermeasures.

## Passing Lanes

A passing lane is an intermittently spaced additional lane on a two-way two-lane highway. Passing lanes provide drivers the opportunity to pass without having to cross into opposite traffic direction. Passing lanes are primarily installed to improve operation and level of service; they also have significant safety benefits. Passing lanes are useful to reduce the delays resulting from following slower moving heavy vehicles, like trucks and recreational vehicles. This could frustrate the following vehicle's driver leading him to take risky decisions to overtake the leading vehicle. Installing passing lanes are commonly chosen as cheaper alternative to adding lanes or dividing the highways.

## Design and Application of Passing Lanes

Different configurations are used for passing lanes for example, isolated, separated, tail-to-tail, head-to-head, alternating, overlapping, and side by side [34]. Isolated passing lane segments are implemented on separate places, only on one side of the roadway. Separated passing lane segments are provided on the both directions of the roadways but with no overlap. Head to head or tail to tail passing lanes segments are provided in both directions such as both passing lanes start from the same point or end at the same point, respectively. Alternating passing lanes segments are combination of few head-to-head type of orientation. Overlapping passing lane segments have common roadway segments of four-lane in total. Side by side passing lanes are actually four-lane undivided roadway segment for the specific portion of the roadway. The level of service increases generally with the increase of the frequency of the passing lanes [35]. The length of passing lanes might vary from 0.25 miles to 5 miles [34] [36].

The HSM provides a CMF of 0.75 for implementing a passing lane segment in one direction of travel on rural two-lane highways [9]. The HSM also provides a CMF of 0.65 for short four-lane sections for total crashes. This CMF applies to limited distance to increase passing opportunities [9]. However, specific sites with different traffic, geometric and weather conditions may result in different CMF values. A study in Missouri concluded that roadway sections with passing lanes have 12 percent to 24 percent lower crash rates than the roadway sections without passing lanes depending on the road classifications [36]. Only crash frequencies and AADT were taken into account for this comparison study. For two-way two lane highways, the comparison was conducted between 26 miles of roadway segments with passing lanes and 568 miles of roadway segments without passing lanes. Five years data from 1997 to 2001 were utilized for the analysis. The roadway segments with passing lanes were found to have 20,19 , and 21 percent lower crash rates for total, F+I, and PDO crash rates, respectively. Another study conducted by Fitzpatrick et al. concluded that passing lanes reduce total crashes by 25 percent and $\mathrm{F}+\mathrm{I}$ crashes by 30 percent in Texas [37]. Persuad et al. (2013) conducted a study in Michigan, using 231 treated segments [38]. It was found that the passing lane segments reduce total and injury crashes by 4 and 51 percent, respectively. An initial study by Schumaker et al. conducted in Wyoming found that passing lanes were 42 and 33 percent effective in reducing total and $\mathrm{F}+\mathrm{I}$ crashes using observational before after with Empirical Bayes (EB). The study was conducted on a 26 miles rural two-lane highway segment on WY 59. The study corridor had 9 passing lane segments comprising a total of 10 miles [35]. The study used simple SPFs to predict the expected crash frequencies in the EB analysis. In this study, full SPFs were developed to predict crash frequencies more accurately and to provide more reliable CMFs.

## Regulatory Headlight Signs

No doubt turning on headlights increase vehicles' conspicuity during daytime, dusk, and dawn. Daytime Running Lights (DRLs) are a low cost technology used to enhance traffic safety by reducing the potential of having a crash. Several researchers were concerned about the safety benefits of using such technology. Some contradicting findings were introduced in the literature providing vague conclusion of the safety effectiveness of DRLs.

Regulatory headlight use sign are traffic control devices to mandate motorists to turn on their vehicle's low-beam headlights manually on certain roadway sections. Headlight use sign is considered a compliance-based countermeasure which may introduce limitations in analyzing their safety effectiveness. Several confounding factors might be presented when analyzing its safety effectiveness such as compliance rates and DRLs technology penetration.

## Daytime Running Lights (DRLs)

In early 1990, several European countries (Denmark, Finland, Hungary, Norway, and Sweden) as well as Canada mandated vehicles to turn on their headlights continuously as a road safety measure. Various studies have proven that DRLs are a statistically efficient measure to reduce multiple-vehicle crashes in daytime, dawn, and dusk. Due to the low ambient light levels in Ireland, where it is permanently dark during the winter, the use of low-beam headlights is
encouraged in daytime. The use of DRLs in Italy, Hungary, and Romania is required outside populated areas, i.e., rural areas, at all times. Turning on low-beam headlights at daytime on certain roads at certain times of year were required in many European countries including Germany, Spain, and France [39], [40], [41], and [42].

Canada Motor Vehicle Safety Standard (CMVSS) required all new vehicles made or imported after January 1990 to come equipped with automatic DRLs. Automakers opposed the DRLs new laws because of the extra cost of adding an additional front lighting device, warranty, and the increased potential of bulb replacement. Later on, the use of reduced-wattage high beam headlamps was allowed. In addition, light color from white to amber or yellow was permitted [43]. In 2011, all passenger cars and vans were required to be equipped with DRLs according to the European Union Directive (EUD). Recently in 2012, the mandate was extended to comprise trucks.

Permitting to manufacture vehicles equipped with DRLs were first discussed in the United States in 1990. However, it was objected by the National Highway Traffic Safety Administration (NHTSA) based on high-intensity that might lead to potential glare issues and problems with turn signal masking. In 1993, DRLs were permitted, but not mandated, in the U.S. [44]. General Motors (GM) equipped most of its vehicles starting 1995 to reduce the automotive manufacturing variation in the North American market. By 1997, all GM vehicles come standard -equipped with DRLs. Federal Motor Vehicle Safety Standard (FMVSS) No. 108 limits the DRLs maximum light intensity output to 7,000 candelas, which represents 10 percent of the standard high-beam headlamp intensity. Because of plentiful complaints regarding the glare resulting from the DRLs, the intensity output was further reduced to 1,500 candelas in 1998. In addition to glare, a study showed that DRLs might make motorcycles, pedestrians, and bicyclists less conspicuous and that DRLs would have an environmental impact [45].

## Crash Modification Factors for DRLs

While several studies showed a positive safety effect of using DRL during daytime, other studies showed that DRLs does not have a significant safety benefits to reduce certain types of crashes. The effect of using DRL is still up to debate [46]. Most of the studies that were conducted to investigate the effect of DRL showed some safety benefits. However, nearly all of these studies have design or analysis weaknesses, which may introduce complications to estimate the true effect of DRL [47]. Elvik et al. 1993, also stated that the evidence to conclude the safety effectiveness of DRL was not firm from a scientific point of view [39]. A reduction of 10 to 15 percent in the number of multivehicle daytime crashes using 17 studies were obtained using a log-odds meta-analysis [48]. Some safety benefits of DRLs were revealed in a study by the National Highway Traffic Safety Administration (NHTSA) in 2004 [49]. Six years of data, 19952001, from the Fatality Analysis Reporting System (FARS) and the General Estimate System (GES) were analyzed utilizing the generalized simple odds, which is considered a conventional statistical technique. DRLs were proven to reduce certain types of crashes. The study showed a 5 percent reduction in opposite direction daytime fatal crashes in addition to a 5 percent reduction in opposite direction/angle daytime non-fatal crashes. Crashes involving non-motorists was also reduced by 12 percent, i.e. pedestrians and cyclists, in addition to a 23 percent reduction in opposite fatal crashes of a passenger vehicle with a motorcycle. It is worth mentioning that the
study controlled for a variety of factors other than DRLs; however, none of these results were found to be statistically significant using odds ratio.

On the other hand, contradicting findings were concluded in a large-scale study conducted by the NHTSA in 2008. Except for a 5.7 percent reduction in the light trucks/vans crashes involved in multi-vehicles crashes, the study showed that the DRLs were statistically insignificant in reducing the studied crash types [50]. Elvik (1993) showed that the total number of multiple vehicles, pedestrian, and twilight crashes were not reduced [39]. Also, the rear end crashes increased by 20 percent. It was also stated that daytime multivehicle crashes were reduced only during the summer by about 1.5 percent. Another study concluded that the data fail to show a clear effect of DRL [51].

## Headlight Use Signs

A study conducted by FHWA recommended to standardize the headlight signs due to the wide variation in the legends used for signs that require road users to turn on their vehicle headlights under certain conditions [52]. Moreover, the regulations of these signs depend on laws that vary from State to State. As an example, Wyoming State requires motorists to turn on low-beam when having rain or any adverse weather conditions. On the other hand, according to the Colorado driving handbook, the use of headlights in adverse weather conditions is not mandated. Due to the variation of regulations across the nation, the FHWA added a new section titled "Headlight Use Signs" in the latest edition of the Manual on Uniform Traffic Control Devices (MUTCD), 2009 [53], to provide uniformity of the sign wording. The Federal Highway Administration (FHWA) replaced the "TURN OFF HEADLIGHTS" sign with "END DAYTIME HEADLIGHT SECTION" as it might provide a misleading message to road users during night-time.

According to the FHWA Office of Safety, lane departure crashes represent 53 percent of annual fatal crashes in 2015 [54]. A lane departure crash includes runs off the road crashes, opposite direction sideswipe crashes and head-on crashes.

The Wyoming Strategic Highway Safety Plan (SHSP), 2012, identified six categorizes which have high potential of crash reduction [55]. The identified six categories were: 1) roadway departure crashes, 2) use of safety restraints, 3) impaired driving, 4) speeding, 5) young drivers, and 6) curve crashes. Among the six determined categories, lane departure consistently produced the highest number of crashes from 2002 to 2010 as shown in Figure 8.

The Wyoming SHSP indicated that lane departure crashes comprised 72 percent of all severe crashes for the years 2008-2010. As a result, the Wyoming SHSP considered these types of crashes as a priority to reduce fatal and serious injury crashes. These types of crashes are often dominated by distracted driving, failure to identify surrounding vehicles, and poor visibility due to inclement weather conditions.

Seven roadway sections in Wyoming utilized the MUTCD "Turn on Your Headlights for Safety Next XX Miles" headlight sign as shown in Figure 9. All roadways having the headlight signs are classified as principal or minor arterial two-way two-lane roads. The first implementation of
the signs was back in 1994 on US287/WY789. The latest signs were implemented in 2012 on WY220 and WY59.


Source: Wyoming Strategic Highway Safety Plan, 2012
Figure 8: Wyoming's Critical Crashes (Incapacitating Injury and Fatal) 2002-2010.


Source: Wyoming Department of Transportation
Figure 9: Headlight Sign Locations in Wyoming.

## INTERSECTIONS

Intersections are at-grade junctions, where two or more roadways cross each other. Roadways include major arterials, minor arterials, collectors and local roads. Intersections are prime places for motor vehicles', bicyclists', and pedestrians' crashes. Vehicles are conflicting with each other while attempting to cross, or turn. Signalization at intersections allow the shared use of road space by separating conflicting movements temporally, which enhance the mobility and safety of traffic movements.

## Safety Performance Functions of Intersections

There are prolific published studies related to intersections explaining numerous relationships between crash frequencies and traffic flows over the years. Safety Performance Functions (SPFs) are used to impart relationships of crash frequency with the measure of exposures [56]. Hauer et al. (1988) stated that intersection crash frequencies correlate directly to the amount of Total Entering Vehicles (TEVs) at that intersection [57]. The authors explained that the advantage of using TEVs, as the only predictor, is 'simplicity' but it might not be suitable for a comprehensive engineering analysis. This approach could be applicable if it were possible to control for other sundry factors such as weather, and driver characteristics in addition to assuming same geometric configurations for all intersections. Generally, full SPFs explain the predicted crash frequencies using roadway geometric characteristics, traffic, and drivers' characteristics [58].

Several studies were conducted in the past to determine the negative impact of drivers' behavior and adverse weather on traffic safety. A study by Shyhalla used 1.4 million motor vehicle crashes from the NHTSA database to evaluate the contribution of other factors such as alcohol involvement to crash initiation and crash severity [59]. Crash data including roadway segment and intersection crashes, collected from multiple police jurisdictions of the United States were used to associate between alcohol involvement and crash initiation. The results showed an increased likelihood of initiating 2 -vehicle crashes and crash severity with alcohol involved driving. As Driving under Influence (DUI) drivers were less likely to use seat-belts, drove faster and were more likely to be distracted than others, which are considered risky driving behaviors. There are also some considerable researches on the impact of adverse weather conditions such as snow, rainfall, and fog on traffic safety. According to the Federal Highway Administration (FHWA), approximately 22 percent of the annual crashes in the US (nearly 1,259,000 crashes) are weather-related crashes. Adverse weather causes poor visibility of intersection control devices and conflicting road users and hence is considered a major cause of intersection related crashes [60]. Booz Allen Hamilton analyzed data from the NHTSA from 2005 to 2014 on causes of crashes. Based on their report, it was found that weather played a role in 22 percent of vehicle crashes on average, as well as 19 percent of crash injuries, and 16 percent of crash fatalities [61].

Many studies have provided methodological concepts to predict intersection crashes. A study using highway safety database administered by the FHWA. The study demonstrated that the conventional linear regression models lack the distributional property to describe adequately the random, discrete, nonnegative and typically sporadic accident events on the road [62]. The use of Poisson regression model has some desirable statistical properties in developing relationships but it may overstate or understate the likelihood of crashes for overdispersed data. The Negative

Binomial (NB) or double Poisson distribution should be used to overcome the overdispersion property of crashes [63].

## Adding Left- and Right-Turn Lanes at Signalized Intersections

Turn lanes are used to separate turning traffic from through traffic. Turning movements at intersections that are made from shared high-speed through traffic lanes may cause delays and impose severe negative impacts on safety [64].

Installation of left-turn and right-turn lanes at intersection has been investigated by researchers for years in various states in the U.S. A study in Nebraska developed safety performance functions for signalized rural and suburban intersections using data from 1988 through 2000 [65]. Negative Binomial regression models were used to accommodate the overdispersion of crash data. The result suggested that natural log transformed traffic volume, area type, roadway horizontal and vertical alignment, and type of left-turn lane (offset left-turn lane) statistically significantly affect the frequency of intersection approach crashes. The model showed increased crash frequency with increasing values of natural logarithm of the exposure, i.e., Total Entering Vehicles. While the presence of offset left-turn lanes decreased number of crashes, raised medians on minor approaches contributed to an increase in the number of expected crashes on the minor approach. The study also investigated crash rates by crash type. The result of the study indicated that rear-end crashes have the highest rate among all crash types on major approaches at four-leg signalized intersections.

A study by Lyon et al. was conducted in Canada to develop SPFs for urban signalized intersections [66]. Crash data obtained from 1950 urban signalized intersections, from 1996 to 2000, were used to develop SPFs for different severity levels. The analyses showed that adding a left-turn lane at major approach of four-leg intersections was significant for PDO crashes. In addition, the effect of $\mathrm{F}+\mathrm{I}$ crashes was found to have low insignificance on 85 percent significance level. On the other hand, an added right-turn lane, at a major approach was not significant in all investigated crash severity types. However, for minor approaches, it was significant for PDO crashes. Yet, it was not included in the full SPFs as it had a high correlation with a left-turn lane.

Harwood et al. performed a well-designed before-after evaluation of the safety efficacy of providing left and right-turn lanes at urban four-leg signalized intersections. Two hundred and eighty treated signalized intersection and 300 similar control sites were analyzed. The study found that installation of a left-turn lane on one major-road approach at signalized intersections reduces total crashes by 18 percent. A reduction of 33 percent of total crashes was found when left-turn lanes are installed on both major-road approaches [67].

The Federal Highway Administration (FHWA) reported that the addition of right-turn lanes at four-leg signalized intersection decreased multiple vehicle total crashes by 11 percent [68].

## Design and Application of Adding Left and Right-Turn Lanes

Adding left- and right-turn lanes are most often chosen for operational reasons. In some cases, adding left- and right-turn lanes at signalized intersections may represent a trade-off between safety and mobility. Several conflicts which are from bicyclists, opposing through traffic, through traffic in same direction and crossing traffic often lead to angle, same direction sideswipe, and rear-end crashes [64]. The demand for a left-turn movement might be used sometimes for operational treatments to minimize the amount of green time that is allocated to left-turn movements.

## Crash Modification Factors for Intersections

In the same manner as developing Safety Performance Functions (SPFs), development of Crash Modification Factors or Functions (CMFs) should be state specific. According to Ezra Hauer, 2012, CMFs are random variables and are not universal constants that apply everywhere at all times [69]. The Federal Highway Administration (FHWA) suggested developing state specific SPFs to account for local road conditions, crash severity, injury severity, collision manner and weather conditions for roadway segments as well as intersections.

## ITS AND SPECIAL FACILITIES

## Snow Fence

## Design and Application of Snow Fence

The actual calculation and design work that goes behind snow fences is relatively straightforward. Compared to many other current roadway safety technologies and practices, snow fences come with a simple process of design and implementation. Additionally, due to the fact that snow fence design is not a new practice, the design recommendations and practices have been significantly refined and simplified over time. Mostly fundamentally, snow fence performance (commonly quantified by the amount of material retained) is primarily a function of geometry. More specifically, performance is primarily a function of fence porosity and height (additionally and less significantly of length, angle, inclination, material, and surrounding topography) [70]. Figure 10, provided by a Montana report, illustrates the relationship between fence height and water storage (when water and snow are used interchangeably, which is common among snow fence related literature, it is useful to know that there is typically a 1:10 snow to water ratio assumed) [71].


Source: ISSW
Figure 10: Simple Relationship between Fence Height and Storage Capacity [71].

While the understanding of this relationship is essential, it still must be realized that additional snow fence characteristics, such as inclination angle, can also greatly affect storage capabilities. The most significant of these additional characteristics is porosity. Porosity is defined as the ratio, or percentage, of open area to the total frontal area excluding the bottom gap [70]. Figure 11 displays storage geometry as a function of fence height, but for varying porosity values [70].


Source: Tabler and Associates
Figure 11: Storage Capabilities at Various Porosities [69].

Additionally, storage quantities and densities are crucial in maintaining targeted or desired snow storage, so that the purpose of the fence can be efficiently achieved. Figure 12 displays the relationship between snow density and snow depth.


Source: Tabler and Associates
Figure 12: Snow Density Change with Depth [69].

Currently, the Wyoming Department of Transportation (WYDOT) utilizes snow fences made primarily from wood, with steel reinforcement and fastening, referred to as anchor clips. Standard plans for snow fence construction call for 12 ft panels of fences with a maximum gap of 1 " between each, as well as a typical offset height of 1.5 ft . A typically inclined fence would have a bracing angle of 62 degrees (measured from the ground on the interior of the fence) and a front panel angle of 75 degrees (also measured the interior of the fence). Also, according to the WYDOT Winter Research Department, the agency now focuses on two individual inclined structural fence sizes, 10 and 12 feet.

## Weather Considerations

In 2007, the Wyoming Department of Transportation implemented numerous snow fences along Interstate 80. In this study, there will be an investigation conducted on an area stretching from MP 325 to MP 344 that includes a very high density of snow fence implementations. This particular stretch of roadway is part of one that is notoriously hazardous during the winter weather season and adverse weather conditions. This is at least partially due to the elevation and geographic characteristics of this area. The roadway elevation in this section reaches a high point of approximately 8,880 feet ( 2,707 meters). This elevation, combined with precipitation rates seen during the primary snow accumulation season, creates an area in which roadway conditions can be highly affected by adverse weather conditions. Figure 13 demonstrates how an increase in elevation affects the length of the snow accumulation season in Wyoming.


Source: Tabler and Associates
Figure 13: Effect of Elevation on the Snow Accumulation Season in Wyoming [69].

According to the Wyoming State Climate Office (WSCO), this area has approximately 12-18 days of snow annually that exceeds 5 inches per day with a maximum 24 hour snowfall amount of 23-26 inches [72]. Additionally, this area can receive anywhere from 63-140 inches of snowfall for an entire year.

In order to better understand the weather in this area, forecasted data was developed for three adjacent $12 \mathrm{~km}(7.46 \mathrm{mi})$ sections covering the investigated roadway segment. From these data, weather patterns over winter seasons (October 15 through April 15), can be analyzed.

In addition to the adverse weather conditions that are seen in this area, the composition of traffic along this roadway tends to be heavily commercially based (approximately 46 percent). In the presence of adverse weather conditions, commercial motor vehicles have shown increased susceptibility to crashes of a higher severity [73]. The United States Department of Transportation (USDOT) and the Federal Motor Carrier Safety Administration (FMCSA) have found that, in the event of snow, commercial motor vehicles can experience approximately 2.67 times the fatal weather related crashes than all other vehicles [73]. This high percentage of commercial traffic, combined with the snowfall rates and adverse weather conditions, as well as high interstate travel speeds ( 75 MPH posted speed, Variable Speed Limit (VSL) systems were initially implemented in Wyoming in 2009) creates a roadway environment that, during the snowfall season, can be extremely problematic to properly maintain in terms of roadway condition and safety.

## CHAPTER 3-METHODOLOGIES

This chapter provides a description of the various methodologies used in this study to calibrate Wyoming-specific Safety Performance Functions (SPFs) and to develop Crash Modification Factors (CMFs) for a subset of countermeasures selected by the Wyoming Department of Transportation (WYDOT). These methodologies ranged from spatial geographical analyses, regression models with various distributions, observational before-after studies, and crosssectional analyses.

## KERNEL DENSITY ESTIMATION

Various spatial techniques were utilized to assist producing a smooth density surface of spatial point events. Among these techniques, the Kernel Density Estimation (KDE) was pointed out as the most promising tool by Chainey et al. and Sabel [74] and [75]. This method can determine the spread of risk of crashes. The spread of risk can be defined as the area around a defined cluster in which there is an increased likelihood for a crash to occur based on spatial dependency. This method also defines an arbitrary spatial unit of analysis homogeneously for all areas which make comparison easier. The KDE has been widely used to assist in decision-making to allocate resources.
"Kernel density estimation involves placing a symmetrical surface over each point, evaluating the distance from the point to a reference location based on a mathematical function, and then summing the value for all the surfaces for that reference location. This procedure is repeated for all reference locations" [76]. This, therefore, allows us to place a kernel over each crash observation, and summing these individual kernels gives the density estimate for the distribution of crash points by Equation 3-1 [76].
$f(x, y)=\frac{1}{n h^{2}} \sum_{i=1}^{n} K\binom{d_{i}}{h}$
Equation 3-1

Where,
$\mathrm{f}(\mathrm{x}, \mathrm{y})$ : density estimate at the location ( $\mathrm{x}, \mathrm{y}$ );
$\mathrm{n} \quad$ : number of observations,
h : bandwidth or kernel size,
K : kernel function, and
Di : distance between the location ( $x, y$ ) and the location of the ith observation.
In this method, a circular area (the kernel) of defined bandwidth is created around each point at which the indicator is observed. This takes the value of the indicator at that point spread into it according to some appropriate function. Summing all of these values at all places, including those at which no incidences of the indicator variable were recorded, gives a surface of density estimates. Density can be measured by two methods; 1) Point Density and 2) Kernel Density.

The kernel density method divides the entire study area into predetermined number of cells. Rather than considering a circular neighborhood around each cell (the point density method), the kernel method draws a circular neighborhood around each feature point (the crash) and then a
mathematical equation is applied that goes from one at the position of the feature point to zero at the neighborhood boundary [77].

## SAFETY PERFORMANCE FUNCTIONS

Safety Performance Functions (SPFs) are mathematical models used to predict average crash frequencies per year as a function of exposure and roadway characteristics. The predictive methods in the HSM offer safety performance functions (SPFs) as a quantitative measure for estimating yearly expected crash frequencies for base conditions. The base conditions for roadway segments on rural two-lane two-way roads as provided in the HSM are [9]:

- Lane width
- Shoulder width
- Shoulder type
- Roadside hazard rating (RHR)
- Driveway density
- Horizontal curvature
- Vertical curvature
- Centerline rumble strips
- Passing lanes
- Two-way left-turn lanes
- Lighting
- Automated speed enforcement
- Grade level

12 feet.
6 feet.
Paved.
3.

5 driveways per mile.
none.
none.
none.
none.
none.
none.
none.
Zero percent.

The HSM provides 18 steps, shown in Figure 14, to estimate the number of crashes by developing site-specific SPF. The predicted average number of crashes is estimated providing the base SPF, followed by calculating the Crash Modification Factors (CMFs), which adjusts for the site-specific conditions, and calibration factor C , which adjust the estimate for accuracy in the state or local area [9].

These components are combined in the general form provided in Equation 3-2 [9]:

$$
\left(\mathbf{N}_{\text {predicted }}\right)=N_{\text {spf }} \mathbf{x}\left(\text { CMF }_{1} \times \text { CMF }_{2} \times \ldots \ldots \times \text { CMF }_{\mathrm{yz}}\right) \times \mathbf{C}_{\mathrm{x}}
$$

Equation 3-2
Where,
$\mathrm{N}_{\text {predicted }}$ : predicted average crash frequency for a specific year for site type x ;
$\mathrm{N}_{\text {spf }}$ : predicted average crash frequency determined for base conditions of the SPF developed for site type x ;
$\mathrm{CMF}_{\mathrm{nx}}$ : crash modification factors specific to SPF for site type x ; and
$\mathrm{C}_{\mathrm{x}} \quad$ : calibration factor to adjust SPF for local conditions for site type x .
Each predictive model is specific to a facility or site type and a specific year. It should be noted that the predictive method can be used to predict crashes for past years based on observed AADT or for future years based on forecasted AADT.


Source: HSM 2010
Figure 14: HSM Predictive Methods.

While the Highway Safety Manual uses Negative Binomial models only to develop SPFs, various models were attempted in this study to find out the best fit for the crash data. These approaches included; Poisson model, Negative Binomial (NB) model, Log-normal (LN) model, Zero Inflated Poisson (ZIP) model, and Zero Inflated Negative Binomial (ZINB) model. Among these models, Log-Normal (LN), and Negative Binomial (NB) models were superior in predicting crashes for roadway segments and intersections, respectively.

## Poisson Model

The Poisson distribution is commonly used to model discrete, nonnegative, and random count data. Let $Y_{i}$ denotes the number of crashes at site $i$, where ( $i=1, \ldots, n$ ) assuming that crashes at the n sites are independent. Poisson distribution is given by Equation 3-3.

$$
Y_{i} \mid \theta_{i} \sim \operatorname{Poisson}\left(\theta_{i}\right)
$$

Equation 3-3
Where,
$\theta_{i}$ is the Poisson parameter. The probability of a site i having $y_{i}$ collisions is given by Equation 3-4.
$P_{r}\left\{Y_{i}=y_{i \mid \theta_{i}}\right\}=\frac{e^{-\theta_{i}} \theta_{i} y_{i}}{y_{i}!}$
Equation 3-4

The Poisson parameter $\theta_{\mathrm{i}}$ is commonly specified as an exponential function of site-specific attributes such as exposure, traffic and geometric characteristics [62]. The Poisson's parameter usually expressed as given in Equation 3-5.
$\theta_{i}=e^{\left(X_{i}^{\prime} \alpha\right)}$
Equation 3-5
Where $X_{i}{ }^{\prime}$ is a row vector of covariates representing site-specific attributes and $\alpha$ is a vector of regression parameters. In the Poisson regression model, the mean and variance of the count variable are constrained to be equal as shown in Equation 3-6.
$E\left(Y_{i}\right) \operatorname{Var}\left(\theta_{i}\right)=\theta_{i}$
Equation 3-6
Kulmala (1995) showed that crash data has an over dispersed characteristics, for which is not applicable with Poisson regression models [78]. Poisson regression cannot handle overdispersion.

## Negative Binomial Model (NB)

Similar to Poisson distribution model, negative binomial distributions describe the occurrence of random and rare events. However, unlike the Poisson distribution, where it is assumed that the mean is equal to the variance, the negative binomial distribution compensates for situations where the variance is greater than the mean, or when the data is overdispersed. Overdispersion for unobserved or unmeasured heterogeneity is addressed, as shown in Equation 3-7.
$\theta_{i}=\mu_{i} e^{\left(\mu_{i}\right)}, \mu_{i}=e^{\left(x_{i}^{\prime} \alpha\right)}$
Equation 3-7

Where the term $e^{\left(\mu_{i}\right)}$ represents a multiplicative random effect. The negative binomial (PoissonGamma) model is obtained by the assumption given in Equation 3-8.
$e^{\left(\mu_{i}\right) \mid \kappa} \sim \operatorname{Gamma}(\kappa, \kappa)$
Equation 3-8
Where $\kappa$ is the inverse dispersion parameter. The dispersion (or over-dispersion) parameter is usually referred to as $\beta=1 / \kappa$. The probability density function of the NB model is given by Equation 3-9 [63].
$\operatorname{Pr}\left(Y_{i}=y_{i} \mid \mu_{i,} \kappa\right)=\frac{\Gamma\left(y_{i}+\kappa\right)}{y_{i}!\Gamma(\kappa)}\left(\frac{\kappa}{\kappa+\mu_{i}}\right)^{\kappa}\left(\frac{\mu_{i}}{\kappa+\mu_{i}}\right)^{y_{i}}$
Equation 3-9
Under the NB model, the mean and variance are given by Equation 3-10.
$E\left(Y_{i}\right)=\mu_{i}, \quad \operatorname{Var}\left(Y_{i}\right)=\mu_{i}+\mu_{i}^{2} / \kappa$
Equation 3-10
When mean will be equal to variance, $\beta$ will go to zero and NB model would be transformed into a Poisson model. The Negative Binomial regression model has been widely applied in the road safety literature.

## Log-Normal Regression Model

A normal distribution with a log link is similar to negative binomial model. Negative binomial model addresses the discrete response variables, while the log-normal model can accommodate continuous response variable [79]. Log-Normal model has a continuous probability distribution of a random variable whose logarithm is normally distributed. The nature of crashes is random and variance is greater than the mean. In addition, crash data are not discrete but count data. That's why this model may fit better than the Negative Binomial (NB) model. The general form of the log normal model is given by Equation 3-11 [79]:
$\ln (Y)=$ intercept $+\alpha_{1} X_{1}+\alpha_{2} X_{2}+\cdots+\alpha_{n} X_{n}$
Equation 3-11

Where,
$\mathrm{Y} \quad$ : Observed crash count during a period for site i
$X_{1}, X_{2} \ldots X_{n}$ : A series of variables, such as shoulder width, truck percentage, number of snowy days per year etc.
$\alpha_{1}, \alpha_{2}, \ldots \alpha_{n}$ : Coefficients to be estimated.

## Zero Inflated Models: Zero Inflated Poisson Model (ZIP) and Zero Inflated Negative Binomial (ZINB)

Zero crash counts can be observed on some roadway segments, especially on low volume rural roadways. This could lead to have a high variance for the observed data than the obtained theoretical model, which is known as over-dispersion. The issue becomes serious when the observed zero counts exceeds the tolerable zero counts by simple Poisson regression and simple Negative Binomial models. With the excess zero counts, the data set becomes a distribution with low sample mean. Zero Inflated Poisson (ZINP) and Zero Inflated Negative Binomial (ZINB)
models can accommodate the low sample mean issue and can provide a better estimation of crash prediction [63].

## Selection of Variables

"Regression models are very accurate tools for predicting the expected total accident experience for a location or a class of locations, but they have not proved satisfactory in isolating the effects of individual geometric or traffic control features" [80]. Therefore, it is not possible to include all the relevant independent variables that could potentially have an impact on safety [81]. Variables were selected considering Wyoming-specific characteristics such as traffic and weather related components.

## Model Evaluation

Models were evaluated by the significance of the estimates and their signs. Significance of estimates are generally done with t-test. Signs should be relevant with the response. For example, logarithm of AADT estimates should be positive in sign explaining increase in crash frequencies or crash rates with the increase in exposure to more traffic volumes. The model goodness of fit is also examined using Akaike Information Criterion (AIC) and log likelihood values. The general equation of AIC is given by Equation 3-12 [82].

AIC $=2 K-2 \log$ (likelihood)
Equation 3-12
Where, K is the number of estimable parameters (degrees of freedom).

## CRASH MODIFICATION FACTORS

Several methodologies were adopted to develop crash modification factors for the selected countermeasures in this study. These methodologies could be concluded as follows:

- Odds, Odds Ratio (OR), and Ratio of Odds Ratio (ROR).
- Naïve Before-After.
- Before-After with Empirical Bayes.
- Cross-Sectional Analysis.

Observational before-after with Empirical Bayes (EB) has the advantage over other studies which is the accommodation of the Regression to the Mean biasness (RTM); a common nature of traffic crash data. This methodology requires implementation dates of the countermeasures in addition to before-after data for the intervention. The safety effectiveness of roadway segment countermeasures were evaluated using before-after with EB in this study. Conversely, Intersection safety evaluation was estimated using cross-sectional method due to unavailability of implementation dates and before period data necessary to perform before-after study.

## Odds, Odds Ratio (OR), and Ratio of Odds Ratio (ROR)

Odds ratio indicates the increased/decreased likelihood of a crash occurring when a treatment is present. It indicates the probability of event occurrence over the non-occurrence probability [83]. Case-controlled data should be selected to conduct the analysis to control for confounding factors, which could affect the real impact of the investigated countermeasure. An odds ratio of less than 1.0 indicated a reduction in crashes, which imply a positive safety effect of the treatment and vice versa. Ratio of odds ratios has a stronger ability to control for possible confounding factor than the simple odd ratio. Ratio of odds ratio would provide a more reliable results [45].

Several studies utilized the odds ratio to assess the safety effectiveness of using different safety treatments [51], [84], and [85]. Equation 3-13 can be used to calculate the odds ratio [86].To evaluate the null hypothesis of the odds ratio, confidence intervals should be calculated. Equation 3-14 and Equation 3-15 provide the confidence intervals for 95 percent confidence level for the odds ratio. The Z-score for 95 percent confidence level multiplied by the square root of the standard error was added to or subtracted from the exponential transformation of the log transformation of odds ratio. To get the upper and lower confidence levels, the result of the above calculation was retransformed using the exponential [86].
$O R=\frac{\pi_{11} / \pi_{12}}{\pi_{21} / \pi_{22}}$
Equation 3-13
$C I_{\text {upper }}=e^{\left[\ln (O R)+Z_{0.05} * \sqrt{S E}\right]}$
Equation 3-14
$C I_{\text {lower }}=e^{\left[\ln (O R)-Z_{0.05} * \sqrt{S E}\right]}$
Equation 3-15

Where:
OR: The odds ratio
$\pi$ : The odds for each group category
$\mathrm{Z}_{0.05}$ : The Z-score for 95 percent confidence level $=1.96$
SE: Standard Error and is obtained by Equation 3-16.
$\frac{1}{\pi_{11}}+\frac{1}{\pi_{12}}+\frac{1}{\pi_{21}}+\frac{1}{\pi_{22}}$
Equation 3-16

## Naïve Before-after Analysis

The simple, or naïve, before-after analysis is a straightforward method of comparison which allows for the crashes that were observed during the before and after periods of the study to be compared, and for a CMF to be determined based solely on crash frequencies which accumulated during their respective periods. Naïve before-after analyses do not include additional roadway and environmental variables. They act as a very basic and preliminary safety effectiveness evaluation method. However, they can allow for the effects of various additional variables to be observed regarding safety effectiveness.

## Before-after Empirical Bayes

The before-after with Empirical Bayes (EB) method was introduced by Hauer (1997) [87]. This method is considered a reliable method as it accounts for the regression to the mean bias (RTM).

Assumptions underlying this method include Poisson distribution of crash frequency, a gamma distribution of means and changes from year to year are similar for all reference sites. This method has 14 steps to calibrate Crash Modification Factors (CMFs). In this study, before-after with EB was utilized to calibrate CMFs for Shoulder Rumble Strips, Passing Lanes, and Snow Fences. The HSM provided this rigorous method consisting of 14 steps as shown in Figure 15 [9].


Source: HSM 2010
Figure 15: Steps of Before-After Empirical Bayes (EB) method.

The estimate of the expected crashes at treatment sites is based on a weighted average of information from treatment and reference sites as given in Equation 3-17 [87]:
$\widehat{E}_{i}=\left(\gamma_{i} \times y_{i} \times n\right)+\left(1-\gamma_{i}\right) \eta_{i}$
Equation 3-17
Where $\gamma_{i}$ is a weight factor estimated from the over-dispersion parameter from the negative binomial regression relationship and the expected 'before' period crash frequency for the treatment sites as shown in Equation 3-18:
$\gamma_{i}=\frac{1}{1+k+y_{i} \times n}$
Equation 3-18
$y i=$ Number of the expected crashes of given type per year estimated from the SPF, $\eta \mathrm{i}=$ Observed number of crashes at the treatment site during the 'before' period, $\mathrm{n}=$ Number of years in the before period, and
$\mathrm{k}=$ Over-dispersion parameter.
A typical SPF was mentioned in Equation 3-2. The overdispersion in the negative binomial model indicates the level of widely dispersion of crashes around the mean. It should be noted that the estimates obtained from Equation 3-17 are the estimates for number of crashes in the before period. Since it is required to get the estimated number of crashes at the treatment site in the after period, the estimates obtained from Equation 3-17 are to be adjusted for traffic volume changes and different before and after periods. The adjustment factors for which are given as Equation 3-19.

## Adjustment for AADT ( $\rho_{\mathrm{AADT}}$ ):

$\rho_{A A D T}=\frac{A A D T_{\text {after }^{\alpha_{1}}}}{A A D T_{\text {before }^{\alpha_{1}}}}$
Equation 3-19

Where, $\mathrm{AADT}_{\text {after }}=\mathrm{AADT}$ in the after period at the treatment site, $\mathrm{AADT}_{\text {before }}=\mathrm{AADT}$ in the before period at the treatment site, and $\alpha_{1}=$ Regression coefficient of AADT from the SPF. Adjustment for different before-after periods ( $\rho_{\text {time }}$ ) is given by Equation 3-20.
$\rho_{\text {time }}=\frac{m}{n}$
Equation 3-20

Where, $\mathrm{m}=$ Number of years in the after period, and $\mathrm{n}=$ Number of years in the before period. Final estimated number of crashes at the treatment location in the after period ( $\hat{\pi}_{i}$ ) after adjusting for traffic volume changes and different time periods is given by Equation 3-21.

$$
\hat{\pi}_{i}=\hat{E}_{i} \times \rho_{A A D T} \times \rho_{\text {time }}
$$

The index of effectiveness ( $\theta \mathrm{i}$ ) of the treatment is given by Equation 3-22.

$$
\widehat{\theta_{l}}=\frac{\widehat{\lambda_{l}} / \widehat{\pi_{l}}}{1+\left(\bar{\sigma}_{l}^{2} / \widehat{\pi_{l}^{2}}\right)}
$$

Where, $\hat{\lambda}_{i}=$ Observed number of crashes at the treatment site during the after period. The percentage reduction ( $\tau \mathrm{i}$ ) in crashes of particular type at each site i is given by Equation 3-23.
$\widehat{\tau}_{L}=\left(1-\widehat{\theta_{l}}\right) \times 100 \%$
Equation 3-23
The odds ratio is given by Equation 3-24.

$$
\hat{\theta}=\frac{\frac{\sum_{i=1}^{m} \widehat{\lambda}_{l}}{\sum_{i=1}^{m} \widehat{\pi}_{l}}}{1+\frac{\operatorname{var}\left(\sum_{i=1}^{m} \hat{\pi}_{l}\right)}{\left(\sum_{i=1}^{m} \widehat{\pi}_{l}\right)^{2}}}
$$

Equation 3-24

Where, $\mathrm{m}=$ total number of treated sites and the variance of $\hat{\pi}_{i}$ can be calculated from Equation 3-25 by Hauer (1997) [87].

$$
\operatorname{var}\left(\sum_{i=1}^{k} \widehat{\pi}_{l}\right)=\sum_{i=1}^{k} \rho_{A A D T}^{2} \times \rho_{\text {time }}^{2} \times \operatorname{var}\left(\widehat{E}_{l}\right)
$$

The standard deviation ( $\hat{\sigma}$ ) of the overall effectiveness can be estimated using information on the variance of the estimated and observed crashes, which is given by Equation 3-26.

$$
\hat{\sigma}=\sqrt{\frac{\theta^{2}\left[\left(\operatorname{var}\left(\sum_{i=1}^{k} \hat{\pi}_{i}\right) /\left(\sum_{i=1}^{k} \hat{\pi}_{i}\right)^{2}\right)+\left(\operatorname{var}\left(\sum_{i=1}^{k} \hat{\lambda}_{i}\right) /\left(\sum_{i=1}^{k} \hat{\lambda}_{i}\right)^{2}\right)\right]}{\left[1+\left(\operatorname{var}\left(\sum_{i=1}^{k} \hat{\pi}_{i}\right) /\left(\sum_{i=1}^{k} \hat{\pi}_{i}\right)^{2}\right)\right]^{2}}}
$$

Where,

$$
\operatorname{var}\left(\sum_{i=1}^{k} \widehat{\lambda_{l}}\right)=\sum_{i=1}^{k} \lambda_{i} s \rho_{\text {time }}^{2} \times \operatorname{var}\left(\widehat{E_{l}}\right)
$$

Equation 3-17 is used to estimate the expected number of crashes in the after period at the treatment sites. This estimated expected number of crashes are compared with the observed number of crashes at the treatment sites in the after period to get the percentage reduction in number of crashes resulting from the treatment.

## Cross Sectional Studies

Different types of cross-sectional studies have evaluated effectiveness of countermeasures over the years. The HSM suggests to use regression models to compare the crash frequencies or rates between sites with and without a safety countermeasure. Cross-sectional study does not need the time for intervention of the treatment, which is considered one of the most important advantages for this method [88]. Cross-sectional studies have two main steps [89]:

- Develop a predictive model.
- Quantify the safety impacts of highway improvements.

To determine the safety effectiveness of a treatment, the Odds Ratio (OR) should be calculated to assess the relative crash risk involving treatment sites and reference sites.

As mentioned earlier, many models and functional forms have been proposed to predict crashes. For this study, NB models were selected, as given in Equation 3- 28.
$Y_{i}=\exp \left(\right.$ intercept $\left.+\alpha 1 X_{1}+\alpha 2 X_{2}+\cdots+\alpha n X_{n}\right)$
Equation 3-28
Where,
$\mathrm{Y}=$ Observed crash count during a period for site i ;
$X_{n}=$ a series of variables, such as existence of left-turn lane of site I; (Used binary input for categorical variables)
$\alpha_{1}, \alpha_{2}, \ldots \alpha_{n}=$ coefficients to be estimated.
Once the model is fitted and coefficients are estimated using observed crash data, the crash modification factor (CMF) for variable n can be then derived as shown in Equation 3- 29.
$\mathrm{CMF}=\exp \left(\alpha_{n}\right)$
Equation 3-29
The expected crash frequency will be multiplied by CMF if the variable n increases or decreases by one unit [90].

CMFs help to estimate the safety impact of the different countermeasures. CMFs can be estimated using the countermeasure related parameter estimates from the regression model [91]. The elasticity is measured as the percentage change in the dependent variable resulting from a 1 percent change in an independent variable. It is obtained by taking the derivative of the crash frequency with respect to the independent variable in Equation 3- 30 [92]:
$E_{i}=\frac{\partial Y}{\partial x_{i}} \mathrm{x} \frac{x_{i}}{Y}$
Equation 3- 30

Where,
E : the Elasticity of the $i^{\text {th }}$ independent variable with respect to crash frequency;
$x_{i}$ : the magnitude of the variable under consideration;
Y : the expected crash frequency from the regression model;
$\alpha_{i}$ : the estimated parameter for the $i^{\text {th }}$ independent variable.
A CMF of 1.0 implies no change has occurred, greater than 1.0 indicates crash has increased and less than 1.0 implies crash reduction after implementing the countermeasure. CMFs for a comprehensive list of safety treatments are contained in the HSM (2010) Part D or online at the Crash Modification Factor Clearinghouse.

An alternative approach estimates CMFs associated with a change in a given roadway attribute in Equation 3- 31 [92]:
CMF $_{x j}=\left(1-e^{\left(\alpha_{j} \Delta x_{j}\right)}\right)$
Equation 3-31

Where $C M F_{x j}$ is the crash reduction factor associated with the $j^{\text {th }}$ independent variable; $\Delta x_{j}$ is the change in magnitude of the variable under consideration; $\alpha_{j}$ is the estimated parameter for the $j^{t h}$ independent variable. CMFs can be computed by the methods above which gives non-linear equations and it the best used for predicting the non-linear changes according to the change in the independent variables. The research used this approach to evaluate the safety effectiveness of the added left-turn lane at intersections.

## CHAPTER 4-ROADWAY SEGMENTS

## INTRODUCTION

The HSM classifies roadway facilities into four major types: 1) roadway segments, 2) intersections, 3) special facilities and 4) road networks. A roadway segment is a portion of the roadway having a consistent geometric, operational, and traffic characteristics. Roadways with significant variations in characteristics should be considered and analyzed as different segments [93]. Different segmentation methods are utilized to identify roadway segments. Fixed length, homogenous, and dynamic segmentation are the methods used in splitting up and identifying roadway segments. In this chapter, data preparation, limitations, challenges, and results for the developed SPFs and CMFs for countermeasures on roadway segments are discussed.

## SHOULDER RUMBLE STRIPS AND PASSING LANES

## Data Preparation and Description for Initial Analysis

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 Critical Analysis Reporting Environment (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 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 beforeafter analysis. Missing implementation dates were imputed by utilizing Pathway Video logs as well as by navigating through the Google Earth Pro ${ }^{\circledR}$ and Google Map Street Views.

Weather is considered a critical component contributing to crashes in Wyoming. Weather stations information obtained from the National Oceanic and Atmospheric Administration (NOAA) were utilized for the study locations.

Wyoming is considered one of top energy production States. It is ranked $4^{\text {th }}$ in gas production, and $8^{\text {th }}$ in oil production in 2014 [94]. Several counties in Wyoming could be considered as oil and gas counties, others could be considered as non-oil and gas counties. Figure 16 shows the crude oil production for the different counties in Wyoming from 2006 to 2015. A threshold of 2 percent from the total oil production of the state was investigated in this study. Ten counties in Wyoming produce less than 2 percent of the total oil production of the State; these counties were considered as non-oil and gas counties.


Figure 16: Crude oil Production from 2006 to 2015 for all Counties in Wyoming.

Accordingly, the data were separated into oil and non-oil counties. About 160 miles of two-way two-lane highways for oil counties and 136 miles for non-oil counties were investigated. Roadways from the top six oil counties (Campbell, Converse, Sublette, Park, Sweetwater, and Natrona) were included in this study. The included highways were US-26/20, US-191, and WY120. The non-oil counties included in this study were Goshen, Lincoln, Platte, Teton, and Weston. US 14, US 16, US 26, US 85 and US 89.

Homogeneous segmentation method was followed in segmentation of the investigated roadways using the vertical and horizontal geometric characteristics. The examined roadways were divided into 709 segments ( 308 segments in oil counties and 401 segments in non-oil counties). The data were collected for 12 years from 2003 to 2014.

The average AADT for non-oil and gas counties was about 1,650 vehicle per day (vpd) and 2,200 vpd for oil and gas counties indicating 32 percent higher traffic volumes in oil counties. Similarly, truck percentage in oil and gas counties, 18 percent, compared to 12 percent in non-oil and gas counties. The crash data were separated into two categories; 1) total crashes and 2) Fatal and Injury $(\mathrm{F}+\mathrm{I})$ crashes.

The Highway Safety Manual (HSM) provides Safety Performance Functions (SPFs) for rural two-lane highways to predict crashes. As mentioned earlier, the SPFs provided in the HSM may not be applicable to Wyoming-specific conditions. Therefore, Wyoming-specific simple and full SPFs were developed for rural two-way two-lane highways using various prediction models. Five different models were applied to develop the crash prediction models: 1) Log-Normal model, 2) Negative Binomial Model, 3) Zero Inflated Negative Binomial Model, 4) Poisson Model and 5) Zero Inflated Poisson Model.

Among these five models, Negative Binomial (NB) model provided the lowest AIC for the initial dataset, which is considered as a measure of model fit. A lower AIC value indicated a better model fit. The description of variables used in this analysis are provided in Table 1. Variables used to develop the SPFs were categorized into four groups. Geometric characteristics, Traffic Data, Crash Data, and Weather Data were the four categories used in this analysis. Each category has two or three variables describing it. Type and level for each variable is shown in Table 1.

Table 1: Description of variables used in developing SPFs for roadway segments

| Dataset | Variable Name | Notation | Variable Type | Description |
| :---: | :---: | :---: | :---: | :---: |
| Geometric Characteristic | Degree of Curvature | DOC | Continuous | Calculated from radius of curvature |
|  | Vertical Grade | VG | Categorical | 4 Categories; $\mathrm{VG}>2$ is $4,0<\mathrm{VG}<2$ is 3 , $2<\mathrm{VG}<0$ is $2, \mathrm{VG}<-2$ is 1 . The reference category is 4 |
|  | Shoulder Width | SW | Discrete | The measurement unit was in feet |
| Traffic Data | AADT | AADT | Discrete | Average Annual Daily Traffic in vehicles per day (vpd) |
|  | Vehicles Miles Traveled | VMT | Continuous | Product of AADT and length of segment |
|  | Truck Percentage | Truck | Continuous | Dividing number of trucks by AADT |
| Crash Data | Total Crashes | Total | Continuous | Total crashes per year per mile for global model; total crashes for other models |
|  | F+I Crashes | F+I | Continuous | Fatal+Injury crashes per year per mile for global model; Fatal+Injury crashes for other models |
| Weather Data | Rainy Days | Rainy | Discrete | Average number of rainy days in a year |
|  | Snowy Days | Snowy | Discrete | Average number of snowy days in a year |

## Initial Results

As mentioned earlier, among the different statistical analysis models used, NB model outperformed other models according to AIC for initial dataset. Table 2 shows the coefficient estimates of the two obtained SPFs for Oil and non-oil counties. Twelve years of data, 2003 to 2014, were used to develop the SPFs for oil and non oil counties in Wyoming.

Table 2: Variables' Estimates of the Developed SPFs using NB Model.

| (A) Calibrated SPFs for Oil Counties of Wyoming |  |  |  |  | (B) Calibrated SPFs for Non-oil Counties of Wyoming |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Variable | Total Crashes |  | F+I Crashes |  | Variable | Total Crashes |  | F+I Crashes |  |
|  | Estimate | p-value | Estimate | p-value |  | Estimate | p-value | Estimate | p-value |
| Intercept | -4.051 | 0.0001 | -4.167 | 0.0110 | Intercept | -4.543 | <. 0001 | -3.506 | 0.0151 |
| DOC | 0.047 | 0.1878 | 0.063 | 0.3051 | DOC | 0.006 | 0.1933 | -0.008 | 0.4002 |
| SRS | -0.342 | 0.0041* | -0.665 | 0.0002* | SRS | 0.033 | 0.8041 | -0.147 | 0.4772 |
| VG1 | 0.155 | 0.4194 | -0.167 | 0.5716 | VG1 | 0.143 | 0.3845 | -0.147 | 0.5757 |
| VG2 | 0.147 | 0.3898 | -0.260 | 0.3068 | VG2 | 0.089 | 0.5661 | -0.114 | 0.6476 |
| VG3 | 0.012 | 0.9471 | -0.284 | 0.2697 | VG3 | -0.015 | 0.9136 | -0.259 | 0.2594 |
| SW | -0.006 | 0.8023 | -0.055 | 0.1180 | SW | -0.022 | 0.4279 | -0.029 | 0.5030 |
| Ln(VMT) | 0.972 | <.001* | 0.673 | <.001* | Ln(VMT) | 0.791 | <.001* | 0.691 | <.001* |
| Truck | -0.004 | 0.8851 | 0.067 | 0.0998\# | Truck | -0.017 | 0.5299 | -0.060 | 0.1534 |
| Speed | -0.023 | 0.0452* | -0.006 | 0.7010 | Speed | -0.002 | 0.8556 | 0.001 | 0.9794 |
| Rainy | -0.001 | 0.8125 | -0.013 | 0.0020* | Rainy | 0.018 | 0.0012* | 0.005 | 0.5846 |
| Snowy | 0.005 | 0.0082* | 0.010 | 0.0031* | Snowy | -0.006 | 0.0245* | -0.004 | 0.3850 |
| Dispersion | 0.273 |  | 0.299 |  | Dispersion | 0.403 |  | 0.712 |  |

* Significant at 95 percent confidence level, \# Significant at 90 percent confidence level.

Shoulder rumble strips (SRS), natural log of vehicle miles traveled (VMT), speed limit and number of snowy days per year were found to be significant at 95 percent confidence level for oil counties for total crashes. It was also found that the same variables were significant at 95 percent confidence level, in addition to the number of rainy days for $\mathrm{F}+\mathrm{I}$ crashes in oil counties. In non-oil counties, $\log$ of VMT, number of rainy and snowy days were significant to predict total crashes but out of these three variables, only log VMT was significant to predict $\mathrm{F}+\mathrm{I}$ crashes at 95 percent confidence level.
Cross-sectional analysis was carried out to quantify the safety effectiveness of Shoulder Rumble Strips (SRS). An observational before-after analysis was not performed for SRS. SRS implementation was started from 2002. There are 2 different versions of crash data before 2003 and after 2003 in Wyoming. There were some discrepancies in crash record. To avoid this issue, an observational before-after analysis was not carried out. The comparison of safety effectiveness between oil and non-oil counties are provided in Table 3.

Table 3: Calibrated Preliminary CMFs of Shoulder Rumble Strips using Cross-sectional analysis for oil and non-oil counties in Wyoming

|  | Oil Counties | Non-oil Counties |
| :--- | :--- | :--- |
| Crash Type | CMF (Safety Effectiveness \%) | CMF (Safety Effectiveness \%) |
| Total | $0.71^{*}(29 \%)$ | $1.00(0 \%)$ |
| Crashes | $0.51^{*}(49 \%)$ | $0.86(14 \%)$ |
| F+I Crashes |  |  |

* Significant at 95 percent confidence level.

The results indicate reductions of 29 percent in total crashes and 49 percent in $\mathrm{F}+\mathrm{I}$ crashes due to the implementation of SRS in Oil counties. These results are in agreement with previous studies [24]. On the other hand, the SRS were found to have to effect on total crashes but reduce 14 percent of $\mathrm{F}+\mathrm{I}$ crashes in Non-oil counties; though the result was not found to be statistically significant.

Utilizing the initial NB model, a Before-after Empirical Bayes (EB) analysis was used to calibrate CMFs for passing lanes. The obtained results are shown in Table 4.

Table 4: Calibrated Preliminary CMFs of Passing Lanes using before-after analysis with EB for oil and non-oil counties in Wyoming

|  | Oil Counties | Non-oil Counties |
| :--- | :--- | :--- |
| Crash Type | CMF (Safety Effectiveness \%) | CMF (Safety Effectiveness \%) |
| Total | $0.69^{*}(31 \%)$ | $0.62^{*}(38 \%)$ |
| Crashes | $0.42^{*}(58 \%)$ | $0.49 \%)$ |
| F+I Crashes | 0.50 |  |

* Significant at 95 percent confidence level.

The results show that passing lanes were found to be significant in both oil and non-oil counties. In non-oil counties, the safety effectiveness of passing lanes was 38 and 59 percent for total and $\mathrm{F}+\mathrm{I}$ crash, respectively. For oil counties, the safety effectiveness was 31 and 58 percent for total and $\mathrm{F}+\mathrm{I}$ crashes, respectively. A previous study on WY59 found that the implementation of passing lane segments reduced total and $\mathrm{F}+\mathrm{I}$ crashes by 42 and 66 percent, respectively [35]. That segment of WY59 was implemented in an oil-county. Results obtained from this analysis were also in agreement with the previous study conducted in Wyoming. However, the previous study used simple SPFs, which do not consider the contribution and potential effect of other geometric and weather characteristics.

## Challenges

This section discusses the issues associated with the development of Wyoming-specific SPFs and CMFs for roadways segments. Several data limitations and gaps were faced while conducting this study. In addition, encountered statistical issues are also discussed.

## Data Collection \& Analysis Issues

## Implementation Dates and Existence of Countermeasures

Although Shoulder Rumble Strips (SRS) were not selected for evaluation as a countermeasure for roadway segments in the first phase of this project, it was important to assess their safety effectiveness in presence of other countermeasures such as passing lanes and overlays. As mentioned earlier, shoulder rumble strips were widely implemented in the State of Wyoming starting 2002. To verify the implementation status of SRS in Wyoming, Pathway Video Logs indicated that SRS may be removed because of an overlay project. The video logs indicated that SRS were reinstated after several years for these locations. This intermittent presence of SRS is
due to cost effective project management strategies in Wyoming. Several roadway segments with new overlay application should be combined to allow for a wide jurisdiction reimplementation of SRS. Observational before-after studies assume a consistent presence of countermeasures; once a location receives a certain treatment, it is assumed that it always exists in the after period. Figure 17 shows an example at ML 34 at MP 42.173 where SRS existed in 2012 and were removed in 2014 when a new overlay was performed. This could cause issues when assuming the presence of SRS after the initial implementation date.


Original Photos © 2016 Pathway Video Logs
Figure 17: Shoulder Rumble Strips On/Off Situation.

Additional effort and analyses were done concerning this particular issue. The research team has invested considerable time reviewing video logs to make sure that countermeasures being evaluated are present consistently throughout the evaluation period. In addition, the analysis were re-performed using the updated information obtained from the video logs to provide a reliable and accurate results. Results from updated analyses are discussed in the final results section in this chapter.

## Roadway Segmentation (Homogenous vs Fixed Length Segments)

Fixed length segmentation is easier to adopt, however, homogeneous segmentation is more reliable 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. In this study, homogeneous segmentation was achieved by considering the degree of curvature, vertical grades, and average
daily traffic to ensure homogenous characteristics within combined segments. Cross sectional elements were not considered in the segmentation process because of the consistency in Wyoming two-lane highways.

## Potential Solutions to Overcome Challenges

Several limitations were discussed in previous sections. However, different methodologies and data imputation techniques were adopted to overcome these limitations. Cross-sectional analysis 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 mean bias (RTM). Therefore, cross-sectional analysis may overestimate or underestimate the safety effectiveness of the treatment.

Implementation dates for treatments could also be estimated using non-traditional data sources. Examining Google Earth Pro ${ }^{\circledR}$ time-lapse satellite imagery provided a general approximation for the countermeasures implementation dates. Moreover, Pathway video logs were also used to provide an estimation for the implementation dates.

According to WYDOT, shoulder rumble strips will be removed for 2 years after implementing an overlay treatment. However, it is a rough assumption, which might not be applicable for all cases. Pathway video logs could also be used as a guide whether the shoulder rumble strips existed in a certain year or not. There are two possible ways to overcome the effect of shoulder rumble strips intermittent situation. Only few of the investigated roadway segments have the intermittent application. To overcome that limitation, those particular sections were excluded from the analysis. This particular solution was adopted and applied in this study. The obtained results are shown in final results section. Another approach could be considering every off situation as before period and every on situation as an after period. Data about overlay implementation should be included in the analysis as well. This alternative approach could provide more reliable results. However, it needs additional effort and analysis, which might be done in future studies and phases.

## Final Results

Shoulder rumble strips were having intermittent application on different roadway sections in the 12 years of the initial analysis. Initially, once a treatment is implemented at a certain roadway segment, initial results of the safety effectiveness of SRS was based on the assumption of a consistent presence of the countermeasure To provide more accurate results, further data reduction and analysis were performed on the same roadway segments excluding the location having the intermittent application of the SRS.
Eliminating segments where SRS were removed resulted in a smaller sample size than the original collected data, this specifically true for the before period. Investigated number of years were also reduced to 7 years instead of 12 years. Data for SPFs for roadway segments were collected from 10 counties in Wyoming; 5 oil counties (Big Horn, Johnson, Converse, Sublette, and Sweetwater) and 5 non-oil counties (Goshen, Niobrara, Platte, Sheridan, and Weston). The highways passing through these counties and utilized in this study were US 191, US 14, US 16,

US 18/20, US 26, US 85 , and WY 59. A total of 174 roadway miles were considered as reference sites (sites that did not receive treatment). Out of the 174 miles, about 107 miles were from nonoil counties and 67 miles were from oil counties. The data were collected from 2008 to 2014.

Homogeneous segmentation method was followed in segmentation of the investigated roadways. The examined roadways were divided into 514 segments; 283 segments in non-oil counties and 231 segments in oil counties.

For combined final data, the average AADT was 1,529 vehicle per day (vpd) and average truck percentage was 14.44 percent. The average AADT for non-oil and gas counties was about 1,332 vehicle per day (vpd) and 1,865 vehicle per day (vpd) for oil and gas counties indicating 40 percent higher traffic volumes in oil counties. Similarly, truck percentage in oil and gas counties, 17.5 percent, compared to 13 percent in non-oil and gas counties. The crash data were separated into two categories; 1) total crashes and 2) Fatal and Injury (F+I) crashes. A total of 854 crashes were observed from 2008 to 2014 time period. Out of 854 crashes, 148 were fatal and injury crashes. Oil counties had a higher crash rate than non-oil counties. Oil counties had 0.85 total crashes/year/mile while non-oil counties had only 0.65 total crashes/year/mile. Again, oilcounties experienced $0.25 \mathrm{~F}+\mathrm{I}$ crashes/year/mile compared to $0.18 \mathrm{~F}+\mathrm{I}$ crashes/year/mile in nonoil counties.

For treatment sites of shoulder rumbles strips, a total length of 46.82 miles were selected; 31 miles from oil counties and 15.82 miles from non-oil counties. Treatment sites for passing lanes were selected from US 85 and WY 59 combining a total of 71 miles of roadway segments; 26 miles from oil counties and 45 miles from non-oil counties.

Five count models with different distributions were utilized to obtain the most accurate crash prediction. Among those, Log-Normal model provided the lowest AIC, which indicates a best fit model. Global models combining oil and non-oil counties were calibrated as well as specific models separating oil and non-oil counties. SPFs for combined data from oil and non-oil counties are shown in Table 5 and specific SPFs for oil and non-oil counties are provided in the Table 6.

Table 5: Variable Estimates and Significance level for SPFs using Log-Normal Model for Rural Two-way Two-lane Highways in Wyoming (Data 2008-2014)

| Variable | Total Crashes |  |  | F+I Crashes |  |
| :--- | ---: | ---: | ---: | :--- | :---: |
|  | Estimate | p-value | Estimate | p-value |  |
| Intercept | -6.165 | $<.0001^{*}$ | -7.559 | $<.0001^{*}$ |  |
| DOC | 0.006 | 0.2421 | 0.010 | 0.2078 |  |
| VG1 | 0.446 | $0.0043^{*}$ | 0.462 | 0.1148 |  |
| VG2 | -0.147 | 0.3188 | -0.621 | $0.0238^{*}$ |  |
| VG3 | 0.170 | 0.2653 | 0.065 | 0.8141 |  |
| SW | -0.033 | $0.0082^{*}$ | -0.085 | $0.0002^{*}$ |  |
| Ln(VMT) | 0.951 | $<.0001^{*}$ | 1.105 | $<.0001^{*}$ |  |
| Truck | -0.055 | $<.0001^{*}$ | -0.057 | $0.0005^{*}$ |  |
| Rainy | -0.012 | $0.0093^{*}$ | -0.023 | $0.0048^{*}$ |  |
| Snowy | 0.016 | $0.0027^{*}$ | 0.027 | $0.002^{*}$ |  |
| Scale | 0.243 |  | 0.135 |  |  |

* Significant at 95 percent confidence level.

Table 6: Variable Estimates and Significance level for SPFs using Log-Normal Model for Oil and Non-oil Counties in Wyoming (Data 2008-2014)

| Variable | (A) SPFs for Total and F+I Crashes for Oil Counties |  |  |  | (B) SPFs for Total and F+I Crashes for Non-oil Counties |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | Total Crashes |  | F+I Crashes |  | Total Crashes |  | F+I Crashes |  |
|  | Estimate | p-value | Estimate | p-value | Estimate | p-value | Estimate | p-value |
| Intercept | -6.3445 | <. 0001 | 1.1958 | 0.2838 | -6.8694 | <. 0001 | -9.9791 | <. 0001 |
| DOC | -0.0195 | 0.4512 | -0.0313 | 0.6582 | 0.0080 | 0.0568** | 0.0105 | 0.0745** |
| VG1 | 0.4951 | 0.0745** | 0.6677 | 0.5183 | 0.6720 | 0.0136* | 1.5499 | 0.0033* |
| VG2 | -0.0055 | 0.9820 | 0.3147 | 0.7239 | 0.1144 | 0.6579 | 0.4625 | 0.3603 |
| VG3 | 0.4606 | 0.0523** | 0.7418 | 0.3862 | 0.2385 | 0.3403 | 0.5452 | 0.2971 |
| SW | -0.0238 | 0.1003 | -0.0916 | <.0001* | -0.0497 | 0.0278* | -0.0905 | 0.0993** |
| Ln(VMT) | 0.8700 | <.0001* | 1.1477 | <.0001* | 0.9923 | <.0001* | 1.1057 | <.0001* |
| Truck | -0.0542 | 0.0569** | -0.3676 | 0.0001* | -0.0478 | <.0001* | -0.0206 | 0.3042 |
| Rainy | 0.0142 | 0.3802 | -0.1362 | <.0001* | -0.0144 | 0.0044* | -0.0199 | 0.0419* |
| Snowy | -0.0221 | 0.3265 | 0.1280 | 0.2838 | 0.0278 | 0.0004* | 0.0491 | 0.0001* |
| Scale | 0.2560 |  | 0.1454 |  | 0.2228 |  | 0.1139 |  |

* Significant at 95 percent confidence level, ** Significant at 90 percent confidence level.

For the combined SPFs, logarithm of Vehicles Miles Traveled (VMT), vertical grades, shoulder width, truck percentage, and average number of rainy and snowy days per year were found to be statistically significant at 95 percent confidence level for both total and $\mathrm{F}+\mathrm{I}$ crashes. The results indicated that steep downgrade increases total crashes. An increase of 1 foot shoulder width, 3 percent total crashes and 8 percent $\mathrm{F}+\mathrm{I}$ crashes are decreased. Park et al. (2015) also found a reduction in total and $\mathrm{F}+\mathrm{I}$ crashes with the increase of shoulder width [32]. Vehicle miles traveled is mostly responsible for increasing number of crashes as it increases the exposure factor, which is in line with the literature [9]. Every 1 percent increase in the truck percentage, reduces 5 and 6 percent total and F+I crashes, respectively. A previous study showed that increasing percentage of trucks, lower the crash rate [20]. This might be because of drivers being more cautious around large trucks. Average number of snowy days increases both total and F+I crashes while average number of rainy days reduces the crashes. Drivers usually get more cautious in both rainy and snowy conditions than normal weather condition. Hawkins (1988) found that reducing the vehicle speed, increasing the gap between vehicles and using warning signs decrease the crash frequency in rainy conditions [95]. However, in snowy conditions, drivers have less control over the vehicles on slippery roads resulting from black ice and blowing snows. Reducing the speed or using warning signs might not be useful to control crashes in this situation. [95]. An increase of one snowy day per year results in an increase of 2 percent of total crashes and 3 percent of F+I crashes. Saha et al. (2015) found crashes increase with the increase of snowy days in Wyoming [96].

The specific SPFs for oil counties have less number of significant variables while the SPFs for non-oil counties have almost similar significant variables as the combined one. The estimates have a different values by a small margin.

An observational before-after analysis with Empirical Bayes (EB) using developed Wyomingspecific full SPFs, shown in Table 5, was carried out to quantify the safety effectiveness of Shoulder Rumble Strips (SRS). Three years of before period and 4 years of after period were considered for this analysis for 71 miles of roadway segments from Natrona, Weston, and Crook Counties. The calibrated Crash Modification Factors (CMFs) are provided in Table 7.

Table 7: Calibrated Final Combined CMFs of Shoulder Rumble Strips (SRS) using beforeafter with EB for Rural Two-way Two-lane Highways in Wyoming

| Crash Type | CMF (Safety Effectiveness \%) |
| :--- | :--- |
| Total Crashes | $1.05(-5 \%)$ |
| F+I Crashes | $0.45 *(55 \%)$ |
| * Significant at 95 percent confidence level. |  |

Shoulder rumble strips (SRS) were found to reduce 55 percent of $\mathrm{F}+\mathrm{I}$ crashes, at 95 percent significance level, but were not effective in reducing total crashes. The obtained results were in agreement with a study utilizing data from Georgia, Kentucky, Minnesota, Missouri, and Pennsylvania [30]. Shoulder rumble strips were found to be more significant in oil counties than non-oil counties for total crashes. The safety effectiveness of SRS was found to be higher than a previous study conducted recently in Wyoming [24]. Moreover, the safety effectiveness of SRS was found to be higher than the initial analysis provided in this study. This might be due to the less treatment sites used in the analysis and more accurate implementation dates. Fewer segments were selected to eliminate the intermittent SRS application encountered in the initial analysis. The obtained CMFs are shown in Table 8.

Table 8: Calibrated Final CMFs of Shoulder Rumble Strips (SRS) using before -after analysis with EB for Oil and Non-oil Counties in Wyoming

|  | Oil Counties | Non-oil Counties |
| :--- | :--- | :--- |
| Crash Type | CMF (Safety Effectiveness \%) | CMF (Safety Effectiveness \%) |
| Total | $0.40^{*}(60 \%)$ | $0.69(31 \%)$ |
| Crashes | F+I Crashes | $0.18^{*}(82 \%)$ |
|  | * Significant at 95 percent confidence level. |  |

CMFs for passing lanes were calibrated using the same developed Wyoming-specific full SPFs (Table 5). Four years in the before period and 4 years in the after period were considered in the before-after analysis with EB method. Table 9 shows the estimated CMFs for passing lanes.

Table 9: Calibrated Final Combined CMFs of Passing Lanes using before-after with EB for Rural Two-way Two-lane Highways in Wyoming

| Crash Type | CMF (Safety Effectiveness \%) |
| :--- | :---: |
| Total Crashes | $0.58^{*}(42 \%)$ |
| F+I Crashes | $0.66^{*}(34 \%)$ |

* Significant at 95 percent confidence level.

Passing lanes were found to be statistically significant to reduce crashes at 95 percent confidence level. They were found to be more effective in reducing total crashes estimating a reduction of 42 and 34 percent of total and F+I crashes, respectively. Passing lanes were found to be more significant in oil counties comparing to non-oil counties for total crashes. Also, the final results of this study indicate higher percentage of crash reduction because of implementation of passing lanes comparing to the initial results of this study and the previous study conducted on WY59 [35]. The results are provided in Table 10.

Table 10: Calibrated Final CMFs of Passing Lanes using before-after analysis with EB for Oil and Non-oil Counties in Wyoming

|  | Oil Counties | Non-oil Counties |
| :--- | :--- | :--- |
| Crash Type | CMF (Safety Effectiveness \%) | CMF (Safety Effectiveness \%) |
| Total | $0.39^{*}(61 \%)$ | $1.29(-29 \%)$ |
| Crashes | $0.41^{* *}(59 \%)$ | $0.36^{* *}(64 \%)$ |
| F+I Crashes |  |  |
| Significant at 95 percent confidence level, ${ }^{* *}$ Significant at 90 percent confidence level |  |  |

## HEADLIGHT SIGNS

Seven roadway sections in Wyoming utilized the MUTCD "Turn on Your Headlights for Safety Next XX Miles" headlight sign as shown in Figure 18. All roadways having the headlight signs are classified as principal or minor arterial two-way two-lane roads. The first implementation of the signs was back in 1994 on US287/WY789. The latest signs were implemented in 2012 on WY220 and WY59.


Source: Wyoming Department of Transportation
Figure 18: Headlight Sign Locations in Wyoming.

## Data Preparation and Description

Three datasets were used to obtain the crash modification factors for the headlight signs. Crash data were extracted from the Wyoming Critical Analysis Reporting Environment (CARE). It should be noted that crash data in the CARE package do not include Vehicle Identification Numbers (VINs). VINs are needed to identify vehicles equipped with automatic Daytime Running Lights (DRLs) in the crash reports. A full list of VINs for vehicles involved in crashes was obtained from WYDOT and matched to crashes in the CARE package. Ten years of traffic data (2004-2013) were also acquired from WYDOT. A Total number of 106,622 crashes for the years 2004-2013 were collected with complete VINs.

Only target crashes, i.e., head-on and opposite side-swipe crashes, with the following criteria were considered in the study; crashes occurred on 2-lane rural highways, posted speed is greater than 55 mph , daytime crashes, no alcohol or drug involved, and no animal crashes. The dataset was further split into; crashes for locations with headlight signs, and crashes for locations without headlight signs.

As mentioned earlier, VIN dataset was used to evaluate the safety benefits of headlight sign based on the existence of automatic Day Time Running Lights (DRLs) in the crashed vehicle. To identify what headlight technology a vehicle might have, the website:
https://www.decodethis.com was used. This website classifies DRL into three groups: "Standard DRL", "No DRL", and "Optional DRL". A total of 6713 VINs ( 6230 randomly sampled target crashes for locations without headlight signs, and all 483 target crashes occurred on locations with headlight signs) were checked to determine the type of headlight technology equipped in vehicles involved in crashes. Only crash data belongs to the "No DRL" and "Standard DRL" were used in the analysis. Figure 19 shows the crash rates, frequencies, and percentages according to DRL equipment for locations with and without headlight signs. The data showed that 70 and 77 percent of vehicles involved in crashes in locations with and without headlight signs are non-DRL equipped vehicles, respectively.


Figure 19: Rates, frequencies and percentages of total and target crashes.
A) Crashes per mile for location without headlight signs
B) Crash frequencies and percentage for locations without headlight signs
C) Crashes per mile for location with headlight signs
D) Crash frequencies and percentage for locations with headlight signs

Table 11 provides descriptive statistics of rates for both total and target crashes for the headlight and non-headlight sign sections from 2004 to 2013. While WY28 experienced the highest number of total crashes per million vehicle miles travelled (MVMT) among all the headlight sections, the US287 had the highest rate of head-on and opposite sideswipe crashes (target crashes). Moreover, the table shows that while the non-treated sections had slightly higher crash rates per MVMT for total crashes, the treated sections had higher crash rates for target crashes on average.

Table 11: Descriptive statistics of crash rates for headlight and non-headlight sign sections

| Segment | Crash rate for total crashes per MVMT (from 2004 to 2013) |  |  |  | Total \# of <br> crashes | Crash rate for target Crash per MVMT (from 2004 to 2013) |  |  |  | Total \# of Target Crashes |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | Min | Mean | Max | St.dev |  | Min | Mean | Max | St.dev |  |
| US 287* | 0.66 | 1.04 | 1.38 | 0.26 | 308 | 0 | 0.05 | 0.11 | 0.03 | 15 |
| US287 / <br> WY 789 * | 0 | 0.97 | 2.18 | 0.64 | 33 | 0 | 0.03 | 0.28 | 0.08 | 1 |
| US 287 * | 0 | 0.72 | 1.82 | 0.51 | 23 | 0 | 0.05 | 0.28 | 0.11 | 2 |
| WY 220 * | 0.75 | 1.03 | 1.36 | 0.23 | 157 | 0 | 0.02 | 0.12 | 0.04 | 3 |
| WY 59 * | 0.4 | 0.71 | 1.02 | 0.18 | 252 | 0 | 0.03 | 0.08 | 0.03 | 11 |
| US20/26* | 0.42 | 0.68 | 0.9 | 0.16 | 283 | 0 | 0.03 | 0.07 | 0.02 | 11 |
| WY 28 * | 1.22 | 2.04 | 3.36 | 0.57 | 426 | 0 | 0.04 | 0.12 | 0.04 | 8 |
| WY22 | 0.92 | 1.38 | 1.82 | 0.34 | 741 | 0.016 | 0.07 | 0.20 | 0.06 | 36 |
| US 191 | 0.7 | 0.97 | 1.27 | 0.20 | 2243 | 0 | 0.01 | 0.03 | 0.01 | 28 |
| US 278 | 0.31 | 0.45 | 0.55 | 0.06 | 1072 | 0 | 0.01 | 0.01 | 0.003 | 17 |
| WY 59 | 3.27 | 4.79 | 6.4 | 1.03 | 3153 | 0.016 | 0.05 | 0.11 | 0.03 | 35 |
| WY 220 | 0.59 | 0.78 | 0.96 | 0.11 | 2725 | 0 | 0.01 | 0.02 | 0.01 | 31 |
| US85 | 0.45 | 0.58 | 0.79 | 0.09 | 1456 | 0.003 | 0.01 | 0.02 | 0.004 | 25 |
| US 30 | 0.7 | 0.89 | 1.29 | 0.16 | 636 | 0 | 0.03 | 0.08 | 0.02 | 21 |
| US 189 | 0.65 | 0.8 | 0.92 | 0.08 | 664 | 0 | 0.01 | 0.03 | 0.01 | 7 |
| US 26 II | 0.48 | 0.96 | 1.58 | 0.34 | 126 | 0 | 0.03 | 0.07 | 0.03 | 3 |
| WY 789 | 0.69 | 0.99 | 1.42 | 0.26 | 296 | 0 | 0.04 | 0.08 | 0.03 | 13 |
| WY 414 | 0.59 | 0.81 | 1.31 | 0.22 | 258 | 0 | 0.01 | 0.03 | 0.01 | 3 |
| WY 387 | 0.56 | 0.87 | 1.26 | 0.22 | 283 | 0 | 0.03 | 0.06 | 0.02 | 10 |
| US 14 | 0.55 | 0.71 | 0.85 | 0.09 | 1203 | 0 | 0.002 | 0.01 | 0.004 | 3 |
| US 16 | 0.48 | 0.89 | 1.27 | 0.23 | 477 | 0 | 0.01 | 0.02 | 0.01 | 4 |
| US 191 | 0.46 | 0.93 | 1.66 | 0.35 | 257 | 0 | 0.01 | 0.07 | 0.02 | 4 |
| WY 120 | 0.69 | 1.05 | 1.47 | 0.22 | 453 | 0 | 0.01 | 0.02 | 0.01 | 3 |
| US 26 | 0.68 | 1.02 | 1.34 | 0.22 | 288 | 0 | 0.02 | 0.06 | 0.02 | 7 |
| Average treated | 0.49 | 1.03 | 1.72 | 0.36 | 211.71 | 0 | 0.04 | 0.15 | 0.05 | 7.29 |
| Average non-treated | 0.75 | 1.11 | 1.54 | 0.25 | 960.65 | 0 | 0.02 | 0.05 | 0.02 | 14.71 |

## Data Limitations and Availability

The headlight signs were implemented on different years as shown in Figure 18. Early implementation of the headlight sign countermeasure was in 1994 on an 11-mile section on US287/WY789. The recent implementation of the countermeasure took place in 2012 at two different locations. It is worth mentioning that the AADT data for Wyoming's highway road network are available from 2003 till present only. This would introduce limitations to conduct observational before-after studies for this specific countermeasure as there is no AADT data existing for the before period. This led in utilizing the odds ratio and ratio of the odds ratio analyses as the major methodologies adopted for this countermeasure.

With the increase in number of vehicles equipped with DRLs and automatic low-beam headlights, many drivers do not comply with regulatory headlight signs. To investigate the effect of the DRL technology penetration on the safety effectiveness of regulatory headlight signs, information about compliance to the headlight light sign and the existence of DRL technology
for the crashed vehicles in the before and after periods are essential. However, it is impossible to obtain such information for the historical crash data.

## Results

Table 12 represents the $2 \times 2$ contingency table for the frequencies of the investigated crash types, DRL equipped state, and existence of headlight signs. It also shows the odds and the odds ratio values of the crashes for headlight and non-headlight sign locations by the DRL equipped state for the crashed vehicles. The odds for the locations with the headlight sign was 24 percent vs 20 percent for locations without headlight signs resulting in an odds ratio of 1.17. This implies that locations with headlight signs receives 17 percent more total crashes than locations without headlight signs, controlling for the DRL factor. The confidence intervals were calculated to range from 0.91 to 1.51 indicating no significant effect of having DRL in crash reduction for two way highways with the presence of headlight signs.

The same analysis was conducted for target crashes. Head-on and sides-wipe opposite crashes were investigated for the same locations to examine the effect of DRL with the presence of headlight signs for certain crash types in two way two lane highways.

Table 12: Two-Way Contingency Table with Odds and Odds Ratio for Total and Target Crashes

| Crash Type | Section description | DRL <br> equipped <br> Vehicles | Non-DRL <br> equipped <br> Vehicles | Odds | Odds <br> Ratio |
| :---: | :---: | :---: | :---: | :---: | :---: |
| Total Crashes | with Headlight signs | 80 | 337 | $23.74 \%$ | 1.17 |
|  | without Headlight signs | 970 | 4799 | $20.21 \%$ | 1.17 |
| Target Crashes | with Headlight signs | 4 | 32 | $12.50 \%$ | 0.56 |
|  | without Headlight signs | 95 | 429 | $22.14 \%$ | 0. |

The odds for the locations with the headlight sign was 13 percent vs 22 percent for location without headlight signs for target crashes. An odds ratio of 0.56 was obtained. Which implies that locations with headlight signs experienced 44 percent less target crashes than locations without headlight signs, having DRL equipment controlled for. The confidence intervals were calculated to range from 0.19 to 1.63 . Confidence intervals indicate that there is no significant effect of having DRL on head-on and sideswipe opposite crashes for two way highways with the presence of headlight signs.

The NHTSA (2011), utilized the ratio of odds ratio (ROR) to show the effectiveness of using DRL technology in reducing crashes [6]. A case-control analysis using ROR was adopted for this treatment. Ratio of odds ratio (ROR) for the headlight sign as a safety countermeasure had a value of 0.45 , which indicates a 54.64 percent reduction in target crashes, controlling for DRL technology. However, the result from the ROR was not significant at 95 percent significance level, as shown in Table 13.

Table 13: Ratio of Odds Ratio Analysis for Headlight Sign Controlling for the DRL Technology


## CHAPTER 5-INTERSECTIONS

## INTRODUCTION

A total number of 174 intersections from 23 cities within 20 counties in the State of Wyoming were chosen as the study sites considering the availability of traffic volume data. Intersections with collector roads in major approaches were selected to ensure that the traffic data are available from WYDOT. In the case of unavailability of minor approach traffic volume data, minor approach AADTs were estimated by vehicle ratio using the Google Earth Pro ${ }^{\circledR}$ imageries. A sample of intersections were inspected to verify the uniformity of geometric characteristics during the study period. It can be assumed that throughout the observed period, the geometric characteristics of the sites remained the same. Data from 2005 to 2014 were used in this study.

## DATA COLLECTION

## Data Source

Crash data for the intersections were collected from the Wyoming Critical Analysis Reporting Environment Package (CARE). Raw data from the package were extracted with the following criteria:

- Mile posted: accounts for roadway segments with mile-posts.
- Non mile posted: accounts for intersections with names.
- Not classified as mile-posted or non-mile posted.

These data were imported into Geographic Information System mapping tool to assign intersection related crashes to intersections. To classify intersection related crashes, intersection influence area should be defined. The intersection safety influence area depends on the intersection geometry, traffic control, and operating features [97]. The State of Indiana among other states used a circular influence area of 250 ft . radius from the center of the intersection [98]. Channelized intersections influence area was defined within 20 ft . beyond the gore of islands or the point at which the turn lane attains [91]. The safety effects could be overestimated if a larger safety influence area is applied to smaller intersections and hence misclassifying roadway segment crashes as intersection crashes [97]. In this data analysis, 250 ft . criterion was used to define intersection influence area. Crashes by severity (i.e., total, $\mathrm{F}+\mathrm{I}$, and PDO), and crashes by types of collision (i.e., angle, rear-end, head-on, sideswipe) were categorized from the extracted data.

Intersection characteristics data such as number of shared and through lanes in each approach, presence of exclusive left and right-turn lanes, angle of intersection skewness, presence of medians (raised or flush), signal heads configurations ( 3,4 or 5 lights) were collected from Google Earth Pro ${ }^{\circledR}$ imageries. This was done manually for every intersection considered in this study. Yearly signal system and timing data were not collected due to unavailability of such archived data.

Traffic volume data were collected from WYDOT. The base conditions set for developing SPFs for four-leg signalized (4SG) intersections in the HSM include AADT ranges up to 67,000 for major and up to 33,000 for minor approaches. AADT data for all intersections were within this range.

Weather data were collected from the National Oceanic and Atmospheric Administrations (NOAA) weather stations. The NOAA's National Centers for Environmental Information (NCEI) provides public access to records for weather data and information. Number of rainy days and snowy days for each intersection were collected from the stations using a proximity of five nautical miles radius from the stations [99].

## Data Preparation and Description

The number of four-leg signalized intersections considered from each county of Wyoming are showed in Figure 20. The number of four-leg signalized intersections in Casper, Natrona County and Laramie, Cheyenne County are 26 and 22, respectively. Due to demographic characteristics and the urban nature of some cities in Wyoming, cities such as from Crook County, Sublette County, and Lincoln County have zero four-leg signalized intersections. Therefore, it is anticipated that crash frequencies and patterns at intersections will differ by cities or counties depending on various characteristics of cities. Table 14 provides number of four-legged signalized intersections, population, land area, density and crash counts in by cities of Wyoming under study.


Figure 20: Number of Four-leg Signalized Intersections Considered from Each County of Wyoming.

Table 14: Different Characteristics of Cities which Contribute to affect the Crash Frequencies in Intersection.

| County | City | Population <br> 2010 | Land Area <br> (sq.mi.) | Density <br> (pop./ <br> sq.mi.) | Crash/sq. <br> mi/pop | 4-leg <br> Signalized <br> Intersections |
| :--- | :--- | :--- | :--- | :--- | :--- | :--- |
| Laramie | Cheyenne | 59466 | 24.52 | 2425.2 | 0.727 | 22 |
| Natrona | Casper | 55316 | 26.9 | 2056.4 | 1.334 | 26 |
| Albany | Laramie | 30816 | 17.74 | 1737.1 | 0.781 | 20 |
| Campbell | Gillette | 29087 | 18.97 | 1533.3 | 1.285 | 19 |
| Sweetwater | Rock Springs | 23036 | 19.34 | 1191.1 | 1.050 | 11 |
| Sheridan | Sheridan | 17444 | 10.93 | 1596 | 0.362 | 10 |
| Sweetwater | Green River | 12515 | 13.72 | 912.2 | 0.072 | 2 |
| Uinta | Evanston | 12359 | 10.27 | 1203.4 | 0.189 | 6 |
| Fremont | Riverton | 10615 | 9.86 | 1076.6 | 0.599 | 9 |
| Teton | Jackson | 9577 | 2.91 | 3291.1 | 0.166 | 6 |
| Park | Cody | 9520 | 10.2 | 933.3 | 0.422 | 10 |
| Carbon | Rawlins | 9259 | 8.24 | 1123.7 | 0.125 | 5 |
| Fremont | Lander | 7487 | 4.66 | 1606.7 | 0.222 | 7 |
| Goshen | Torrington | 6501 | 4.62 | 1407.1 | 0.059 | 3 |
| Converse | Douglas | 6120 | 4.58 | 1336.2 | 0.099 | 5 |
| Washakie | Worland | 5487 | 4.56 | 1203.3 | 0.076 | 5 |
| Johnson | Buffalo | 4585 | 4.46 | 1028 | 0.011 | 1 |
| Platte | Wheatland | 3627 | 4.1 | 884.6 | 0.020 | 2 |
| Weston | Newcastle | 3532 | 2.55 | 1385.1 | 0.009 | 1 |
| Hot Springs | Thermopolis | 3009 | 2.38 | 1264.3 | 0.017 | 1 |
| Big Horn | Lovell | 2360 | 1.1 | 2145.5 | 0.010 | 1 |
| Big Horn | Greybull | 1847 | 1.81 | 1020.4 | 0.028 | 1 |
| Niobrara | Lusk | 1567 | 2.07 | 757 | 0.009 | 1 |

In order to allocate the appropriate resources to improve safety, identification of intersection crash "hotspots," "blackspots," "high risk", or "high collision concentration locations" is a first step to be taken. Some researchers [100] and [101] incorporated some powerful analytical tools in GIS software such as buffer, nearest neighbor method, simple density, and Kernel Density Estimation (KDE) methods of crash cluster identification. These methodologies help in visualizing spatial distribution of crashes.

Kernel Density Estimation (KDE) is a geostatistical-based approach for identifying crash hotspots in a road network. Kernel Density and Point Density tools smooth out the crash frequencies visually which is easy to understand. In Geographic Information Systems (GIS) the result of a KDE has a density value that is weighted according to distance from the features for example crash frequency. The distribution of effects are represented by the diameter of that circle by heat map.

In almost all cases, crashes form clusters in geographic spaces. Actual crash locations are random which can occur anywhere spatially and temporally; but we can attempt to quantify how likely it is that intersection related crashes would take place at a particular intersection. A crash density map of Wyoming is generated using Geographic Information System (GIS) at city levels.


Figure 21: Kernel Density Map using Intersection Crashes (crash/sq. mile).

Spatial distribution of intersection crashes are shown in Figure 21. Red colored regions have more crashes than the green regions. The likelihood of crash occurrence depends on many factors such as road geometry, driver characteristics, and location characteristics. Cities with high population and large metropolitan areas tend to have more crash density. Figure 21 shows the heat map of crashes per square miles for four-leg signalized intersections for the year 2005 to 2014. This map can be interpreted as a predictive risk surface for the intersection crashes.

Crash density (crashes/sq. mile) values are normalized using population of the cities. The crash density map shows Casper has the largest red region of diameter ( 22.8 miles), which indicates the city has the highest crash density in Wyoming. The normalized crash density value for Casper is 1.33 crashes/capita/sq. miles, the highest among all the cities. Gillette is in close proximity to Casper for 4-leg intersection crashes, having a red zone of 18.4 mile diameter and normalized crash density of 1.28 Crashes/Population/Sq. Miles. Rock Springs is the second hazardous city with a red zone diameter of 18.2 meter and a density of 1.05 crash/Population/Sq. Miles. The locations can be classified into three levels according to the crash densities. Casper, Gillette, Rock Spring, Cheyenne and Laramie can be considered as the highest level of hazardous location due to having the highest crash densities. Casper, Gillette and Rock Spring have the most oil and gas productions among all counties. Cheyenne and Laramie are among the top most densely populated cities in Wyoming (Table 14). Sheridan, Riverton, and Cody indicate medium
hazard levels while Jackson, Lander, and Evanston indicate low hazard levels.

A total of 174 observations were used in the analysis accounted for about 12,000 crashes in which around 23 percent were Fatal +Injury ( $\mathrm{F}+\mathrm{I}$ ) crashes and the remainder were the Property Damage Only (PDO) crashes, as shown in Figure 22.


Figure 22: Crash Frequencies and Average Yearly Crash Rates by Severity.

The average yearly F+I crashes were found to be 294.2 which is 23 percent of total crashes. F+I crashes were 336 ( 25 percent) in 2005 and were reduced to 206 ( 20 percent) in 2014. Therefore, intersection PDO crashes increased throughout the period.


Figure 23: Crash Frequencies by Crash Type.


Figure 24: Crash Proportions by Crash Type.

Crash frequencies and crash proportions by crash types (maneuvers) are shown in Figure 23 and Figure 24, respectively. Percentages of rear-end and angle crashes are the highest among all crash types. Therefore, turning maneuvers should be emphasized more to understand crash trends.

Intersection crash proportions by type of collision for Wyoming were compared to crash proportions provided in the HSM in Table 15 and

Table 16 for multi-vehicle and single vehicle, respectively. Crash proportions by the HSM were calculated based on data from the Highway Safety Information System (HSIS) data for California (2002-2006) [9].

Table 15: Comparison of Crash Distribution by Types between Wyoming and HSM for Multi-vehicle

| Crash Types | Rear-End | Head-On | Angle | Side-Swipe | Other |  |
| :--- | :--- | :---: | :---: | :---: | :---: | :---: |
| F+I | WY | 0.400 | 0.050 | 0.390 | 0.020 | 0.117 |
|  | HSM | 0.450 | 0.049 | 0.347 | 0.099 | 0.055 |
| PDO | WY | 0.387 | 0.031 | 0.348 | 0.102 | 0.111 |
|  | HSM | 0.483 | 0.030 | 0.244 | 0.032 | 0.211 |

Two crash severity levels and five crash types were considered for the comparison in which all crash types seem to have similar distribution except rear-end, angle, and sideswipe crashes. Intersection crash proportions for Wyoming are higher than the HSM proportions for angle
crashes by 5 percent for $\mathrm{F}+\mathrm{I}$ crashes and 10 percent for PDO crashes. Therefore, angle crashes should be analysed extensively to find out the contributing factors. PDO Sideswipe crash proportions for Wyoming were 7 percent more than the HSM. Simple SPFs were calibrated for Wyoming conditions with similar crash types as provided in the HSM. Moreover, full SPFs were calibrated to examine the impacts of various factors on angle and sideswipe crashes at fourleg signalized intersections in Wyoming.

Table 16: Comparison of Crash Distribution by Types between Wyoming and HSM for Single-vehicle.

| Crash Severity | Parked Vehicle | Animal | Fixed Object | Object | Other | Non-collision |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| F+I | WY | 0.000 | 0.029 | 0.234 | 0.541 | 0.065 | 0.135 |
|  | HSM | 0.001 | 0.002 | 0.744 | 0.072 | 0.040 | 0.141 |
|  | WY | 0.000 | 0.167 | 0.544 | 0.022 | 0.249 | 0.018 |
| PDO | HSM | 0.001 | 0.002 | 0.870 | 0.070 | 0.023 | 0.034 |

According to the Wyoming Highway Patrol (WHP), animal crashes were found to be the highest throughout central and northwest Wyoming. The cities of Lander, Riverton, Greybull, Thermopolis, and Cody are some of the areas which are included in this analysis. Most wildlifevehicle collisions occur during the fall and winter [102]. Wildlife-vehicle crashes at intersection should be further analyzed in future studies to have an increased level of understanding about when, where and why wildlife is most likely to be present near the road.

## Challenges and Potential Solutions

To assess the safety performance of four-leg signalized (4SG) intersections in Wyoming, extensive data should be collected. These data included site characteristics, crash data, traffic data, and weather data. Some challenges were faced during data collection task for signalized intersections. These challenges were mitigated by utilizing data imputation techniques.

## Site Characteristics Data

Site characteristic data collected were functional class of the intersecting roads, number of shared and turning lanes, lane width, speed limit, and other roadway characteristics. Google Earth Pro ${ }^{\circledR}$ was used as a source of geometric characteristics data for the intersections. This is a geographical information program providing 3D images obtained from satellite imageries for different years. Historical satellite imageries collected manually from Google Earth Pro ${ }^{\circledR}$ from previous years were blurry; therefore, it was not possible to ensure if the geometric characteristics remained same throughout the study period (2005-2014), as shown in Figure 25.


Original Photo: © 2017 Google Earth Pro ${ }^{\circledR}$
Figure 25: Inspection of Intersection Characteristics Variation by Year from Google Earth Pro ${ }^{\text {®. }}$

Although all of the intersections are signalized, signal timing and phasing may be different from one intersection to another. The signal head configurations (3, 4, or 5 lights) also differs. Signal configuration cannot be classified from the Google Earth Pro ${ }^{\circledR}$ imageries. This information should be collected for further analysis in future. Signal timing and phasing are controlled by local transportation authorities. Due to unavailability of historical data of signal timing and phasing this step was not feasible to perform and should be studied in future.

## Crash Data

Crash data are compiled into two CARE packages of different time durations. Both CARE packages are needed to do an extensive analysis and to identify intersections crash trends in Wyoming since 1994. Moreover, most of the treatments (e.g., signalization of intersections, adding turn lanes, etc.) were implemented before 2000. The first version of CARE package was from 1994 to 2010 and the updated version was from 2005 to 2015. These two versions showed different crash frequencies for overlapping years. Discrepancies are shown in Table 17 and Table 18 for four intersections in Cheyenne; C7, C6, C3, and C24 in WYDOT project no. B109079. Total number of crashes from a previous package of CARE does not match the latest one. CARE package from the year 1994 to 2010 showed total crash frequency for the years 2005, 2006, and 2007 were 24,19 , and 20, respectively. The later one showed total crash frequency 28,22 , and 22 for the same years which are higher than the previous CARE package. Therefore, data were extracted from the latest package only (2005-2015) to maintain consistency.

Table 17: Intersection Crash Data from CARE 1st Compilation Package 1994-2010

| Site | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 |
| :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- |
| ID | 19 | 4 | 11 | 3 | 6 | 8 | 4 | 12 | 12 | 9 | 12 | 9 | 6 | 4 |
| C7 | 4 | 4 | 11 | 9 | 8 | 8 | 14 | 9 | 13 | 8 | 10 | 12 | 9 | 14 |
| C6 | 2 | 8 | 11 |  |  |  |  |  |  |  |  |  |  |  |
| C3 | 2 | 1 | 1 | 1 | 1 | 3 | 1 | 2 | 1 | 2 | 2 | 2 | 4 | 2 |
| C24 | 2 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 |
| Total | 10 | 14 | 23 | 13 | 15 | 19 | 19 | 23 | 26 | 19 | 25 | 24 | 19 | 20 |

Table 18: Intersection Crash Data from CARE 2nd Compilation Package 2005-2015

| Site ID | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | Total |
| :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- |
| C7 | 11 | 7 | 5 | 9 | 15 | 6 | 6 | 13 | 7 | 10 | 4 | 93 |
| C6 | 14 | 10 | 16 | 9 | 8 | 13 | 16 | 8 | 9 | 5 | 5 | 113 |
| C3 | 2 | 5 | 1 | 5 | 10 | 3 | 5 | 1 | 3 | 1 | 0 | 37 |
| C24 | 1 | 0 | 0 | 1 | 0 | 0 | 3 | 0 | 1 | 0 | 0 | 10 |
| Total | 28 | 22 | 22 | 24 | 33 | 22 | 30 | 22 | 20 | 16 | 9 | 253 |

Another issue with crash data was identifying intersection-related crashes. Intersection data which were taken from CARE with "non-mile posted" location option show the crashes with the name of the intersection of occurrence. Two intersections in Cheyenne with their crash locations were plotted in GIS as shown in Figure 26. Three types of crashes from CARE; 1) Mile-posted crashes, 2) Non mile-posted crashes, and 3) Without considering mile-posted and non-mileposted crashes, were visualized in GIS to identify intersection-related crashes. Figure 26 shows that non-mile posted crashes, which are identified as intersection-related crashes are also located outside the 200 ft intersection influence area. Therefore, more investigations may be required using original crash reports, which may also require labor intensive manual work. Collision diagrams can be constructed from original crash reports to understand the crash patterns occurred at intersections to differentiate intersection-related vs roadway segment-crashes in the vicinity of intersections.

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Figure 26: Identification of Intersection-Related Crashes in GIS.

## Traffic Volume Data

For selected intersections, traffic volumes were available for the study years in Annual Average Daily Traffic (AADT) for at least the major approach roadways. Traffic volumes for most of the minor approach roads were not available as local roads' traffic volume are not recorded in WYDOT database. Typically, traffic volume estimates are made for local road sections without traffic counts and AADT by comparing the road section to other similar road sections without traffic count data [99]. The minor roadway AADTs were assumed as a percentage of major roadway AADT considering the existing traffic ratio at each intersection from Google Earth Pro ${ }^{\circledR}$ imageries. However, this procedure could be inaccurate as it assumes traffic volume for a specific instant time.
For more accurate results, minor AADTs should be estimated based on field data collection. As collecting field data is always associated with cost and time. Therefore, developing a traffic demand model could be a feasible solution for that particular issue.

## Data Requirements

One of the most challenging tasks is collecting appropriate sample size in accordance with the HSM for different statistical techniques. [103]. The HSM recommends sample size of 30-50 sites with at least 100 crashes per year for nearly all facility types including signalized intersections [9]. The larger the sample, the more accurate the estimates are. However, due to limited resource and data collection burdens, researchers sometimes compromise this requirement. In the case of the HSM, many of the data variables needed for deriving the calibration factors are currently unavailable in Wyoming's Roadway Characteristics Inventory (RCI) database. These data were alternatively collected from other non-traditional sources. From a study in Florida, a minimum size of 80 intersections constituting 1,300 crashes per year was recommended for urban and suburban four-leg signalized intersections [103]. This study constitutes 174 four-leg signalized intersections having 1,200 crashes per year which yielded calibration factors at 95 percent confidence level.

## RESULTS

## SPFs for Intersections

Several statistical techniques were utilized to calibrate Wyoming-specific SPFs for four-leg signalized intersections; e.g., Negative Binomial (NB), Zero Inflated Poisson (ZIP), and Zero Inflated Negative Binomial Models (ZINB). The general form of the SPF for intersection provided in the HSM for Negative Binomial regression model is in Equation 5-1.
$N_{S P F}=e^{\left(a+b \times \ln \left(A A D T_{m a j}\right)+c \times \ln \left(A A D T_{\text {min }}\right)\right)}$
Equation 5-1

Where,
$A A D T_{m a j}=$ Annual Average Daily Traffic Volume (Vehicles/Day) for Major Approach $A A D T_{m i n}=$ Annual Average Daily Traffic Volume (Vehicles/Day) for Minor Approach $a, b, c=$ regression coefficients.

The Highway Safety Manual calibrated Safety Performance Functions for single and multivehicle crashes by severity for four-leg signalized intersection as shown in Table 19.

Table 19: The HSM Simple SPFs of Single and Multi-Vehicle Crashes by Crash Severity for Four-leg Signalized Intersections [9].

SPF Coefficients for Intersections by Crash Severity

|  |  |  |  |  |  |  |
| :--- | :--- | :--- | :--- | :--- | :--- | :--- |
|  |  |  | Intercept | $\mathrm{AADT}_{\text {maj }}$ | $\mathrm{AADT}_{\text {min }}$ | Overdispersion |
| Parameter |  |  |  |  |  |  |

As previously mentioned, SPF calibration is needed to account for variations among different jurisdictions, such as driver population, age, crash reporting threshold, and adverse weather. Table 20 describes the data and variables used in this study.

Table 20: Description of Variables

| Data Set | Name of variables | Type of Variables | Description of Variables |
| :---: | :---: | :---: | :---: |
| Geometric <br> Characteristics | Lane $_{\text {maj }}$ | Categorical | Number of lanes in major approach roadway of the intersection |
|  | Lane $_{\text {min }}$ | Categorical | Number of lanes in minor approach roadway of the intersection |
|  | $\mathrm{RL}_{\text {maj }}$ | Categorical | Presence of right-turn lane in major \& minor approach or any approach of the intersection |
|  | $R L_{\text {min }}$ |  |  |
|  | RL |  |  |
|  | $L_{L}^{\text {maj }}$ | Categorical | Presence of left-turn lane in the intersection in major \& minor approach or of the intersection |
|  | $\mathrm{LL}_{\text {maj }}$ |  |  |
| Traffic Data | $\mathrm{AADT}_{\text {maj }}$ | Discrete | Annual Average Daily Traffic in major approach roadway |
|  | $\mathrm{AADT}_{\text {min }}$ | Discrete | Annual Average Daily Traffic in minor approach roadway |
| Crash Data | Total | Discrete | Total crashes per year per intersection |
|  | F+I | Discrete | Fatal+Injury crashes per year per intersection |
|  | PDO | Discrete | Property Damage Only crashes per year per intersection |
|  | Angle | Discrete | Angle crashes per year per intersection |
|  | Rear-end | Discrete | Rear-end crashes per year per intersection |
|  | Head-on | Discrete | Rear-end crashes per year per intersection |
|  | Sideswipe | Discrete | Rear-end crashes per year per intersection |

Model estimates for crash severity for single and multiple vehicle crashes for simple SPFs are shown in Table 21.

Table 21: Wyoming-specific Simple SPF Coefficients of Generalized and Single and Multiple Vehicle Crashes

| Crash Types |  | Intercept (a) | AADTmaj (b) | AADTmin (c) | Overdispersion <br> Parameter |
| :--- | :--- | :--- | :--- | :--- | :--- |
| All <br> Crash | Total | -5.92 | 0.76 | 0.34 | 0.29 |
|  | F+I | -8.20 | 0.79 | 0.40 | 0.35 |
|  | PDO | -6.13 | 0.77 | 0.32 | 0.30 |
|  | Total | -6.29 | 0.79 | 0.34 | 0.33 |
|  | F+I | -8.93 | 0.83 | 0.42 | 0.41 |
| Multiple | PDO | -6.46 | 0.80 | 0.32 | 0.34 |
| Vehicle Crash | Angle | -6.94 | 0.77 | 0.32 | 0.39 |
|  | Rear-End | -8.92 | 0.94 | 0.36 | 0.39 |
|  | Sideswipe | -8.69 | 0.91 | 0.20 | 0.50 |
|  | Head-On | -5.96 | 0.43 | 0.31 | 0.51 |
|  | Total | -5.77 | 0.48 | 0.37 | 0.25 |
| Single | Vehicle | F+I | 0.60 | 0.29 | 0.15 |
| Crash | PDO | -6.00 | 0.42 | 0.41 | 0.45 |

All Estimates are at 95th Significance Level.
The intercept values of Wyoming-specific SPFs are larger than the HSM calibrated SPFs intercept values. This could be due to smaller AADT for minor and major approaches of Wyoming intersections than the HSM. This may indicate that predicted crashes in Wyoming are higher than their national average counterparts. Moreover, the characteristics of Wyoming intersections in terms of geometric features, driver's characteristics, and weather are different from the features used in the HSM calibration. Adverse weather conditions and a higher population of elderly drivers characterize Wyoming intersections, which might have an impact on the crash frequencies.

Wyoming-specific full SPFs are shown in Table 22 using other geometric characteristics of fourleg signalized intersections. Models were developed by crash severity and types of maneuvers. This table shows impacts of adding left-turn and right-turn lanes on intersection-related crashes. The literature showed that rear-end and angle crashes benefit most from these treatments [64]. Number of through lanes also affect the number of intersection-related crashes.

Table 22: Wyoming-specific Full SPF Coefficients for Four-leg Signalized Intersections

| Crash Types | Total Crash | $\mathrm{F}+\mathrm{I}$ | PDO |
| :--- | :--- | :--- | :--- |
| Intercept | -8.0088 | -9.5092 | -7.81 |
| AADT $_{\text {maj }}$ | 0.9119 | 0.7975 | 0.8617 |
| AADT $_{\text {min }}$ | 0.1381 | 0.2219 | 0.1346 |
| Lane $_{\text {maj }}$ | -0.0546 | 0 | 0 |
| Lane $_{\text {min }}$ | 0.5226 | 0.5532 | 0.4915 |
| LL $_{\text {maj }}$ | -0.2496 | 0 | -0.4 |
| LL $_{\text {min }}$ | 0 | 0 | 0.1709 |
| $\mathrm{RL}_{\text {maj }}$ | 0.2647 | 0 | 0.286 |
| $\mathrm{RL}_{\text {min }}$ | 0.3819 | 0 | 0.3535 |
| $\mathrm{RL}^{\text {Dispersion }}$ | 0.0668 | 0 | 0 |

All Estimates are at 95th Significance Level

Three SPFs were developed for four-leg signalized intersections for different crash severities (Total, F+I, and PDO). Average $\mathrm{AADT}_{\text {maj }}$ and $\mathrm{AADT}_{\text {min }}$ values were used to represent the AADT for the study years (2005-2014) for each intersection. The predictors of developed SPFs shown in table 4 are all significant at a 95 percent confidence level.

The variable estimates of all severity types of crashes showed trends of crashes for that specific type of severity. For total crash models, increasing number of major approach lanes had positive effect on crash reduction. The result is in line with a study conducted by Bauer and Harwood (1996) [104]. They observed that the expected number of crashes at the four-leg signalized intersections decreases as the number of lanes on major road increases using a negative binomial regression model. But minor approach number of lanes had negative impact for all models, as it represents crash increase with adding more lanes. More lanes in minor approaches mean more traffic in minor approaches hence an increase in probability of collision with the major approach traffic. The number of total lanes at an intersection that represents the size of that intersection could be a surrogate to traffic volume [105]. Therefore, number of lanes could be correlated with AADT. These variables were kept in the model to evaluate their safety effectiveness regardless possible correlation with AADT.

Adding right-turn lanes showed increased crash frequencies for total and PDO crashes by 25 and 29 percent, respectively, for major approaches; as well as 38 and 35 percent, respectively, for minor approaches. From an operation standpoint, addition of right-turn lane may increase the potential for rear-end and sideswipe crashes on the departure lanes as the vehicles turning onto the crossroad may conflict with other traffic streams [64].

## CMFs for Left-Turn and Right Turn-Lanes

Full SPFs developed for Wyoming were used to calculate crash modification factors by cross sectional methodology. Added left-turn lanes in major approach of four-leg signalized intersections found to reduce 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 approach increases total and PDO crashes. All CMFs are provided in Table 23. Table 20 describes the data and variables used in this study.

Table 23: CMFs for Four-leg Signalized Intersections

| Crash Modification Factors |  |  |  |
| :---: | :---: | :---: | :---: |
|  | Total Crash | F+I | PDO |
| $L_{\text {maj }}$ | 0.78 | N/A | 0.67 |
| $\mathrm{LL}_{\text {min }}$ | N/A | N/A | 1.19 |
| $\mathrm{RL}_{\text {maj }}$ | 1.3 | N/A | 1.33 |
| $\mathrm{RL}_{\text {min }}$ | 1.47 | N/A | 1.42 |
| RL | N/A | 1.46 | N/A |
| N/A- Insignificant Variable |  |  |  |

## SECTION SUMMARY

One of the goals of this research was to estimate the effectiveness of adding left and right-turn lanes at four-leg signalized intersections and effect of geometric characteristics on crash frequency by severity and crash types. To explicitly understand the effects of the geometric characteristics on crashes, there was a necessity to develop safety performance functions.

With crash frequency by severity and types as response variables and intersection geometric characteristics as explanatory variables, Negative Binomial form was found to perform the best among several other forms. From the added left-turn lanes at intersections, safety effectiveness was evaluated by the cross-sectional method, which resulted in reduction of total and PDO crashes by a significant amount. Models also found that all crashes are negatively affected by installing right-turn lanes and left-turn lanes at minor approaches.

Intersection minor approach roadway AADT were estimated by assumptions based on number of vehicles counted in imagery in the Google Earth Pro ${ }^{\circledR}$ satellite imagery. However, the comparison of one road to another can be inaccurate and difficult to perform. These limitations need to be addressed in future by developing and implementing travel demand models and AADT prediction models for non-mile-posted roads of Wyoming. Statistical techniques which allow multilevel data structure to analyze the data at geographic region level and traffic site level could be adopted for a better understanding of contributing factors. The crash data which has correlated observations within groups are also better represented by hierarchical models [106].

Future research in this area includes the estimation of CMFs for more explanatory variables in multilevel or hierarchical models applying Bayesian approach for more reliable results.

An intersection database can be developed through combining information collected in this study with data provided by WYDOT. The database should have traffic characteristics of each intersection and its unique node number. This database can be combined with crash database (CARE) to form a master data.

## CHAPTER 6-ITS AND SPECIAL FACILITIES

## INTRODUCTION

In order to properly understand the effect that the snow fence installations have on the roadway and its users, crash data was collected. The crash data was acquired from the Critical Analysis Reporting Environment (CARE) crash database software. This is a desktop software that is updated and maintained by WYDOT and allows for the acquisition of crash data through various analysis methods and criteria. This allowed for the milepost limitations to be applied and, from there, the data were trimmed to only display and analyze that which occurred during the winter season (October 15 through April 15).

This study investigated the safety effectiveness of snow fence implementations by comparing crash data both before and after the installation of fences between MP 325 and MP 344 along Interstate 80 (Route ML80) in Southeastern Wyoming using odds ratios, naïve before-after, and before-after with Empirical Bayes that utilizes a Negative Binomial Wyoming-specific Safety Performance Function (SPF).

## DATA COLLECTION

## Data Source

The data included in this study is a combination of weather data and crash data. The primary sources of data were the CARE software, which was collected from October 2003 to April 2011 and aggregated on a winter weather season basis, as well as reconstructed hourly winter weather data for the investigation location that was collected from three adjacent 12 kilometer ( 7.5 mile) sections.

## Data Description

In order to understand and quantify the safety effectiveness of snow fence implementations within the state of Wyoming, an area from mile post (MP) 325 to 344 along Interstate 80 (ML80B) was selected for investigation. This section of roadway was selected primarily due to the heavy presence of snow fences along this section. Furthermore, this section of I-80 is characterized by mountainous terrain, intense adverse weather conditions, and high traffic volumes (relative to other Wyoming highways and freeways).

The snow fences included along Interstate 80 between MP 325 and 344 were found to have been either constructed or reconstructed in 2007. For this reason, the investigation period for this particular study spans from 2003 to 2011. More specifically, the study investigates various data from October $15^{\text {th }}, 2003$ to April $15^{\text {th }}, 2011$. This was done in order to more accurately understand crashes and weather conditions that occurred only during the winter weather season, which is typically defined as October 15 to April 15 for analysis purposes. In total, the investigation period includes eight full winter weather seasons, with four coming before the implementation of snow fences, and four coming after.

## Challenges and Limitations

Many of the complications in evaluating the effectiveness of snow fence implementations came in the consistency of design throughout the study area. As it has been previously mentioned, WYDOT currently displays standard design specifications for only one fence type (at two separate heights). However, a visual inspection of many fences along the study area shows that there are many more than two separate fence sizes and designs. This raises the question of difference in safety performance based on fence type and design.
Additionally, the weather data that is involved in this study does not originate from a state agency, as such data has not been made available on an archived basis. The acquisition of data from systems coincident with the roadway network, such as RWIS, is ideal for such a study, but is not available at this time.

Finally, the overall lack of information and previous studies on snow fences and their effect on traffic safety has been found somewhat lacking. Snow fence design seems to be an extremely under investigated engineering implementation. Snow fences act as an extremely economic method of snow management, which is increasingly significant when dealing with transportation agencies whose funding may not allow for additional spending on auxiliary areas (such as snow removal) within the realm of transportation. It has been historically proven that snow fence implementation can be, on average, up to 100 times cheaper than traditional snow plowing techniques [72]. This is primarily, but not solely, derived from a Wyoming study that is used as a basis for many snow fence studies conducted today, but its relevancy, as a 10+ year old study, may be questioned.

## Potential Recommendations to Overcome Challenges

The issue of contrasting snow fence designs and their suspected differences in safety and storage performance is something that will ultimately come down to additional studies. Decomposing the crash analysis performed in this study, to only compare crashes at locations of same-type snow fences, which will likely occur only after all different designs and sizes of fences along the investigation location have been synthesized and distinguished is essential to the understanding of their performance.

The lack of readily available archived winter weather data for Wyoming roadways is something that is in the process of being resolved. The data that was utilized in this study certainly has relevance and proximity to the crash investigation location, but currently, weather data from the Meteorological Assimilation Data Ingest System (MADIS) of the National Centers for Environmental Prediction (NCEP) are being processed. This is an extremely promising and rich data source that will hopefully provide more accurate and aligned weather data to the crash investigation location.

## RESULTS

## Weather Conditions

See Table 24 for a brief overview of the weather data gathered during the winter season for the investigation location. Note that the mobile and blowing snow rates found in Table 24 are not given as velocities, but rather as a total depth, in millimeters, per hour of time.

Table 24: Weather Data from Study Location

|  | Average 2.5 <br> m Wind | Average <br> Mobile | Average <br> Blowing |  |  |
| :--- | :--- | :--- | :--- | :--- | :--- |
| Speed |  |  |  |  |  |
|  | Total <br> $(\mathrm{m} / \mathrm{sec})$ | Snow Rate <br> $(\mathrm{mm} / \mathrm{hr})$ | Snow <br> $(\mathrm{mm} / \mathrm{hr})$ | Rate <br> Snowfall <br> $(\mathrm{mm})$ | Average <br> Air Temp <br> $\left({ }^{\circ} \mathrm{C}\right)$ |
| $2004-2007$ | 6.013 | 0.196 | 0.104 | 300.6 | -0.478 |
| $2007-2010$ | 6.272 | 0.231 | 0.144 | 332.6 | -1.423 |
|  | $\uparrow 4.37 \%$ | $\uparrow 17.9 \%$ | $\uparrow 38.5 \%$ | $\uparrow 10.6 \%$ | $\downarrow 0.945^{\circ} \mathrm{C}$ |

## SPFs for Freeways

The SPFs utilized for the safety analysis of snow fence implementations followed the model of a simple SPF where the included parameters were AADT and segment length. Additionally, these SPFs were calibrated for Wyoming-specific conditions that included mountainous terrain and the winter weather season. Table 25 shows coefficients involved in the NB model for this analysis.

Table 25: Wyoming-specific SPFs for Interstate Freeways during Winter Months

| Crash <br> Type | Intercept <br> Estimate | Log(AADT) <br> Estimate | Dispersion <br> $(\mathrm{k})$ |
| :--- | :--- | :--- | :--- |
| F+I | -8.2786 | 2.1192 | 0.1501 |
| PDO | -11.3416 | 3.1278 | 0.2512 |
| Total | -12.7676 | 3.5971 | 0.3857 |

Calibration for the Crash Modification Factors (CMFs) for several countermeasures were conducted. Below are the countermeasures and the preliminary results obtained for the CMF calibration.

## CMFs for Snow Fence

The odds ratio and subsequent ratio of odds ratios were found to understand the relationship between total crashes that occur in the winter weather period and target crashes (adverse weather crashes) that occur within the same period. The comparison between target and total crashes was compared before and after the implementation, and the results can be found in Table 26.

Table 26: Contingency Table with Odds Ratio for Total and F+I Crashes

|  | Total |  |  |  | F+I |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | Total Crashes | Target Total Crashes | Odds | Odds <br> Ratio | F+I Crashes | Target F+I Crashes | Odds | Odds <br> Ratio |
| Before Implementation | 496 | 268 | 54\% | 0.72 | 156 | 87 | 56\% | 0.77 |
| After <br> Implementation | 457 | 342 | 75\% |  | 107 | 78 | 73\% |  |

As it can be seen in the above table, the odds ratio for total crashes was found to be 0.75 , indicating a lesser portion of crashes during adverse weather was experienced prior to the implementation of snow fences. The odds ratio for the F+I crashes was found to be 0.77 . This value indicates, similar to the total crash OR, that a higher portion of the fatal and injury crashes, during adverse weather conditions, came after the installation of the snow fences. However, the confidence intervals for the total crashes and the F+I crashes were found to be 0.57 to 0.88 and 0.52 to 1.14 , respectively, which both indicate that there was no statistically significant effect as a result of snow fence implementation with regard to either crash type during the winter weather season. The ratio of odds ratios shows that the ratio of OR's for total crashes (0.72) and for $\mathrm{F}+\mathrm{I}$ crashes ( 0.77 ) is equal to 1.07 . This is promising as it 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 yielded very straightforward results. The comparison of F+I and PDO crashes before and after the implementation year showed numerous results. Of the total crashes that occurred during all-weather types, 31 percent were $\mathrm{F}+\mathrm{I}$ before the implementation of snow fences and 23 percent were $\mathrm{F}+\mathrm{I}$ after, showing a 31.41 percent decrease in fatal and injury crashes. Additionally, there was a 2.94 percent increase in PDO crashes after the implementation of snow fences. The crashes that occurred under adverse weather conditions during winter months were expected to be more representative of the true effect of the snow fences. There was a 10.34 percent decrease seen in fatal and injury crashes that occurred in adverse weather, but a 45.86 percent increase in PDO crashes and a 27.61 percent increase in total crashes. These results do not seem reliable as they suggest a significant increase in total and PDO crashes after the time of snow fence implementation. The before-after analysis using EB showed predictably more refined results as the SPFs used for this analysis took AADT and segment length into account. By involving these parameters in the model, their expected contributions to crashes were taken into account and a hopefully truer representation of the safety effectiveness of the snow fences was found. This allowed for the safety effectiveness of the snow fence implementations, or CMFs to be calculated (as well as their standard error to test statistical significance). These cumulative analysis results can be found in Table 27.

Table 27: Naïve Vs EB Analysis Results for the Snow Fences

|  | Analysis Method |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | Naïve (All Weather) |  | Naïve (Adverse Weather) |  | EB (All Weather) |  | EB (Adverse Weather) |  |
| Crash <br> Type | CMF <br> (Safety <br> Effectiveness) | S.E. | CMF <br> (Safety Effectiveness) | S.E. | CMF <br> (Safety <br> Effectiveness) | S.E. | CMF <br> (Safety <br> Effectiveness) | S.E. |
| F+I | $\begin{aligned} & 0.69 \\ & (\mathbf{3 1 . 4 1 \%}) \end{aligned}$ | $\begin{aligned} & 0.64 \\ & 64.11 \% \end{aligned}$ | $\begin{aligned} & 0.9 \\ & (\mathbf{1 0 . 3 4 \%}) \end{aligned}$ | $\begin{aligned} & 0.61 \\ & 61.17 \% \end{aligned}$ | $\begin{aligned} & 0.41 \\ & \mathbf{( 5 9 . 0 9 \%}) \end{aligned}$ | $\begin{aligned} & 0.047 \\ & 4.75 \% \end{aligned}$ | $\begin{aligned} & 0.38 \\ & (61.98 \%) \end{aligned}$ | $\begin{aligned} & 0.051 \\ & 5.15 \% \end{aligned}$ |
| PDO | $\begin{aligned} & 1.03 \\ & (-2.94 \%) \end{aligned}$ | $\begin{aligned} & 0.71 \\ & 70.55 \% \end{aligned}$ | $\begin{aligned} & 1.46 \\ & (-45.86 \%) \end{aligned}$ | $\begin{aligned} & 0.78 \\ & 78.32 \% \end{aligned}$ | $\begin{aligned} & 0.77 \\ & (\mathbf{2 3 . 2 1 \%}) \end{aligned}$ | $\begin{aligned} & 0.056 \\ & 5.57 \% \end{aligned}$ | $\begin{aligned} & 0.94 * \\ & (5.98 \%)^{*} \end{aligned}$ | $\begin{aligned} & 0.08 \\ & 7.99 \% \end{aligned}$ |
| Total | $\begin{aligned} & 0.92 \\ & (\mathbf{7 . 8 6 \%}) \end{aligned}$ | $\begin{aligned} & 0.85 \\ & 85.34 \% \end{aligned}$ | $\begin{aligned} & 1.28 \\ & (-27.61 \%) \end{aligned}$ | $\begin{aligned} & 0.86 \\ & 85.98 \% \end{aligned}$ | $\begin{aligned} & 0.75 \\ & (\mathbf{2 5 . 3 \%}) \end{aligned}$ | $\begin{aligned} & 0.047 \\ & 4.72 \% \end{aligned}$ | $\begin{aligned} & 0.84 \\ & (\mathbf{1 5 . 6 7 \%}) \end{aligned}$ | $\begin{aligned} & 0.063 \\ & 6.33 \% \end{aligned}$ |

Bold indicates significant crash reduction, S.E. $=$ Standard Error
*Indicate statistical insignificance
The before-after analysis using EB offers extremely promising results as CMFs of 0.75 and 0.84 for total crashes in all weather conditions and adverse weather conditions, respectively, indicate significant increases in safety. Additionally, the CMFs for F+I crashes in all weather and adverse weather conditions were found to be 0.41 and 0.38 , respectively. These results indicate significant safety increases as a result of the presence of snow fences for multiple crash types during the winter weather season during all weather conditions as well as adverse weather conditions.

## SECTION SUMMARY

The historical effects of snow fences on roadway travel have indicated positive results, but in depth analysis of their quantitative safety effectiveness helps to understand and explain the effects. Throughout this study, crashes were evaluated primarily as a total, PDO, and fatal and injury ( $\mathrm{F}+\mathrm{I}$ ). This was performed in order to help better understand the effect that the snow fences have on both crash frequency and severity. Furthermore, crashes were categorized into those that occurred during all weather conditions within the winter weather season and those that occurred only during adverse weather conditions within the winter weather season (October 15 to April 15).

The naïve before-after analysis showed signs that snow fence installations were positively affecting the frequency of $\mathrm{F}+\mathrm{I}$ crashes ( 31.41 percent decrease in all weather conditions, 10.34 percent decrease in adverse weather) but the results for PDO and total crashes indicated decreased safety effectiveness during winter months due to the implementation of snow fences.

These results were refined through the EB method, by the calibration of Wyoming-specific SPFs, and it became evident how the safety effectiveness with regard to each crash type (as well as their associated standard error) was adjusted and better-developed by considering changes in time and traffic volumes. The EB method showed that all types of crashes, regardless of weather conditions, were reduced by the presence of snow fences during the winter months. Most
significantly, there was a 59.09 percent decrease in $\mathrm{F}+\mathrm{I}$ crashes during all weather conditions and a 61.98 percent decrease during adverse weather conditions. In addition to this, PDO crashes displayed a decrease of 23.21 percent in all weather conditions and a 5.98 percent decrease in adverse weather conditions and total crashes displayed a decrease of 25.3 percent in all weather conditions and a 15.67 percent decrease in adverse weather conditions as a result of snow fence presence. These values reflect extremely well on the safety effectiveness of the snow fence installations and provide assurance that crashes, as a result of inclement winter weather conditions and their effects, have been significantly reduced in terms of frequency and severity. These results are especially encouraging when combined with the findings that winter weather conditions at this location have only worsened when investigating data for wind speed, mobile snow, blowing snow, total snowfall, and air temperature.

## 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 U.S., tens of thousands lose their lives every year in traffic crashes. Contrasting fatalities in Wyoming to the national average revealed that Wyoming experience higher fatality rates compared to all states in the U.S. Adhering only to standards will not address this issue. Shifting and moving to substantive safety should be considered. This could be achieved by quantifying the safety performance of roadway facilities in Wyoming following a scientific-based approach is needed. 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. It proposes alternative solutions to overcome data limitations and challenges to implement a scientificapproach following the HSM.

Two main tasks were accomplished in this study, starting with developing Safety Performance Functions (SPF) for Wyoming-specific conditions followed by calibrating Crash Modification Factors (CMFs) for different countermeasures implemented in Wyoming's road network. Several limitations were encountered to calibrate SPFs and CMFs presented in the Highway Safety Manual (HSM). Data used to develop crash prediction models for the HSM was obtained from only a few states. Yet, states from the mountain plains region are not represented. 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, energy activities in different counties, and implementation dates and locations for treatments were all required. A number of data sources were utilized to prepare and develop 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 developing and calibrating CMFs for three groups of roadway facilities; 1) Roadway segments, 2) Intersections, and 3) ITS and special facilities. Calibrating reliable CMFs required having SPFs for the site-specific conditions. Safety Performance Functions for roadway segments and intersections 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. Negative Binomial models (NB), Zero Inflated Poisson (ZIP) models, and Zero Inflated Negative

Binomial models (ZINB) were adopted. Comparisons between the obtained models were performed to select the most accurate and reliable SPFs.

Several SPFs were developed for roadway segments. Initially, general SPFs for roadway segments were developed including simple and full SPFs. Simple SPFs only account for the Average Annual Daily Traffic (AADT). In order to account for other confounding factors affecting crash prediction, full SPFs were developed. Roadway segments were categorized into two groups; roadways in oil and gas counties and roadways in non-oil and gas counties. Separate SPFs were established for the two roadway groups. In addition, simple and full SPFs for four-leg signalized intersections were calibrated.

The Highway Safety Manual (HSM) provides multiple statistical techniques to calibrate CMFs. Odd, odds ratio, ratio of odds ratio, cross-sectional studies, observational before-after studies using Empirical Bayes (EB) method, and before-after studies using naïve method were the methods used to calibrate the crash modification factors. Each method has its own strengths and weaknesses. Obtained results for SPFs and CMFs for the various roadway facilities are located in their corresponding chapter and summarized in Appendix A.

## CONCLUSIONS

## Shoulder Rumble Strips and Passing Lanes

Observational before-after with Empirical Bayes method was used to quantify the safety effectiveness of shoulder rumble strips in this study. Full safety performance functions were developed to predict crashes. Shoulder rumble strips were found to reduce 55 percent of F+I crashes in rural two-way two-lane highways in Wyoming. Comparing between oil and non-oil counties, shoulder rumble strips were found to be more effective in oil counties. Crash modification factors for oil counties were calculated as 0.40 and 0.18 for total and $\mathrm{F}+\mathrm{I}$ crashes, respectively. For non-oil counties, shoulder rumble strips were effective to reduce F+I crashes but not effective to reduce total crashes.

In general, passing lanes were found to be statistically significant to reduce total and F+I crashes in rural two-way two-lane highways in Wyoming. Passing lanes reduce 42 and 34 percent of total and F+I crashes, respectively. Passing lanes were more effective to reduce crashes in oil counties by 61 and 59 percent for total and $\mathrm{F}+\mathrm{I}$ crashes, respectively. In non-oil counties, passing lanes were found to reduce $\mathrm{F}+\mathrm{I}$ 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 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.

## 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.

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 $\mathrm{F}+\mathrm{I}$ crashes and 10 percent for 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.

## Snow Fences

It was found that snow fences in Wyoming have had significant impacts on traffic safety for freeway travel during the winter months. The calculated ratio of odds ratios shows that the ratio of OR's for total crashes ( 0.72 ) and for $\mathrm{F}+\mathrm{I}$ crashes ( 0.77 ) is equal to 1.07 . This is promising as it 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 $\mathrm{F}+\mathrm{I}$ before the implementation of snow fences and 23 percent were $\mathrm{F}+\mathrm{I}$ 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 found 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.

## RECOMMENDATIONS

Several limitations and challenges have been discussed in previous sections and overcome by various data imputation 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 for future work. One instance of this is that crash data are currently compiled into two separate CARE packages, both of which are required to perform extensive analyses for studies in Wyoming since 1994. Moreover, many of the treatments included in this report were implemented before 2000. The first version available for CARE ranges from 1994 to 2010 and the second version covers 2005 to 2015. The overlapping years between the two versions were found to have discrepancies in crash frequencies.

Additionally, a lack of archived implementation dates could greatly aid this study. Implementation dates for treatments had to, at times, be estimated using non-traditional data sources. Examining Google Earth Pro ${ }^{\circledR}$ time-lapse satellite imagery provided a general approximation for the countermeasures implementation dates. Additionally, Pathway video logs were also used to provide an estimation for the implementation dates that were not readily available.

Similar to this issue, the ambiguous implementation dates of shoulder rumble strips needs to be addressed. According to WYDOT, shoulder rumble strips will be removed for 2 years after implementing an overlay treatment. However, it was found that this is a rough assumption and therefore is not reliable for safety analysis. It was found that there are two possible ways to overcome the effect of shoulder rumble strips intermittency. The first, and most simple of these was to exclude these particular sections from the analysis. This particular solution was adopted and applied in this study. The alternative approach could be considering every off situation as before period and every on situation as after period. Data about overlay implementation should be included in the analysis as well. However, this information proved to be extremely difficult to acquire. This alternative approach could provide a more reliable results, however, it needs additional effort and analysis, which might be done in future studies and phases.

Additional limitations are introduced with AADT data and headlight signs. The headlight signs included in this study were found to be implemented in 1994, and later in 2012, however, the AADT data provided for Wyoming roads are only available from 2003. This introduces limitations to conduct proper observational before-after studies for this particular countermeasure (and others that encounter the same issue with AADT data availability) as there is no relevant and applicable AADT data.

With the increase in number of vehicles equipped with DRLs and automatic low-beam headlights, many drivers do not comply with the regulatory headlight signs. To investigate the
effect of the DRL technology penetration on the safety effectiveness of regulatory headlight signs, information about compliance to the headlight light sign and the existence of DRL technology for the crashed vehicles in the before and after periods are essential. However, it is impossible to obtain such information for the historical crash data. This is another issue that can be addressed in future studies, to add to what has already been presented.

The issue of contrasting snow fence designs and their suspected differences in safety and storage performance is something that will ultimately come down to additional studies. Decomposing the crash analysis performed in this study, to only compare crashes at locations of same-type snow fences, which will likely occur only after all different designs and sizes of fences along the investigation location have been synthesized and distinguished is essential to the understanding of their performance.

The lack of readily available archived weather data for Wyoming roadways is something that is in the process of being resolved, but requires further work. The data that was utilized in this study certainly has relevance and proximity to the respective crash investigation locations, but currently, weather data from the Meteorological Assimilation Data Ingest System (MADIS) of the National Centers for Environmental Prediction (NCEP) are being processed as hopefully superior alternatives.

Currently, several additional countermeasures are being considered for future work. These countermeasures include, but are not limited to, roadway widening and overlay, climbing lanes, centerline rumble strips, combining shoulder and centerline rumble strips, roadway information systems (DMS), and VSL. 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 particularly strong correlation to the upcoming connected vehicles and the future work within this field that will take place on Wyoming roads.

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## APPENDIX A

## SAFETY PERFORMANCE FUNCTIONS (SPFS)

Table A-1: Variable Estimates and Significance level for SPFs using NB Model for Oil and Non-oil Counties in Wyoming (Data 2003-2014)

| (A) Calibrated SPFs for Oil Counties of Wyoming |  |  |  |  | (B) Calibrated SPFs for Non-oil Counties of Wyoming |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Variable | Total Crashes |  | F+I Crashes |  | Variable | Total Crashes |  | F+I Crashes |  |
|  | Estimate | p-value | Estimate | p-value |  | Estimate | p-value | Estimate | p-value |
| Intercept | -4.051 | 0.0001 | -4.167 | 0.0110 | Intercept | -4.543 | <. 0001 | -3.506 | 0.0151 |
| DOC | 0.047 | 0.1878 | 0.063 | 0.3051 | DOC | 0.006 | 0.1933 | -0.008 | 0.4002 |
| SRS | -0.342 | 0.0041* | -0.665 | 0.0002* | SRS | 0.033 | 0.8041 | -0.147 | 0.4772 |
| VG1 | 0.155 | 0.4194 | -0.167 | 0.5716 | VG1 | 0.143 | 0.3845 | -0.147 | 0.5757 |
| VG2 | 0.147 | 0.3898 | -0.260 | 0.3068 | VG2 | 0.089 | 0.5661 | -0.114 | 0.6476 |
| VG3 | 0.012 | 0.9471 | -0.284 | 0.2697 | VG3 | -0.015 | 0.9136 | -0.259 | 0.2594 |
| SW | -0.006 | 0.8023 | -0.055 | 0.1180 | SW | -0.022 | 0.4279 | -0.029 | 0.5030 |
| Ln(VMT) | 0.972 | <.001* | 0.673 | <.001* | Ln(VMT) | 0.791 | <.001* | 0.691 | <.001* |
| Truck | -0.004 | 0.8851 | 0.067 | 0.0998 \# | Truck | -0.017 | 0.5299 | -0.060 | 0.1534 |
| Speed | -0.023 | 0.0452* | -0.006 | 0.7010 | Speed | -0.002 | 0.8556 | 0.001 | 0.9794 |
| Rainy | -0.001 | 0.8125 | -0.013 | 0.0020* | Rainy | 0.018 | 0.0012* | 0.005 | 0.5846 |
| Snowy | 0.005 | 0.0082* | 0.010 | 0.0031* | Snowy | -0.006 | 0.0245* | -0.004 | 0.3850 |
| Dispersion | 0.273 |  | 0.299 |  | Dispersion | 0.403 |  | 0.712 |  |

* Significant at 95 percent confidence level, \# Significant at 90 percent confidence level

Table A- 2: Variable Estimates and Significance level for SPFs using Log-Normal Model for Rural Two-way Two-lane Highways in Wyoming (Data 2008-2014)

| Variable | Total Crashes |  | F+I Crashes |  |  |
| :--- | :--- | :--- | :--- | :--- | :---: |
|  | Estimate | p -value | Estimate | p -value |  |
| Intercept | -6.165 | $<.0001^{*}$ | -7.5588 | $<.0001^{*}$ |  |
| DOC | 0.006 | 0.2421 | 0.0096 | 0.2078 |  |
| VG1 | 0.4458 | $0.0043^{*}$ | 0.4616 | 0.1148 |  |
| VG2 | -0.1471 | 0.3188 | -0.6206 | $0.0238^{*}$ |  |
| VG3 | 0.1695 | 0.2653 | 0.065 | 0.8141 |  |
| SW | -0.0334 | $0.0082^{*}$ | -0.0854 | $0.0002^{*}$ |  |
| Ln(VMT) | 0.951 | $<.0001^{*}$ | 1.1054 | $<.0001^{*}$ |  |
| Truck | -0.0551 | $<.0001^{*}$ | -0.0571 | $0.0005^{*}$ |  |
| Rainy | -0.0117 | $0.003^{*}$ | -0.0228 | $0.0048^{*}$ |  |
| Snowy | 0.0157 | $0.007^{*}$ | 0.0271 | $0.002^{*}$ |  |
| Scale | 0.2432 |  | 0.1346 |  |  |

* Significant at 95 percent confidence level

Table A- 3: Variable Estimates and Significance level for SPFs using Log-Normal Model for Oil and Non-oil Counties in Wyoming (Data 2008-2014)

| Variable | (A) SPFs for Total and F+I Crashes for Oil Counties |  |  |  | (B) SPFs for Total and F+I Crashes for Non-oil Counties |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | Total Crashes |  | F+I Crashes |  | Total Crashes |  | F+I Crashes |  |
|  | Estimate | p-value | Estimate | p-value | Estimate | p-value | Estimate | p-value |
| Intercept | -6.3445 | <. 0001 | 1.1958 | 0.2838 | -6.8694 | <. 0001 | -9.9791 | <. 0001 |
| DOC | -0.0195 | 0.4512 | -0.0313 | 0.6582 | 0.0080 | 0.0568** | 0.0105 | 0.0745** |
| VG1 | 0.4951 | 0.0745** | 0.6677 | 0.5183 | 0.6720 | 0.0136* | 1.5499 | 0.0033* |
| VG2 | -0.0055 | 0.9820 | 0.3147 | 0.7239 | 0.1144 | 0.6579 | 0.4625 | 0.3603 |
| VG3 | 0.4606 | 0.0523** | 0.7418 | 0.3862 | 0.2385 | 0.3403 | 0.5452 | 0.2971 |
| SW | -0.0238 | 0.1003 | -0.0916 | <.0001* | -0.0497 | 0.0278* | -0.0905 | 0.0993** |
| Ln(VMT) | 0.8700 | <.0001* | 1.1477 | <.0001* | 0.9923 | <.0001* | 1.1057 | <.0001* |
| Truck | -0.0542 | $0.0569 * *$ | -0.3676 | 0.0001* | -0.0478 | <.0001* | -0.0206 | 0.3042 |
| Rainy | 0.0142 | 0.3802 | -0.1362 | <.0001* | -0.0144 | 0.0044* | -0.0199 | 0.0419* |
| Snowy | -0.0221 | 0.3265 | 0.1280 | 0.2838 | 0.0278 | 0.0004* | 0.0491 | 0.0001* |
| Scale | 0.2560 |  | 0.1454 |  | 0.2228 |  | 0.1139 |  |

* Significant at 95 percent confidence level, ** Significant at 90 percent confidence level

Table A- 4: Wyoming-specific SPFs for Interstate Freeways during Winter Months

| Crash <br> Type | Intercept <br> Estimate | Log(AADT) <br> Estimate | Dispersion <br> $(\mathrm{k})$ |
| :--- | :--- | :--- | :--- |
| F+I | -8.2786 | 2.1192 | 0.1501 |
| PDO | -11.3416 | 3.1278 | 0.2512 |
| Total | -12.7676 | 3.5971 | 0.3857 |

Table A- 5: The HSM Calibrated Simple SPF Coefficients of Single and Multi-Vehicle Crashes by Crash Severity for Signalized Intersections
SPF Coefficients for Intersections by Crash Severity

|  |  | Intercept | AADT $_{\text {maj }}$ | $\mathrm{AADT}_{\text {min }}$ | Overdispersion <br> Parameter |
| :--- | :--- | :--- | :--- | :--- | :--- |
| Multiple | -Veh | Total | -10.99 | 1.07 | 0.23 |
| Crashes | F+I | -13.14 | 1.18 | 0.22 | 0.39 |
|  |  | PDO | -11.02 | 1.02 | 0.24 |
| Single -Veh Total -10.21 0.68 0.27 <br> Crashes  F+I -9.25 0.43 0.29 | PDO | -11.34 | 0.78 | 0.25 | 0.36 |

Table A- 6: Wyoming-specific Simple SPF Coefficients of Generalized and Single and Multi-vehicle Crashes

| Crash Types |  | Intercept (a) | AADTmaj (b) | AADTmin (c) | Overdispersion <br> Parameter |
| :--- | :--- | :--- | :--- | :--- | :--- |
| All  <br> Crash Vehicle | F+I | -5.92 | 0.76 | 0.34 | 0.29 |
|  | PDO | -8.20 | 0.79 | 0.40 | 0.35 |
|  | Total | -6.13 | 0.77 | 0.32 | 0.30 |
|  | F+I | -6.29 | 0.79 | 0.34 | 0.33 |
| Multiple | PDO | -8.93 | 0.83 | 0.42 | 0.41 |
| Vehicle Crash | Angle | -6.46 | 0.80 | 0.32 | 0.34 |
|  | Rear-End | -6.94 | 0.77 | 0.32 | 0.39 |
|  | Sideswipe | -8.92 | 0.94 | 0.36 | 0.39 |
|  | Head-On | -8.69 | 0.91 | 0.20 | 0.50 |

All Estimates are at 95th Significance Level

Table A- 7: Wyoming-specific Full SPF Coefficients for Four-Legged Signalized Intersections

| Crash Type | Total Crash | F+I | PDO |
| :--- | :--- | :--- | :--- |
| Intercept | -8.0088 | -9.5092 | -7.8100 |
| $\mathrm{AADT}_{\text {maj }}$ | 0.9119 | 0.7975 | 0.8617 |
| $\mathrm{AADT}_{\text {min }}$ | 0.1381 | 0.2219 | 0.1346 |
| Lane $_{\text {maj }}$ | -0.0546 | 0 | 0 |
| Lane $_{\text {min }}$ | 0.5226 | 0.5532 | 0.4915 |
| $\mathrm{LL}_{\text {maj }}$ | -0.2496 | 0 | -0.4000 |
| $\mathrm{LL}_{\text {min }}$ | 0 | 0 | 0.1709 |
| $\mathrm{RL}_{\text {maj }}$ | 0.2647 | 0 | 0.2860 |
| $\mathrm{RL}_{\text {min }}$ | 0.3819 | 0 | 0.3535 |
| $\mathrm{RL}_{\text {Dispersion }}$ | 0 | 0.0668 | 0.3804 |
| All Estimates are at 95th Significance | 0 |  |  |

## CRASH MODIFICATION FACTORS (CMF)

Table A- 8: Calibrated Preliminary CMFs of Shoulder Rumble Strips using Cross-sectional analysis for oil and non-oil counties in Wyoming

|  | Oil Counties | Non-oil Counties |
| :--- | :--- | :--- |
| Crash Type | CMF (Safety Effectiveness \%) | CMF (Safety Effectiveness \%) |
| Total | $0.71^{*}(29 \%)$ | $1.00(0 \%)$ |
| Crashes | $0.51^{*}(49 \%)$ | $0.86(14 \%)$ |
| F+I Crashes | * Significant at 95 percent confidence level |  |

Table A- 9: Calibrated Preliminary CMFs of Passing Lanes using before-after analysis with EB for oil and non-oil counties in Wyoming

|  | Oil Counties |  |
| :--- | :--- | :--- | Non-oil Counties

* Significant at 95 percent confidence level

Table A- 10: Calibrated Final Combined CMFs of Shoulder Rumble Strips (SRS) using before-after with EB

| for Rural Two-way Two-lane Highways in Wyoming |  |
| :--- | :--- |
| Crash Type | CMF (Safety Effectiveness \%) |
| Total Crashes | $1.05(-5 \%)$ |
| F+I Crashes | $0.45^{*}(55 \%)$ |

* Significant at 95 percent confidence level

Table A- 11: Calibrated Final CMFs of Shoulder Rumble Strips (SRS) using before -after analysis with EB for Oil and Non-oil Counties in Wyoming

|  | Oil Counties | Non-oil Counties |
| :--- | :--- | :--- |
| Crash Type | CMF (Safety Effectiveness \%) | CMF (Safety Effectiveness \%) |
| Total | $0.40^{*}(60 \%)$ | $0.69(31 \%)$ |
| Crashes | F+I Crashes | $0.18^{*}(82 \%)$ |

Table A- 12: Calibrated Final Combined CMFs of Passing Lanes using before-after with EB for Rural Twoway Two-lane Highways in Wyoming

| Crash Type | CMF (Safety Effectiveness \%) |
| :--- | :---: |
| Total Crashes | $0.58^{*}(42 \%)$ |
| F+I Crashes | $0.66^{*}(34 \%)$ |

* Significant at 95 percent confidence level

Table A- 13: Calibrated Final CMFs of Passing Lanes using before-after analysis with EB for Oil and Non-oil Counties in Wyoming

|  | Oil Counties | Non-oil Counties |
| :--- | :--- | :--- |
| Crash Type | CMF (Safety Effectiveness \%) | CMF (Safety Effectiveness \%) |
| Total | $0.39^{*}(61 \%)$ | $1.29(-29 \%)$ |
| Crashes | $0.41^{* *}(59 \%)$ | $0.36^{* *}(64 \%)$ |
| F+I Crashes |  |  |

* Significant at 95 percent confidence level, ** Significant at 90 percent confidence level

Table A- 14: Two-Way Contingency Table with Odds and Odds Ratio for Total and Target Crashes for Headlight Signs

| Crash Type | Section description | DRL <br> equipped <br> Vehicles | Non-DRL <br> equipped <br> Vehicles | Odds | Odds <br> Ratio |
| :---: | :---: | :---: | :---: | :---: | :---: |
| Total Crashes | with Headlight signs | 80 | 337 | $23.74 \%$ | 1.17 |
|  | without Headlight signs | 970 | 4799 | $20.21 \%$ | $12.50 \%$ |
|  | with Headlight signs | 4 | 32 | 0.56 |  |

Table A- 15: Ratio of Odds Ratio Analysis for Headlight Sign Controlling for the DRL Technology

| Simple odds and odds ratioanalysis | Headlight Locations |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | Target crashes | Control crashes | Odds | OR |
|  | DRL | 4 | 76 | 0.05 | 50 |
|  | No DRL | 32 | 305 | 0.10 | . 50 |
|  | Non-Headlight Locations |  |  |  |  |
|  |  | Target crashes | Control crashes | Odds | OR |
|  | DRL | 95 | 875 | 0.11 | 11 |
|  | No DRL | 429 | 4370 | 0.10 | . 1 |
|  | Lower bound |  | ROR | Upper bound |  |
|  | 0.11 |  | 0.45 | 1.97 |  |
|  | Lower bound \% |  | Effectiveness \% | Upper bound \% |  |
|  | -35.54\% |  | 54.64\% | 84.82\% |  |

Table A- 16: Contingency Table with Odds Ratio for Total and F+I Crashes

|  | Total |  | F+I |  |  |  |  |  |
| :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- |
|  | Total <br> Crashes | Target <br> Total <br> Crashes | Odds | Odds <br> Ratio | F+I <br> Crashes | Target <br> F+I <br> Crashes | Odds | Odds <br> Ratio |
| Before <br> Implementation <br> After <br> Implementation | 496 | 268 | $54 \%$ |  | 156 | 87 | $56 \%$ |  |

Table A-17: Naïve Vs EB Analysis Results for the Snow Fences

|  | Analysis Method |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | Naïve (All Weather) |  | Naïve (Adverse Weather) |  | EB (All Weather) |  | EB (Adverse Weather) |  |
| Crash <br> Type | CMF <br> (Safety <br> Effectiveness) | S.E. | CMF <br> (Safety <br> Effectiveness) | S.E. | CMF <br> (Safety <br> Effectiveness) | S.E. | CMF <br> (Safety <br> Effectiveness) | S.E. |
| F+I | 0.69 | 0.64 | 0.9 | 0.61 | 0.41 | 0.047 | 0.38 | 0.051 |
|  | (31.41\%) | $\begin{aligned} & 64.11 \\ & \% \end{aligned}$ | (10.34\%) | 61.17\% | (59.09\%) | 4.75\% | (61.98\%) | 5.15\% |
| PDO | 1.03 | 0.71 | 1.46 | 0.78 | 0.77 | 0.056 | 0.94* | 0.08 |
|  | (-2.94\%) | $\begin{aligned} & 70.55 \\ & \% \end{aligned}$ | (-45.86\%) | 78.32\% | (23.21\%) | 5.57\% | (5.98\%)* | 7.99\% |
| Total | 0.92 | 0.85 | 1.28 | 0.86 | 0.75 | 0.047 | 0.84 | 0.063 |
|  | (7.86\%) | $\begin{aligned} & 85.34 \\ & \% \\ & \hline \end{aligned}$ | (-27.61\%) | 85.98\% | (25.3\%) | 4.72\% | (15.67\%) | 6.33\% |

Bold indicates significant crash reduction, S.E. $=$ Standard Error
*Indicate statistical insignificance

Table A- 18: CMFs for Four-leg Signalized Intersections

| Crash Modification Factors |  |  |  |
| :--- | :--- | :--- | :--- |
|  | Total Crash | F+I | PDO |
| $\mathrm{LL}_{\text {maj }}$ | 0.78 | N/A | 0.67 |
| $\mathrm{LL}_{\text {min }}$ | N/A | N/A | 1.19 |
| $\mathrm{RL}_{\text {maj }}$ | 1.3 | N/A | 1.33 |
| $\mathrm{RL}_{\text {min }}$ | 1.47 | N/A | 1.42 |
| RL | N/A | 1.46 | N/A |

N/A- Insignificant Variable

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