Calibrating Crash Modification Factors for Wyoming-Specific Conditions: Application of the Highway Safety Manual - Part D Phase II

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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 Highway Safety Manual was published in 2010 by the American Association of State Highway and Transportation Officials (AASHTO). The HSM is considered the sole national source to scientifically quantify the safety performance of roadway facilities and to 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 U.S. As a result, the Implementation Guide for Managers was published in 2011 to assist highway agencies in implementing the HSM (1). 21 states participated in the NCHRP 17-50 project, 13 of them were considered as lead states, and 8 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 development processes of highway projects. 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 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, 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, might not be easily transferrable to Wyoming conditions. Developing accurate CMFs that represent Wyoming-specific conditions will help in prioritizing and selecting the most appropriate and cost-effective countermeasures for the situation.

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 4) Part D – Crash Modification Factors.

The HSM Parts C and D provide methods to predict the frequency and severity of different crash types and to quantify the safety impact of a particular countermeasure. 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. Additionally, they quantify the change in predicted crashes because of the implementation of different treatments, which allows practitioners to compare 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 that relate crash frequencies to site characteristics (e.g. AADT, vertical grades, the rate of curvature, lane width, shoulder width, weather conditions etc.). Historical crash data between certain jurisdictions or regions with similar roadway and traffic characteristics, driver population, and weather condition are used to develop the SPFs.

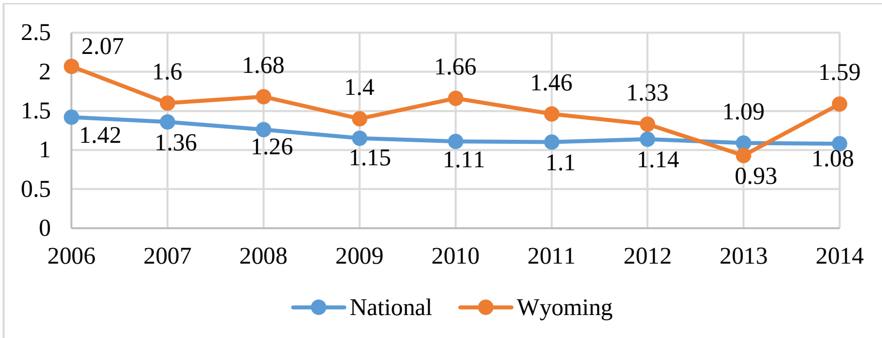
The HSM Part D provides Crash Modification Factors or Functions (CMFs) in four different categories. Roadway segments (e.g., roadside elements, alignment, signs, rumble strips, etc.), intersections (e.g., traffic control), special facilities (e.g., Highway-rail crossings, and interchanges), and road networks.

CMFs are defined as a measure of the safety effectiveness of a particular treatment or a design element. CMFs 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 minimal data requirements) and observational before-after with Comparison Group (CG) methods. The EB method does not only account for regression to the mean (RTM) effects, but it also accounts for traffic volume changes when identifying the CMFs. 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 a valuable tool to enable practitioners within the Wyoming Department of Transportation (WYDOT) to:

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

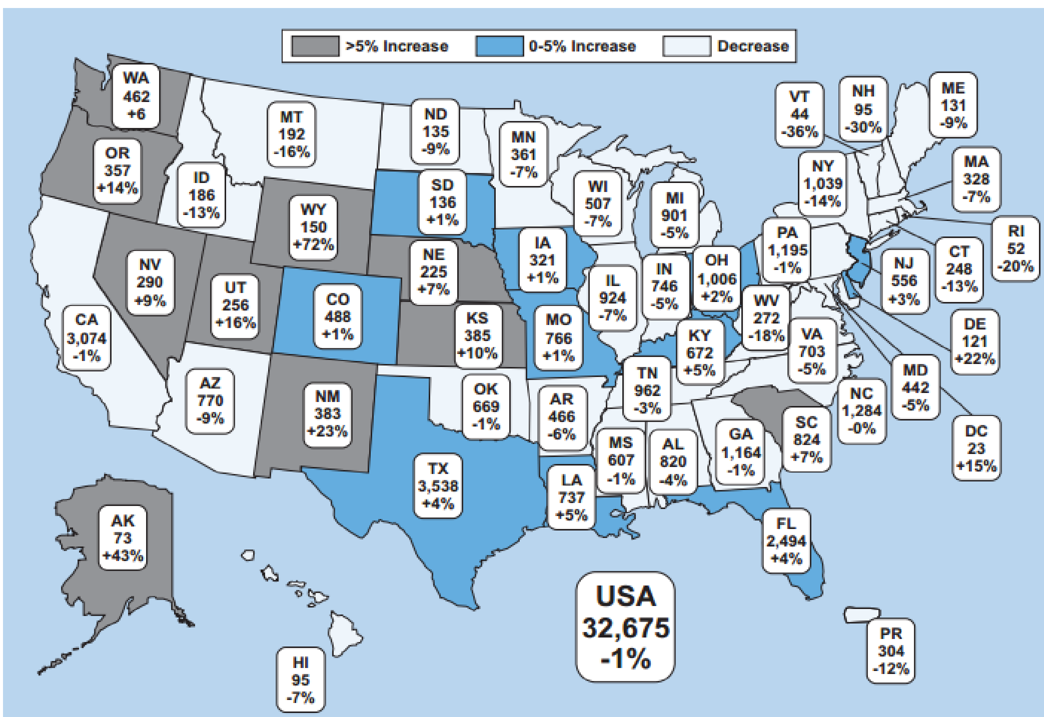
Transferability and Limitations of the HSM

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 significant rates. Figure 2 shows the difference between fatality rates in Wyoming and the national rates per 100 Million Vehicle Miles Traveled (MVMT). Figure 3 also shows that Wyoming has shown a 72 percent increase in fatality rates, which is considered the greatest fatality rate increase from 2013 to 2014.



Source (Traffic Safety Facts 2006 to 2014)

Figure 2: Fatality rates in Wyoming and U.S. from 2006 to 2014.



Source (Traffic Safety Facts 2014)

Figure 3: Percentage increase in fatality rates from 2013 to 2014 in the U.S.

This only raises the need for a statewide implementation of the HSM to quantify the safety effectiveness of different countermeasures on different roadway types and intersections in Wyoming. Such an implementation 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 HSM SPFs 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 very few states, as 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).

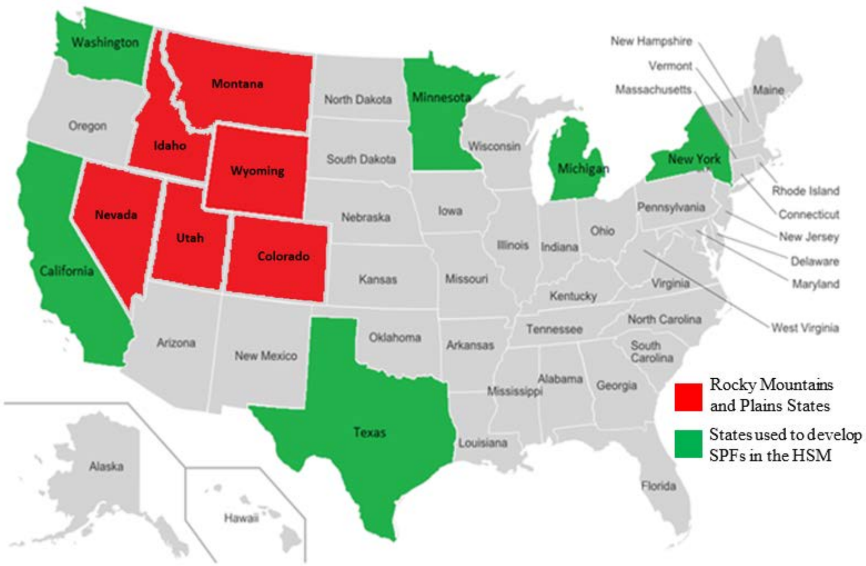
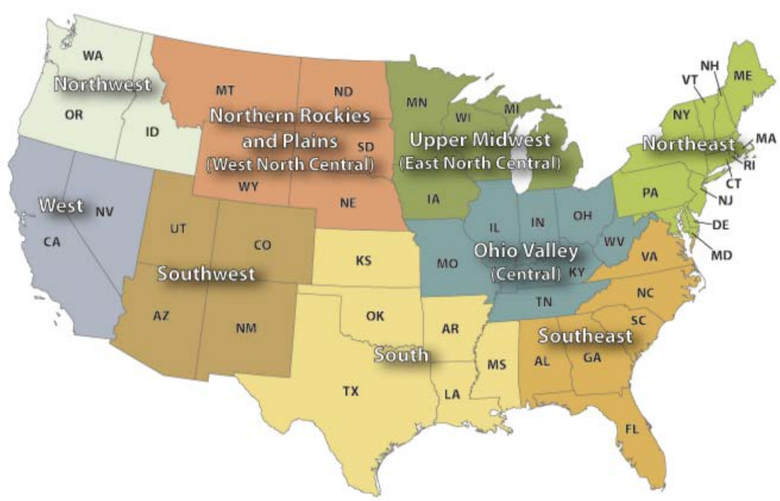


Figure 1. States Represented in the HSM

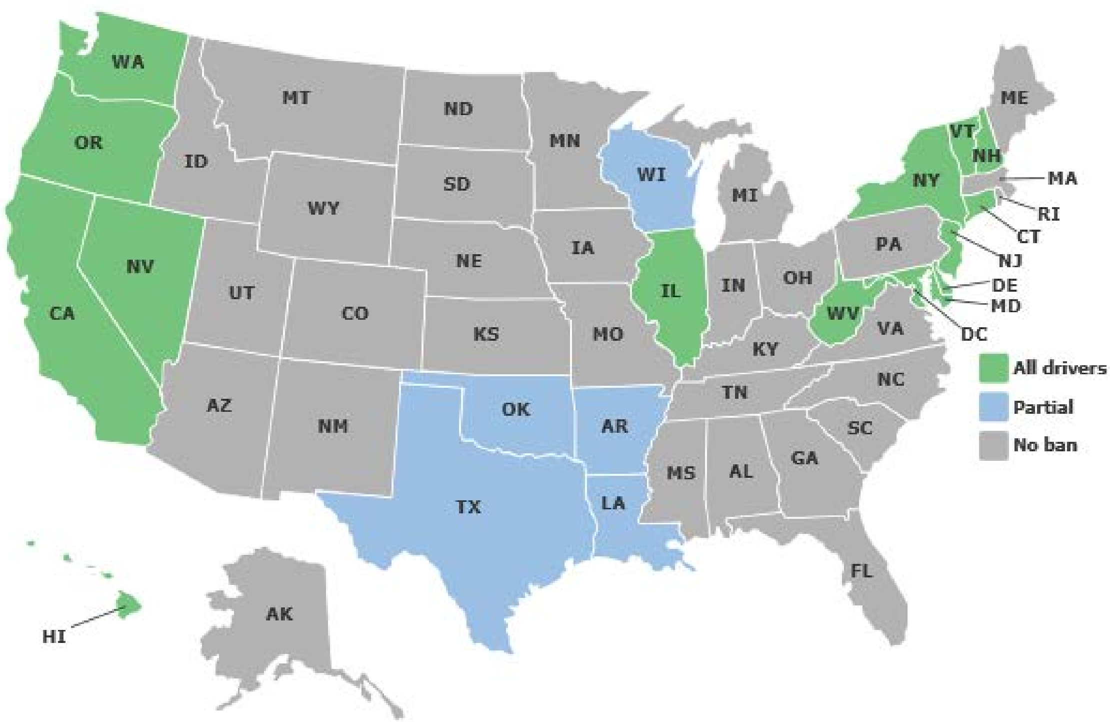


Source (National Centers for Environmental Information)

Figure 2. U.S. Climate regions identified by NOAA. (Source: National Centers for Environmental Information)

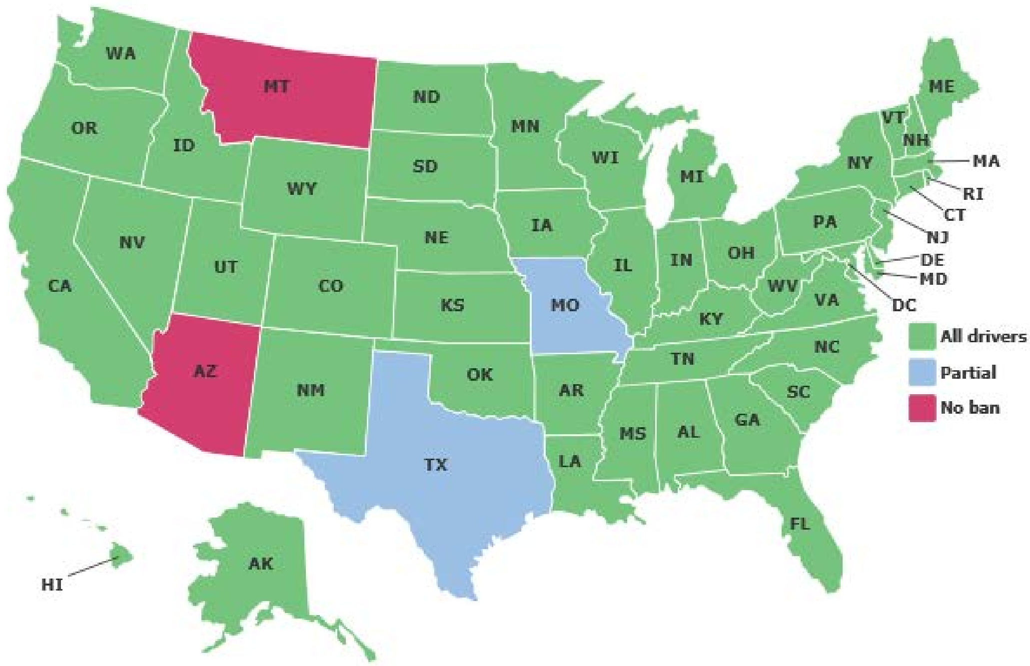
Many factors contribute to crash occurrence. These factors may include driver behavior, traffic, geometric characteristics, weather conditions, and the interrelationships between these different factors. Unfortunately, driver behavior factors are usually not available and are difficult to incorporate 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. 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 3. Map of hand-held cell phone bans (all drivers) (Source: Insurance Institute for Highway Safety)



Source (Insurance Institute for Highway Safety)

Figure 4. Map of texting bans, (Source: Insurance Institute for Highway Safety)

The following 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:

1. Certain facility types are not addressed, including rural roadways with low traffic volumes, challenging roadway geometry, and high percentage of heavy trucks,
2. Each state of the above mentioned states has different crash reporting thresholds and uses different reporting forms,
3. Driving behavior and regulations in the mountain plains region are different from the aforementioned states,
4. Adverse weather conditions within the region are not considered, and
5. The effect of specific activities in some areas (e.g., energy-related activities) is 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, and 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.

Phase 1 Results

SUMMARY

As previously mentioned, data from states in the Mountain Plains region were not considered while developing the HSM. Investigating the applicability and transferability of the HSM to the Mountain Plains region was carried out in Phase 1 on selected countermeasures. The main goal of this study is to continue the implementation efforts of the HSM techniques, and adjust them to be compatible with Wyoming-specific conditions. The application of the Highway Safety Manual - Part D was first attempted in 2016; project number RS03216. However, this should be a continuous effort to account for temporal data variation (e.g. change in AADT, weather, in-vehicle technology and infrastructure). According to the HSM, updating and recalibrating the developed SPFs and CMFs should be done every two to three years (9) and (10). In addition, some limitations and possible improvements of the implementation of the first edition of the HSM for Wyoming-specific Conditions have been identified in Phase 1.

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 naive before-after, and before-after with Empirical Bayes (EB). Other techniques such as odds ratio and the odds of odds ratio were also developed. Wyoming-specific Simple and Full Safety Performance Functions (SPFs) were calibrated as part of the CMF 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.

Two major tasks were accomplished in Phase 1, 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 were obtained from few states. Yet, states from the mountain plains region are not represented. The mountain plains region has different traffic characteristics and composition, roadway characteristics, and weather conditions, which make them unique in their nature when compared to the states utilized to develop crash prediction models for the HSM.

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

One major and arduous 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 gasps and limitations were identified and discussed in the attached Phase 1 report. 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 utilized. Comparisons between the obtained models were performed to elect 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 also 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.

Data requirement for the deployment of the HSM could be extensive. Depending on the data availability and time constraints in Phase 1, CMFs for six countermeasures were completed. The countermeasures considered in Phase 1 were; 1) shoulder rumble strips, 2) passing lanes, 3) regulatory headlight use 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 freeway segments. Data collection and preparation for access management (TWLTL), climbing lanes, and widening and overlay were completed.

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 naive method comprise the methods that were 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 are 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 F+I crashes, respectively. For non-oil counties, shoulder rumble strips were effective to reduce F+I crashes but not effective to reduce total crashes.

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 F+I crashes, respectively. In non-oil counties, passing lanes were found to reduce F+I crashes but not effective to reduce total crashes.

Headlight Signs

The results of observational before-after and cross-sectional analyses showed no significant effect of the headlight use signs. The design of the ratio of odds ratio analysis accounted for other confounding factors, such 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 a 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 F+I crashes and 10 percent for PDO crashes.

The safety effectiveness of adding turn lanes at four-leg signalized intersections was 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 F+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 F+I before the implementation of snow fences and 23 percent were F+I after, showing a 31 percent decrease in fatal and injury crashes after the implementation of snow fences. Additionally, there was about a 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 a 46 percent increase in PDO crashes and a 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 faced and overcome by various data imputation techniques in Phase 1. 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. Having a longer time duration will mitigate the issue of Inflated Zero Crashes on roadway segments. 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® 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 Phase 1. The alternative approach could be considering every off situation as a before period and every on situation as an 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 results that are more reliable; however, it needs additional effort and analysis, which might be investigated in Phase 2.

Additional limitations are introduced with AADT data and headlight signs. The headlight signs included in this study were 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. AADT may be estimated based on the growth factor in later year.

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 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 and improve 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, Advanced Traveler Information Systems (ATIS), 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.

As previously mentioned, several countermeasures are still under study and others still need to initiate investigating their safety effectiveness. For roadway segments, cable median barrier and adding lanes could be potential countermeasures for future studies. Again, multiple countermeasures exist at the same time in one roadway segments which lead us to a direction of analyzing safety effectiveness of multiple countermeasures. Effectiveness of multiple countermeasures is not easy to calculate. The HSM does not provide a method to estimate combined effects of countermeasures accurately. There are few methods to utilize for this, but some do underestimation, others do overestimation. That is why proper analysis of combined effectiveness of multiple countermeasures is difficult, but important. In addition, updating the analysis using other advanced statistical analysis, such as utilizing intervention models would also help to more accurately investigate and recognize the safety effect for the countermeasures.

Different statistical approaches would be used for proper and specified analyses. Multilevel or hierarchical models would be attempted to see the impact on crashes from different predictor levels instead of only an aggregate level model. Panel data should also be attempted to evaluate the trend of crashes over the years for different factors. This could provide the effect of the combined countermeasures.

Average Annual Daily Traffic is considered as the main variable affecting crash frequency. However, it reflects the traffic effect on crashes at an aggregate level. Variation across different seasons, months, days, and hours are not expressed in the developed SPFs. Advancing the analysis and predicting daily crash rates, or even hourly crash rates, would enhance the accuracy of the developed SPFs. Wyoming-specific SPFs would be used to evaluate the impact of countermeasures for roadway segments and intersections.

Another future investigation should be done to understand the intersection related crashes and to determine the influencing area of the intersection crashes and intersection related crashes in rural states, like Wyoming.

Phase 2 Objectives

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. Addressing this issue requires considering more than adherence to standards. Quantifying the safety performance of roadway facilities in Wyoming, following a scientific-based approach, is needed. Moreover, to allocate limited transportation resources more appropriately, evaluation of the safety effectiveness of various countermeasures is a crucial step. The focus of Phase 2 of this study is continuing the validation of the applicability and transferability of the HSM to Wyoming-specific conditions. In addition, Phase 1 elucidated data limitations and challenges to conduct traffic safety analyses in Wyoming. It proposed alternative solutions to overcome data limitations and challenges to implement a scientific-approach to quantitative safety following the HSM.

Figure 8 shows the lists of countermeasures that were identified to calibrate their CMFs and quantify their safety benefits. The figure summarizes countermeasures whose safety effectiveness were quantified, in addition to countermeasures whose data were collected in Phase 1 (i.e., overlay and TWLTL). Additional countermeasures for consideration in Phase 2 are also provided; the ones in green are potential countermeasures for evaluation. It is worth mentioning that the evaluation of the safety effectiveness of the listed countermeasures for Phase 2 is highly dependent on data availability. According to the HSM, at least three years in the after period are needed for any countermeasure to calibrate its CMF. Adding lanes and dividing the roadway, centerline rumble strips, and combined shoulder and centerline rumble strips are countermeasures newly implemented in Wyoming with less than three years of data currently available. These countermeasures are categorized as future consideration countermeasures, it is anticipated that their CMFs could be evaluated by 2018.

In continuation of the previous efforts performed for developing SPFs for different roadway facilities and calibrating CMFs for certain treatments, updating and calibrating SPFs for other facilities as well as calibrating CMFs for other treatments will take place in Phase 2. Countermeasures with available data will be considered in Phase 2, data for overlay and TWLTL have been collected in Phase 1. For other countermeasures, the research team will investigate data the existing data and determine the final list for evaluation. The study objectives of this research project can be listed as follows:

1- Applying the lessons learned in Phase 1 to mitigate data shortcomings.
2- This will be used to assess the safety effectiveness of additional selected countermeasures such as Cable Median Barriers, Resurfacing, Variable Speed Limit, Advanced Traveler Information Systems, Diverging Diamond Interchange, etc.
3- Investigate the safety effectiveness of combined countermeasures (e.g., resurfacing + SRS + passing lanes).
4- Provide recommendations on the most cost-effective countermeasure(s) by conducting cost-benefit analyses for countermeasures based on the calibrated Crash Modification Factors.

Figure 5. Selected Candidate Countermeasure Flowchart

Project Tasks

Eight tasks will be carried out to complete the study as shown in Figure 9.

Task 1 –Countermeasures Selection

Application of the HSM is a data-intensive process. The first task is identifying potential countermeasures for evaluation based on data availability and WYDOT recommendations.

Task 2 – Review of the Literature

For the selected countermeasures, a review of the literature will be carried out. The review of the literature will extend over the first 12 months to ensure up-to-date information.

Task 3 – Data Collection

Following the methodology developed in Phase 1, various datasets will be obtained from WYDOT and other sources. These data include construction dates, crash data, and road geometric and traffic characteristics. In addition, weather data will be 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 will be collected from the stations using a proximity of five nautical miles radius from the stations as verified in Phase 1. A recent WYDOT report by Ohara has provided more detailed weather data; these data will be investigated and utilized as appropriate.

Task 4 – Data Imputation

Gaps and limitations are usually presented in data collected for analysis. Various data imputation and validation techniques will be conducted to obtain reliable results. Other manual data collection techniques utilizing non-traditional data sources will be utilized. Pathway video logs as well as satellite imagery from Google Earth Pro® and Google Maps will be manually reduced to substitute missing construction dates and to obtain accurate roadway geometric characteristics.

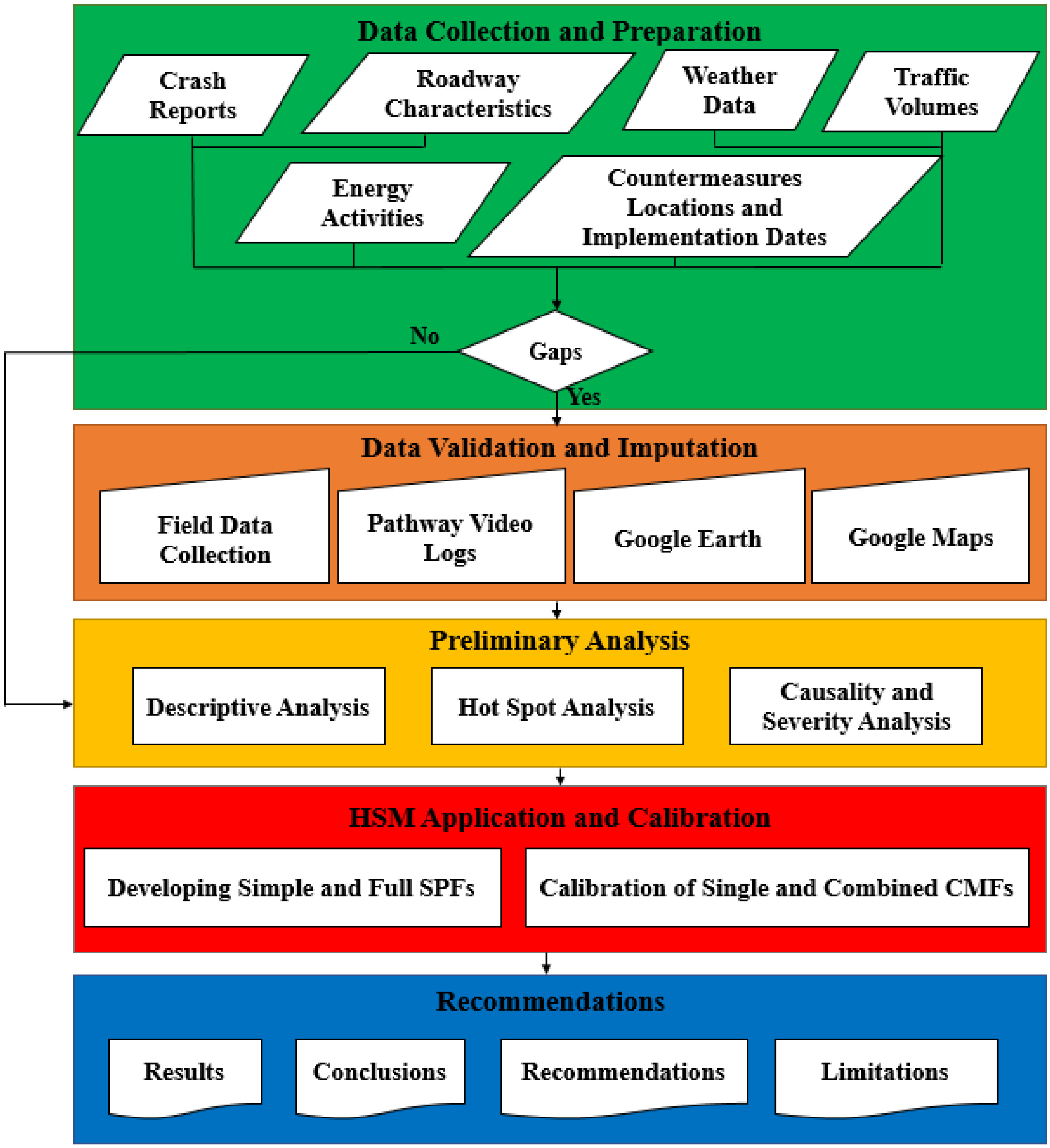


Figure 6. Study Development Flowchart

Task 5 – Preliminary Analysis

Preliminary analysis on all data collected will be conducted, starting with descriptive analysis to provide understandings about the data in hand. Hotspot analyses will be carried out to identify the crash prone locations that should receive certain treatments. In addition, causality and severity analyses will be conducted.

Task 6 – SPFs and CMFs Development

Simple SPFs provided in the HSM will be utilized in addition to developing Wyoming-specific full SPFs to reflect the variation among the counties for each roadway facility. Several classical statistical techniques utilized in Phase 1 will be used to develop SPFs, e.g., Negative Binomial (NB), Zero Inflated Poisson (ZIP), and Zero Inflated Negative Binomial Models (ZINB). In addition, advanced statistical models, such as Fixed and Random effects models, longitudinal data analysis, as well as Full Bayesian approach will be attempted. These advanced statistical techniques will be used to mitigate data limitations. The HSM procedure will be applied to additional countermeasures selected by WYDOT. CMFs obtained from this task will be compared to CMFs in the literature, the HSM, and CMF Clearinghouse.

Task 7 and 8 – Recommendations

The final objective of this research would be to reach specific conclusions about how to implement the HSM Part D more effectively in Wyoming and to provide recommendations for the most cost-effective countermeasures. Based on the calibrated Crash Modification Factors for selected countermeasures, cost-benefit analyses will be conducted. The calibrated CMFs will be shared with local governments around the state. In addition, the research results will be disseminated through technical paper publications and presentations in academic venues and press releases using media outlets. The technology transfer activities in this project will benefit both the scientific community and authorities responsible for traffic safety and decision-making, and will be a key to the implementation of the Highway Safety Manual process of calibrating Crash Modification Factors.

Project Kickoff Meeting

A kick-off meeting shall be scheduled to occur within the first 30 days of execution by the University. The preferred method for the kick-off meeting is via teleconference or video conference. At minimum, the project manager and the principal investigator will attend. The Research Center staff must be advised of the meeting and given the option to attend. Other parties may be invited, as appropriate. The subject of the meeting will be to review and discuss the project's tasks, schedule, milestones, deliverables, reporting requirements, and deployment plan. A summary of the kick-off meeting shall be included in the first progress report.

Deliverables

Quarterly progress report will be submitted. In addition, any major achievement, i.e., the completion of tasks will be reported to the project managers. Calibrated Crash Modification Factors, draft final report and a final report incorporating the project managers' comments and corrections will be submitted at the end of the project.

Progress Reports

The university will submit quarterly progress reports to the Research Center. The first report will cover the activity that occurred in the 90 days following the issuance of the task work order.

Draft Final Report

The Draft Final Report is due 90 days prior to the end date of the task work order. The draft final report will be submitted to the WYDOT Research Center. It should be edited for technical accuracy, grammar, clarity, organization, and format prior to submission to the Department for technical approval.

Final Report

Once the draft final report has been approved, the university shall prepare the final report. The university will deliver a CD or DVD containing the final report in PDF as well as MS Word format.

Project Closeout Presentations

The findings of this study will be presented to the SMS committee as well the WYDOT RAC at the conclusion of the project.

Timeline

It is envisioned that the total time required for Phase 2, including the submission of the final report, would be 24 months beginning summer 2017.

Table 1: Work Plan Schedule

Research Task	Month																							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Task 1																								
Select Countermeasures																								
Task 2																								
Literature Review																								
Task 3																								
Data Collection																								
Task 4																								
Data Preparation and Imputation																								
Task 5																								
Exploratory Analysis																								
Task 6																								
SPFs and CMFs Calibration																								
Task 7																								
Recommendations																								
Task 8																								
Technology Transfer																								
Documentation and Deliverables Schedule																								

Quarter Reports | Draft Final Report | Final Report

Budget

As shown in Table 2, the total cost of the project is $155,943. That cost will cover all data collection and analysis activities as well as technology transfer. In addition, it will cover the salaries of one PhD student for two years, one MS student for one year, and one month salary per year for one faculty member.

Table 2: Project Budget

Budget Year: 2017-2019			
Mohamed Ahmed - University of Wyoming			
CATEGORY	Budgeted Amount from WYDOT	Budgeted Matching Funds - MPC	Explanatory Notes
Center Director Salary			
Faculty Salaries	$17,696	$7,000	
Administrative Staff Salaries	$0	$0	
Other Staff Salaries	$0	$0	
Student Salaries	$70,500	$20,500	
Staff Benefits	$11,665	$4,245	
Total Salaries and Benefits	**$99,861**	**$31,745**	
Student Support Other Than Salaries	$26,910	$5,463	Tuition/No indirects
Permanent Equipment	$2,000	$1,200	No indirects
Expendable Property, Supplies, and Services	$500	$500	
Domestic Travel	$2,500	$2,000	
Foreign Travel	$3,000	$0	
Other Direct Costs (specify)	$0	$6,000	
Total Other Direct Costs	**$34,910**	**$15,163**	
F&A (Indirect) Costs	$21,172	$8,049	
TOTAL COSTS	**$155,943**	**$54,957**	

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	0.0093*	-0.0228	0.0048*
Snowy	0.0157	0.0027*	0.0271	0.0092*
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)

	(A) SPFs for Total and F+I Crashes for Oil Counties				(B) SPFs for Total and F+I Crashes for Non-oil Counties			
Variable	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 Type	Intercept Estimate	Log(AADT) Estimate	Dispersion (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	$AADT_{maj}$	$AADT_{min}$	Overdispersion Parameter
Multiple -Veh Crashes	Total	-10.99	1.07	0.23	0.39
	F+I	-13.14	1.18	0.22	0.33
	PDO	-11.02	1.02	0.24	0.44
Single -Veh Crashes	Total	-10.21	0.68	0.27	0.36
	F+I	-9.25	0.43	0.29	0.09
	PDO	-11.34	0.78	0.25	0.44

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

Crash Types		Intercept (a)	AADTmaj (b)	AADTmin (c)	Overdispersion Parameter
All Vehicle 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
Multiple Vehicle Crash	Total	-6.29	0.79	0.34	0.33
	F+I	-8.93	0.83	0.42	0.41
	PDO	-6.46	0.80	0.32	0.34
	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
Single Vehicle Crash	Total	-5.77	0.48	0.37	0.25
	F+I	-7.37	0.60	0.29	0.15
	PDO	-6.00	0.42	0.41	0.45

All Estimates are at 95th Significance Level

Table A- 6: Wyoming-specific Full SPF Coefficients for Four-Legged Signalized Intersections

Crash Type	Total Crash	F+I	PDO
Intercept	-8.0088	-9.5092	-7.8100
$AADT_{maj}$	0.9119	0.7975	0.8617
$AADT_{min}$	0.1381	0.2219	0.1346
$Lane_{maj}$	-0.0546	0	0
$Lane_{min}$	0.5226	0.5532	0.4915
LL_{maj}	-0.2496	0	-0.4000
LL_{min}	0	0	0.1709
RL_{maj}	0.2647	0	0.2860
RL_{min}	0.3819	0	0.3535
RL	0	0.3804	0
Dispersion	0.0668	0	0.0384

All Estimates are at 95th Significance Level

CRASH MODIFICATION FACTORS (CMF)

Table A- 7: 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 Crashes	0.71* (29%)	1.00 (0%)
F+I Crashes	0.51* (49%)	0.86 (14%)

* Significant at 95 percent confidence level

Table A- 8: 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 Crashes	0.69* (31%)	0.62* (38%)
F+I Crashes	0.42* (58%)	0.41* (59%)

* Significant at 95 percent confidence level

Table A- 9: 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- 10: 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 Crashes	0.40* (60%)	0.69 (31%)
F+I Crashes	0.18* (82%)	0.16* (84%)

* Significant at 95 percent confidence level

Table A- 11: 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

Table A- 12: 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 Crashes	0.39* (61%)	1.29 (-29%)
F+I Crashes	0.41** (59%)	0.36** (64%)

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

Table A- 13: Two-Way Contingency Table with Odds and Odds Ratio for Total and Target Crashes for Headlight Signs

Crash Type	Section description	DRL equipped Vehicles	Non-DRL equipped Vehicles	Odds	Odds Ratio
Total Crashes	with Headlight signs	80	337	23.74%	1.17
	without Headlight signs	970	4799	20.21%	
Target Crashes	with Headlight signs	4	32	12.50%	0.56
	without Headlight signs	95	429	22.14%	

Table A- 14: Ratio of Odds Ratio Analysis for Headlight Sign Controlling for the DRL Technology

Simple odds and odds ratio analysis	Headlight Locations				
		Target crashes	Control crashes	Odds	OR
	DRL	4	76	0.05	0.50
	No DRL	32	305	0.10	
	Non-Headlight Locations				
		Target crashes	Control crashes	Odds	OR
	DRL	95	875	0.11	1.11
	No DRL	429	4370	0.10	
ROR @ 95% confidence level	Lower bound		ROR	Upper bound	
	0.11		0.45	1.97	
	Lower bound %		Effectiveness %	Upper bound %	
	-35.54%		54.64%	84.82%	

Table A- 15: Contingency Table with Odds Ratio for Total and F+I Crashes

	Total				F+I			
	Total Crashes	Target Total Crashes	Odds	Odds Ratio	F+I Crashes	Target F+I Crashes	Odds	Odds Ratio
Before Implementation	496	268	54%	0.72	156	87	56%	0.77
After Implementation	457	342	75%		107	78	73%	

Table A- 16: Naïve Vs EB Analysis Results for the Snow Fences

	Analysis Method							
	Naïve (All Weather)		Naïve (Adverse Weather)		EB (All Weather)		EB (Adverse Weather)	
Crash Type	CMF (Safety Effectiveness)	S.E.	CMF (Safety Effectiveness)	S.E.	CMF (Safety Effectiveness)	S.E.	CMF (Safety Effectiveness)	S.E.
F+I	0.69	0.64	0.9	0.61	0.41	0.047	0.38	0.051
	(31.41%)	64.11 %	(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%)	70.55 %	(-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%)	85.34 %	(-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- 17: CMFs for Four-leg Signalized Intersections

Crash Modification Factors			
	Total Crash	F+I	PDO
LL_{maj}	0.78	N/A	0.67
LL_{min}	N/A	N/A	1.19
RL_{maj}	1.3	N/A	1.33
RL_{min}	1.47	N/A	1.42
RL	N/A	1.46	N/A

N/A- Insignificant Variable

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