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MOTORCYCLE SAFETY ASSESSMENT IN WYOMING AND UTAH: CRASH CHARACTERISTICS AND CONTRIBUTING FACTORS

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16. Abstract

Motorcycle riders and passengers are much more likely to be killed or severely injured in a crash, and on average, about 15% of all traffic fatalities include motorcyclists. The study uses 12 years of motorcycle crash data (2008–2019) from Wyoming, and eight years of data from Utah (2014–2021) and applies multinomial logistic and Bayesian multilevel regression modeling to determine the effects of various exposure measures on injury severity. Four models were developed and analyzed: (1) rural single motorcycle crashes; (2) rural multi-vehicle motorcycle-related crashes; (3) urban single motorcycle crashes; and (4) urban multi-vehicle motorcycle-related crashes. Overall, it was found that the most common factors affecting injury severity in motorcycle-related crashes include vehicle maneuver, driver action, junction relation, alcohol, animal and speed involvement, and helmet use. The vicinity of intersections significantly increases the odds of injury crashes in all urban and the rural multi-vehicle crashes, compared to no injury. Vehicle maneuvers, such as overtaking/passing, changing lanes, and negotiating a curve, are also associated with a more severe crash outcome. Helmet use was generally found to reduce fatal and serious injuries in crashes, with some exceptions, where other factors were more significant. Future work will include more detailed analysis on vehicle and person levels.

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MOTORCYCLE SAFETY ASSESSMENT IN WYOMING AND UTAH: CRASH CHARACTERISTICS AND CONTRIBUTING FACTORS

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ABSTRACT

Motorcycle riders and passengers are much more likely to be killed or severely injured in a crash, and on average, about 15% of all traffic fatalities include motorcyclists. The study uses 12 years of motorcycle crash data (2008–2019) from Wyoming, and eight years of data from Utah (2014–2021) and applies multinomial logistic and Bayesian multilevel regression modeling to determine the effects of various exposure measures on injury severity. Four models were developed and analyzed: (1) rural single motorcycle crashes; (2) rural multi-vehicle motorcycle-related crashes; (3) urban single motorcycle crashes; and (4) urban multi-vehicle motorcycle-related crashes. Overall, it was found that the most common factors affecting injury severity in motorcycle-related crashes include vehicle maneuver, driver action, junction relation, alcohol, animal and speed involvement, and helmet use. The vicinity of intersections significantly increases the odds of injury crashes in all urban and the rural multi-vehicle crashes, compared to no injury. Vehicle maneuvers, such as overtaking/passing, changing lanes, and negotiating a curve, are also associated with a more severe crash outcome. Helmet use was generally found to reduce fatal and serious injuries in crashes, with some exceptions, where other factors were more significant. Future work will include more detailed analysis on vehicle and person levels.

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EXECUTIVE SUMMARY

Even though motorcycle fatalities comprise a large percentage of traffic fatalities in the United States (in excess of 15%), comprehensive studies on motorcycle safety on the national level are lacking. According to the NHTSA, the mean fatality crash rate for motorcycles is about five times higher than that for passenger cars. From 2015 on, the five-year rolling average of fatal motorcycle crashes per million population in Wyoming has increased from 26 in 2015 to 32 in 2018. In 2018, there were 15 motorcycle fatalities in Wyoming. In Utah, the average motorcycle fatalities between 2015 and 2020 were 41 per year, which constituted about 15.1% of all highway fatalities, even though the motorcycle VMTs represent less than 1% of all VMTs. Most fatal and serious-injury motorcycle crashes happen between April and September with the peak occurring in August. Wyoming requires helmets for riders/passengers ages 17 or younger, with the exception for mopeds, while Utah requires helmets for riders/passengers 20 or younger, regardless of motorcycle type.

This research included a comprehensive motorcycle safety assessment for Wyoming and Utah, using eight to 12 years of detailed crash data. It analyzed crash characteristics, severities, types and contributing factors for different facilities and area types, and recommended countermeasures that have the potential to reduce the frequency and severity of motorcycle crashes. There are no recent studies on motorcycle safety in Wyoming and Utah; however, fatal and serious motorcycle crashes represent a significant percentage of all crashes. A comprehensive study is needed to determine motorcycle crash characteristics, contributing factors, and potential countermeasures.

This study assessed the correlation between different characteristics and factors and their individual and mutual effects on motorcycle crash severities in Wyoming and Utah. Four types of motorcycle-related crashes were analyzed in this research, depending on the setting and the number of vehicles involved: (1) rural single motorcycle crashes; (2) rural multi-vehicle motorcycle-related crashes; (3) urban single motorcycle crashes; and (4) urban multi-vehicle motorcycle-related crashes. The separate assessment was performed as it was initially found that the characteristics and contributing factors differ based on the setting (urban or rural) and the number of vehicles involved in a motorcycle crash (single or multi-vehicle).

In addition to the descriptive statistics of motorcycle-related crashes in Wyoming and Utah, this study developed and implemented two types of statistical models to analyze the effects of various contributing factors with a focus on fatal and severe injury crashes: multinomial logistic regression (MLN) and Bayesian multilevel regression (BR) models.

The application of MLN models in Wyoming found that speeding and alcohol involvement increase the odds of any injury crash multifold in all types of motorcycle related crashes. For single motorcycle crashes, vehicle maneuver and driver action exposure measures were found to have significant effects on injury level. Helmet use can reduce the odds of fatal and serious injuries in single motorcycle crashes. For multi-vehicle crashes, it was found that junction relation and vehicle maneuver exposure measures have significant effects on odds ratios of injury crashes compared to no injury. Additionally, road and weather conditions impact injury severity level in single, rural motorcycle crashes, while weather also impacts the severity level in single, urban motorcycle crashes. Manner of collision factors have additional effects on the severity of urban, multi-vehicle motorcycle related crashes. Helmet use is found to reduce the odds of fatality and non-incapacitating injuries in urban, multi-vehicle crashes.

The application of MLN models in Utah found that the most common factors that increase the odds of fatal and injury crashes include unlighted environment, changing lane and U-turn maneuvers, overtaking in traffic, aggressive driving, DUI, disregard for traffic control, collisions with fixed objects, speeding, wrong-way driving, and older riders. Involvement of commercial vehicles in motorcycle-related crashes increases the odds in multi-vehicle crashes. Roadway geometry was found to increase the odds of fatal and injury single motorcycle crashes. Wrong-way driving increases the odds of fatal and injury crashes in single, rural and urban multi-vehicle crashes. Not wearing a helmet increases the odds of fatal and serious injury crashes in single motorcycle crashes, while it does not have a significant effect in multi-vehicle crashes.

BR modeling application in Wyoming found that alcohol involvement, animal involvement, certain reduced lighting, inclement weather, roadway surface condition, and majority of driver actions other than going straight increase the odds of fatal and severe injury crashes in all types of analyzed crashes. Not wearing a helmet was found to significantly increase the odds of severe and fatal crashes in rural areas and in urban, single motorcycle crashes. The BR models did not find speed to be a significant contributor to severe and fatal outcomes in Wyoming.

Utah BR models found that speed, aggressive driving, DUI, disregard for traffic control, collisions with fixed objects, involvement of commercial vehicles, and certain reduced lighting, inclement weather, roadway surface condition and majority of driver actions other than going straight increase the odds of fatal and severe injury crashes. Not wearing a helmet increases the odds of severe and fatal crashes in rural, single motorcycle crashes, while it was not found to be a significant factor in other types of crashes. Wrong-way driving and intersection relation increase the odds of severe crashes in multi-vehicle collisions.

The study also recommends certain roadway, maintenance, education and enforcement countermeasures that should be implemented to reduce the frequency and severity of motorcycle-related crashes. This study is generalized, meaning it does not focus on specific locations and types of crashes. In future studies, the analysis should be expanded and provide more detailed analysis for certain locations and include more information from the vehicle and person crash databases. The approach and results of this study would present a good starting point for future motorcycle safety studies in Wyoming, Utah, and other states.

1. INTRODUCTION

Motorcycle fatalities comprise a large percentage of traffic fatalities in the United States in excess of 15% (National Motorcycle Institute, n.d.), and are closely followed by serious injuries. According to the National Highway Traffic Safety Administration (NHTSA), the mean fatality crash rate for motorcycles is more than six times higher than that for passenger cars, and motorcycles account for about 0.6% of all Vehicle Miles Traveled (VMT) (NHTSA, 2021). Between 2015 and 2019, the average number of motorcycle fatalities in the United States was 5,129 per year, with the peak in 2016 (5,337). From 2015 on, the five-year rolling average of fatal motorcycle crashes per million population in Wyoming has been increased from 26 in 2015 to 32 in 2018 (National Motorcycle Institute, n.d.). In 2019, there were 13 motorcycle fatalities in Wyoming, representing 9% of all traffic fatalities in the state. The state of Wyoming does not have a comprehensive helmet requirement law, and the helmet is only required for riders and passengers ages 17 or younger with the exception of mopeds (IIHS, 2022). Of all motorcycle fatalities in Wyoming, it is estimated that 57% were not using a helmet (NHTSA, 2021). The average motorcycle fatalities in Utah between 2016 and 2021 were 35.6 per year, which constituted about 15.6% of all highway fatalities, even though 1.8% of all crashes involved motorcycles, and motorcycle VMTs represent less than 1% of all VMTs (Utah Department of Public Safety, n.d.).

Various factors affect the frequency and severity of motorcycle crashes. Roadway geometry, road, weather, environmental and traffic conditions, setting (urban or rural), the number of vehicles involved, relation to a junction, helmet use, driver condition and action (e.g., riding under the influence or speeding), are some of the most common factors attributed to motorcycle crashes. It is generally accepted that motorcycle crashes result in higher severity due to the exposure of the riders and the lack of construction and restrain elements, which exist in other vehicle types. Even though efforts are being made to improve motorcycle safety, a more proactive and collaborative approach is needed to address this issue.

This study assesses the correlation between different characteristics and factors, and their individual and mutual effects on motorcycle crash severities in Wyoming and Utah. Four types of motorcycle-related crashes are analyzed in this research, depending on the setting and the number of vehicles involved: (1) rural, single motorcycle crashes; (2) rural, multi-vehicle motorcycle-related crashes; (3) urban, single motorcycle crashes; (4) urban, multi-vehicle motorcycle-related crashes. The separate assessment was performed as it was initially found that the characteristics and contributing factors differ based on the setting (urban or rural), and the number of vehicles involved in a motorcycle crash (single or multi-vehicle).

The data used in the analysis are obtained through the Wyoming Department of Transportation (WYDOT) Critical Analysis Reporting Environment (CARE) system and include 12 years of crash data (2008–2019). Furthermore, the researchers received access to the AASHTOW, the safety system which houses traffic crash data from Utah. In Utah's case, eight years of motorcycle-related crash data (2014–2021) were obtained. Various factors affect the frequency and severity of motorcycle crashes. Roadway geometry, road, weather, environmental and traffic conditions, setting (urban or rural), the number of vehicles involved, relation to a junction, helmet use, driver condition and action (e.g., riding under the influence or speeding) are some of the most common factors attributed to motorcycle crashes.

Motorcycle riders and passengers are overrepresented in traffic fatalities. It is generally accepted that motorcycle crashes result in higher severity due to the exposure of the riders and the lack of construction and restrain elements, which exist in other vehicle types. Even though efforts are being made to improve motorcycle safety, a more proactive and collaborative approach is needed to address this issue.

1.1 Study Objectives and Methodology

The goal of this study is to assess the characteristics of motorcycle safety in Wyoming and Utah with the focus on fatal and severe injury crashes and provide a set of recommendations with a potential to reduce the frequency and severity of motorcycle-related crashes. The main research objectives of this study are to:

- Summarize motorcycle crash characteristics for Wyoming and Utah.
- Develop statistical models for motorcycle safety assessment, using multiple years of crash data.
- Determine the major contributing factors for severe and fatal motorcycle crashes.
- Develop recommendations for countermeasures.

The study first presents the descriptive statistics of motorcycle crash characteristics in Wyoming and Utah. These statistics show crash characteristics, such as crash types, severities, locations, contributing factors, and other elements of importance. They show the current state of motorcycle safety and needs for improvements.

Multiple years of crash data from Wyoming and Utah are used to develop statistical safety models for motorcycle crashes. The data are organized by selected variables (crash characteristics, traffic, environmental conditions, and roadway characteristics) and imported into statistical software — RStudio. The developed statistical models show the significance of various contributing factors and variables, which are used to recommend countermeasures. These statistical models can be used to create location-specific Safety Performance Functions (SPF) for motorcycle-related crashes.

Through both descriptive data analysis and statistical modeling, the study determined the major contributing factors for motorcycle crashes with a focus on severe injury and fatal crashes. The contributing factors show the direction for needed improvements in the motorcycle safety area for the two states. Finally, the study recommends potential countermeasures for the reduction of severe and fatal motorcycle crashes.

2. LITERATURE REVIEW

In the United States and other developed countries, motorcycles are primarily used for recreation and leisure and are typically considered a luxury item (Broughton and Walker, 2019). The motorcycle share for commuting trips in the United States is negligible. In developing countries, especially in Asia, motorcycling is the predominant transportation mode (Jittrapirom and Knoflacher, 2017). Due to the lower use of resources and less required space, motorcycles can contribute to more sustainable transportation systems (Jittrapirom and Knoflacher, 2017; Rose et al, 2012). The motorcycle can utilize up to five times less space than a car (Jittrapirom and Knoflacher, 2017; Bakker, 2018), consumes less energy in production and operation, and emits less CO2 (Pfaffenbichler and Circella, 2009). However, motorcycles are usually treated solely on the basis of their safety characteristics (Wigan, 2002). This is due to the fact that motorcyclists are overrepresented in traffic fatalities. According to the NHTSA, motorcyclists are about 29 times as likely as passenger car occupants to die in a motor vehicle traffic crash (NHTSA, 2021). In 2019, 5,014 motorcyclists were killed in crashes in the United States, which accounted for 14% of all traffic fatalities. No systematic motorcycle transportation policy exists, although steps have been taken to develop an active motorcycle safety agenda.

The prevention of crashes and alleviation of crash consequences are associated with education and regulations but also with the use of appropriate rider gears, such as helmets and jackets. The regulations for helmet use, education and licensing, and recommended behavior on actuated signalized intersections differ from state to state (Shinkle and Teigen, 2012). Regardless of the regulations, the percentage of motorcycle fatalities continues to increase. Motorcycle traffic shares only 0.6% of all vehicle miles traveled (VMT) in the United States, with narrowly 3% of all registered vehicles (Highway Traffic Safety Administration and Department of Transportation, 2019). Even though this is a small percentage, motorcycle traffic is associated with 14% of all traffic fatalities. In the previous 10 years, the fatalities increased by 20% in the United States, while only from 2019 to 2020 increased by 11% (Motorcycles – Injury Facts, n.d.). Using data from the 2016 Motorcycle Crash Causation Study (MCCS), the National Transportation Safety Board (NTSB) analyzed factors that lead to motorcycle crashes throughout the nation (National Transportation Safety Board, 2018). The study found that 65% of motorcycle crashes occur in urban areas and arterial roadways. Considering the weekly crash distribution, more than half of crashes and half of fatal crashes occur on Fridays, Saturdays, and Sundays. Most motorcycle crashes include at least one additional motor vehicle (81%), while only 19% are single motorcycle crashes. Half of the single motorcycle crashes are fatal, which is not a surprise, considering that 38% of the single motorcycle crashes occurred due to speeding by 10 mph or more over the speed limit or hitting a barrier. However, human errors either by motorcycle riders or other drivers caused 94% of crashes. Based on crash data from 2007, 27% of riders involved in motorcycle-related fatal crashes in the United States were intoxicated (Fell et al., 2009). From 2010 to 2020, almost 95% of motorcycle fatalities involved alcohol (Dangerous States for Motorcycle Riders | QuoteWizard, n.d.). The use of alcohol or drugs is also associated with a higher probability that motorcycle riders do not use a helmet (Rossheim et al., 2014).

Similar to national trends, motorcycles use has also risen in Utah and Wyoming. Motorcycle crashes make up 2% of total crashes and 16% of all fatalities in Utah. The number of fatalities (47) was the highest in 2018, while in 2019, that number decreased by 28% (34). The number of injuries followed the same trend. In 2020, the number of fatalities in motorcycle crashes increased by 29%, while the number of injuries increased by 38%. In the previous year, the number of fatalities was slightly reduced, but the number of injuries grew by 18% (Utah SHSP, n.d.). Currently, Wyoming has about 30,000 registered motorcycles, which are about 1% of the total registered vehicles in the state. A comparison of average crashes that include motorcycles in the period from 2011 to 2015 and from 2016 to 2020 shows a decrease of 30%. Considering the separate years, 2020 has an increase in both injuries and fatalities (Wyoming Report on Traffic Crashes, n.d.). In the last five years, motorcycle riders did not wear a protective helmet in 64% of fatalities and 55% of injuries. Based on a study by Rezapour et al., 2020, 34% of all motorcycle crashes in Wyoming are fatal.

The factors that could enhance motorcycle crashes differ from state to state. Based on a report by Dangerous States for Motorcycle Riders | QuoteWizard, n.d., Wyoming is placed in eighth place of all states, considering the number of fatalities that includes alcohol. Studies found that besides speeding and rider impairments, the leading causes of crashes are related to horizontal curve design and animal hits. A study by Farid et al., 2019 conducted an analysis of factors that are contributing to motorcycle crashes on low-volume roads in Wyoming that are the prevailing type of roads. Using the ordinary logistic regression, the study found that the main factors for motorcycle crashes on low-volume roads are speeding and driver impairment. The study also showed that the most severe crashes occur due to horizontal curves and animal crashes. On the contrary, the study found that wet roads without changes in other road conditions reduce the risks of severe crashes involving motorcycles. In Utah, 1.2% of all crashes are animal-related crashes, while 94% of animal-motorcycle-related crashes ended up with an injury compared to the 11% of other vehicle-animal crashes. Particularly in Utah, animal-related crashes consider domestic and wild animals. While the percentage of domestic animal-related crashes is low (16%), they are usually more severe than wild animal-related crashes (Perrin, 2003). Based on statistics from 2014, the first five causes of the motorcycle crashes in Utah are speeding (12%), failure to keep in line (11.2%), short following distance (11.1%), other improper driving (8.3%), and different evasive actions (5.8%) (MSF, n.d.).

Factors that cause crashes that include motorcycles could be different, such as road and weather conditions, riders' skills and impairment, and other vehicular traffic. This information could be found from data collected through previous years, while some of the information could be missed due to different standards from state to state for the data collection on the scene. Based on research by Farid et al., 2022, Wyoming Highway Patrol (WHP) officers are collecting the following information about motorcycle crashes: whether the motorcyclist or passenger affected by the crash were wearing a helmet and other appropriate gear, such as jackets and boots, and whether the motorcyclist was riding in a group of motorcyclists or alone. Further collected information is related to motorcyclist impairment and blood alcohol concentration (BAC).

Based on a study by Chaudhuri et al., 2019, the fatality rate per 100,000 population consistently increased from 2000 to 2016. The study also found that fatality rates for those older than the age of 60 rose notably in this period. Considering the age-and-sex standardized state fatality, Wyoming consistently has the highest rate with South Dakota and South Carolina. A study by Rezapour et al., 2020, aimed to find factors that could affect the severity of at-fault motorcycle crashes on two-lane highways in Wyoming. The authors used parametric (Binary logistic regression) and non-parametric (classification tree) methods to predict motorcycle at-fault injury severity. The study used data from 2007 to 2016, considering driver, motorcycle, roadway, crash, environmental and temporal variables. The study results showed that speeding and alcohol impairment are major causes of motorcycle at-fault crashes. Based on an old study by Byrd & Parenti, 1978, in a group of 220 motorcycle crashes in Utah, speed is the most important factor for head injury severity. Together with rollover crashes, the motorcycle crashes on Utah Highways are more often followed by severe injuries (Schultz et al., 2020).

Over the years, researchers have been analyzing motorcycle safety with the aim to determine the most common contributing factors, severity levels and potential countermeasures to reduce motorcycle crash frequencies or their severities. Various approaches have been used in motorcycle safety research. A study using the naturalistic motorcycle driving study analyzed the most common crash and near-crash occurrences, types and contributing circumstances (Williams et al, 2016). It found that the most common incident type was a ground impact at low speeds (in 57% of recorded incidents), which includes maneuvers at low speeds (parking, slow turns, U-turns and similar). It was followed by road departures, and other vehicles turning across the motorcycle path (10% each of total crashes). Motorcycles rear-ending other vehicles were represented by 7% of all motorcycle-related crashes. Other crash types were represented by 3% or less. The Motorcycle Crash Causation Study (MCCS), sponsored by the Federal Highway Administration (FHWA), performed a detailed analysis on 351 on-scene crash investigations and 702 control cases with motorcycle involvement, aimed at identifying the factors leading to crashes and the resulting injuries (Nazametz et al, 2019). The study found that 40 crashes (11.4%) were fatal, 269 crashes (76.6%) involved multiple vehicles, and 22 fatalities (26.8%) were single vehicle cases. Close to 80% of multi-vehicle crashes were intersection related. The absence of traffic control, horizontal curves, roadside fixed objects, and view obstructions were some of the common contributing circumstances found in the study. Another study focused on crash occurrence on horizontal curves of rural two-way undivided highways in Florida (Xin et al, 2017). The authors used a random-parameters negative binomial (RPNB) model to assess the factors that determined the occurrence of motorcycle crashes. The study found that the horizontal curve radius significantly influences motorcycle crash occurrence on these types of roads. Particularly horizontal curves with the radius of less than 460 m were found to increase the likelihood of motorcycle crashes and the probabilities of severe injuries. Similarly, a study conducted in Norway applied a matched case-control study design to analyze the safety effects of horizontal curves, lane and shoulder widths on single motorcycle crashes (Kvasnes et al, 2021). The study found significant effects of sharp horizontal curves (less than 200 m) on single motorcycle crash occurrences. A significant number of motorcycle-related, multi-vehicle crashes in urban areas occur at intersections. These crashes also result in more fatalities, where about 30% of fatal motorcycle crashes occur at intersections (Scopatz et al, 2018).

As motorcycle crashes result in more fatalities and serious injuries, research efforts have been focused on analyzing motorcycle crash severities and contributing factors using various methods. A 2006 study using crash data from Indiana applied nested logit and multinomial logit models to assess motorcyclists' injury severities in single and multi-vehicle crashes (Savolainen and Mannering, 2007). The results showed that increasing age is correlated with more severe injuries and that collision type, roadway characteristics, alcohol, helmet use and unsafe speed were all significant factors related to injury severity. A recent study on single motorcycle crashes explored the effects of motorcyclists' age in combination with other factors using the mixed logit model and crash data from Florida (Islam, 2021). The results indicated inter-correlation between different factors and age (e.g., speeding, helmet use, alcohol consumption, motorcycle type, etc.). As an example, the study found that not wearing a helmet increases the likelihood of fatal injury for the age group of 50 and above, while it decreases for the middle age group (30–49). However, not wearing a helmet increases the likelihood of severe injury for the middle age group but decreases it for the older age group. This study also showed the importance of analyzing multiple factors in combination when it comes to the injury severity outcomes of motorcycle crashes. Another study used 20 years of crash data from Pennsylvania and an integrated spatiotemporal analytical approach to assess correlations between risk factors and injury severity in motorcycle-related crashes (Li et al, 2021). The results showed that multiple factors, such as helmet use, engine size, vehicle age, motorcyclist age, pillion passenger, at-fault striking, and speeding, are significantly related to motorcyclist injury severity. A study using crash data from Iowa and latent class multinomial logit models examined the factors affecting single vehicle motorcycle crash severity outcomes (Shaheed and Gkritza, 2014). This research found a significant relationship between severe motorcycle crash injuries and factors, such as speeding, run-off road, collision with fixed object, overturn or rollover, riding on high-speed and rural roads, rider's age more than 25, not using a helmet, and riding under the influence. A study using motorcycle crash data from Texas applied multinomial logit models to identify differences in factors affecting motorcycle crash injury severity (Geedipally et al, 2011). The analysis was performed on crashes in urban and rural areas. The results showed that alcohol, gender, lighting, and horizontal and vertical curves have significant impact on motorcyclists' injury severity in urban areas. In rural areas, the significant factors affecting injury severity were found to be similar as in urban areas, with the addition of motorcyclists' age (older than 55), single vehicle crashes, angular crashes, and divided highways. A previous research study on motorcycle safety in Wyoming applied binary and mixed binary logistic models with random parameters to assess the injury severity of single and multi-vehicle motorcycle-related crashes (Farid and Ksaibati, 2021). The study found that the most severe single motorcycle crashes involve collisions with animals and traffic barriers, followed by horizontal curves and older drivers. Riding under the influence and on roads with higher posted speed limits resulted in higher severity for both single- and multi-vehicle crashes.

The use of a protective helmet could impact motorcycle crash outcomes. A report by (Cook et al., 2009) found that motorcyclists that were using helmets experienced less severe head injuries and traumatic brain injury during crashes. In the United States, less than half of states (19) have a law that proposes mandatory wearing of protective helmets during riding of motorcycles for riders and passengers. Other states usually request helmeting for drivers under the age of 20 years. In Utah, the helmet law that requests wearing a USDOT-approved helmet applies only to riders under the age of 20 (Utah SHSP, n.d.). In Wyoming, the age boundary for mandatory helmeting for motorcycle riders is the age of 17. After a peak of motorcycle fatalities in 2005 when it reached a rate of 44.79 per 100 million vehicle miles traveled, the helmet use in the United States increased by over 20% (Fatal Motorcycle Crashes per Mileage in U.S. | Statista, n.d.).

Similar to the helmet law, the states have different approaches to licensing motorcycle riders. Of 14 states that require motorcycle licensing, New Jersey and Utah require testing of future riders on the motorcycle size they intend to ride (National Transportation Safety Board, 2018). In Utah, anyone willing to obtain a driver's license for a motorcycle has to go through the licensing procedure that considers taking a motorcycle skill test. The potential motorcycle riders must be age 16 or older to be eligible for the motorcycle license. The state offers different rider courses to help riders learn how to manage risks, control rear-wheel skids, recognize and avoid hazardous situations, and keep traction. In Utah, it is allowed to use lane filtering in specific circumstances, such as more than one lane per direction, speed limit up to 45 mph, the vehicle being overtaken is stopped, or the motorcycle does not travel more than 15 mph (MSF, n.d.). In Wyoming, the license can be issued to an individual at the age of 16 or older if pass the vision, writing, and skill tests.

Previous research has found the most common contributing factors affecting injury severity in motorcycle related crashes and applied different methodologies to assess the significance of these factors. The studies showed that the crash variables are inter-correlated and, when combined, have different effects on severity outcomes than when observed as isolated. This study adds to the current body of knowledge on motorcycle-related crash injury severity by exploring different types of crashes based on the setting and the number of vehicles involved, and the combination of factors affecting each type. The study is using the multinomial logistic and Bayesian multilevel regression to determine the individual and mutual effects of different characteristics and factors on motorcycle crash severities in Wyoming and Utah.

3. DATA PREPARATION AND DESCRIPTIVE STATISTICS

The data used in this study were obtained from the WYDOT's CARE system (for Wyoming), and the AASHTOWare Safety system (for Utah). The data were categorized on crash, vehicle, and person levels. As needed, the three data sets were combined to retrieve all the information needed for analysis and the development of statistical models. Crash severity level categories used in the analysis and in the report are adopted directly from the databases. In the Wyoming data, the severity levels are categorized as Fatal (K), Incapacitating (A), Non-incapacitating (B), Possible (C), and No injury (O). The Utah data categorizes the severity levels as Fatal, Suspected Serious Injury, Suspected Minor Injury, Possible injury, and No injury/PDO.

3.1 Wyoming Descriptive Statistics

This study uses 12 years of Wyoming crash data (2008-2019) obtained through WYDOT's CARE crash database. The crash data include separate databases on crash, vehicle, and person levels. As this study only focuses on the crash-level, databases were combined to extract the needed parameters (e.g., helmet use exists in the person database), so it was matched using the crash ID number. There were 3,429 motorcycle-related crashes during the 12-year analysis period, with 202 being fatal (K), 875 incapacitating injury (A), 1,356 non-incapacitating injury (B), 508 possible injury (C), 186 no injury (property damage only) (O), and 302 crashes of unknown severity. The crash factors used in this research include the crash case number, year, month, day, number of vehicles (single and multi-vehicle), setting (urban and rural), route, manner of collision, vehicle maneuver, driver action, junction relation, lighting, weather, driver age and gender, alcohol, wild animal and speeding involvement, helmet use, and crash severity (KABCO scale). The breakdown of 12-year motorcycle crashes with respect to the number of vehicles and setting is provided in Table 3.1.

Table 3.1 12-Year Motorcycle-Related Crash Frequencies in Wyoming

	Total	Fatal (K)	Incapacitating (A)	Non-incapacitating (B)	Possible (C)	No injury (O)	Unknown
Single	2,058	115	583	920	273	85	82
Multi	1,371	87	292	436	235	101	220
Rural	1,601	143	563	614	166	106	9
City	1,828	59	312	742	342	80	293
Rural Single	1,225	91	433	499	127	68	7
Rural Multi	376	52	130	115	39	38	2
City Single	833	24	150	421	146	17	75
City Multi	995	35	162	321	196	63	218

Out of all motorcycle-related crashes during the 12-year period, 60% involved a single motorcycle and 40% were multi-vehicle crashes with motorcycle involvement. Of the injury crashes, 57% of fatal and 67% of incapacitating injury crashes were with single motorcycle involvement. Even though more than 53% of all motorcycle-related crashes occurred in urban environments, the majority of fatal (71%) and incapacitating injury crashes (64%) were recorded in rural areas. In rural areas, the majority of total (77%), fatal (64%), and incapacitating injury (77%) crashes involved a single motorcycle. In urban areas, most of the total (54%), fatal (59%), and incapacitating injury (52%) crashes involved multiple vehicles.

The majority of motorcycle crashes in Wyoming occur during the summer months (June to September). The breakdown of the 12-year motorcycle-related crash frequencies by month is provided in Table 3.2. The majority of the total (20%), fatal (29%), and injury (28%) crashes occurred in August.

Table 3.2 12-Year Wyoming Motorcycle-Related Crash Frequencies by Month

Month	Total	Fatal (K)	Incapacitating (A)	Non-incapacitating (B)	Possible (C)	No injury (O)	Unknown
January	20	0	2	6	4	1	7
February	39	1	5	11	8	5	9
March	114	4	29	33	34	3	11
April	171	4	48	70	22	7	20
May	312	19	68	132	49	18	26
June	561	38	147	226	72	29	49
July	695	43	182	287	89	34	60
August	944	59	262	382	124	61	56
September	372	22	94	135	68	20	33
October	130	8	26	44	25	5	22
November	55	2	12	24	8	2	7
December	16	2	0	6	5	1	2
Sum	**3,429**	**202**	**875**	**1,356**	**508**	**186**	**302**

Motorcycle crash data analysis for the 12-year period also shows the following trends:

- Close to 60% of fatalities and incapacitating injuries occurred to motorcycle riders and passengers who were not wearing a helmet.
- 21% of single, rural motorcycle crashes involved run-off-road.
- 69% of multi-vehicle, urban crashes with motorcycle involvement were intersection/interchange/driveway related.
- 19% of all motorcycle crashes occurred during reduced visibility conditions.
- Of all motorcycle-related crashes, 18.4% involved speeding, 10.7% involved alcohol, and 6.4% involved animal collision.

The data also revealed the routes along which motorcycle-related crash frequencies are higher. The routes with more than 30 motorcycle-related crashes during the 12-year period are presented in Table 3.3. It is worth noting that these are crashes occurred along the entire length of the route.

Table 3.3 12-Year Motorcycle-Related Crash Frequencies by Route (>30)

Rural Route	Rt. 85	Rt. 601	Rt. 37	Rt. 10	Rt. 36	Rt. 80I	Rt. 1507	Rt. 607	Rt. 34	Rt. 38	Rt. 2000	I-80D	Rt. 31	I-90D
Crash Count	88	86	62	57	52	46	46	44	42	38	35	34	31	31

As the crashes in the database are geo-located, this information was used to plot the crash locations for the covered 12-year period, as shown in Figure 3.1.

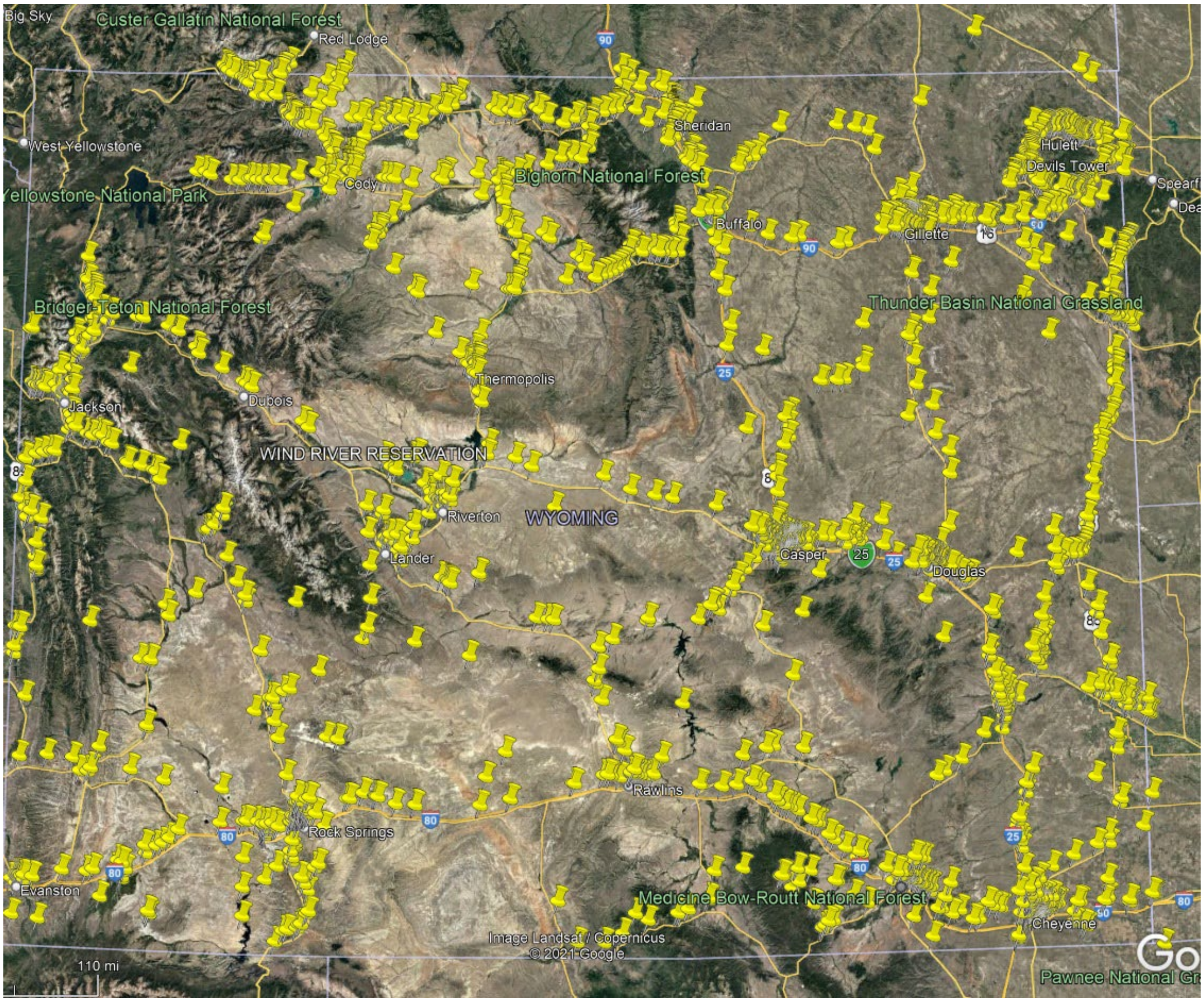

Figure 3.1 Geo-Location of Motorcycle-Related Crashes in Wyoming (2008 – 2019)

Motorcycle crashes typically involve more than one contributing factor; therefore, there are combined effects that affect motorcycle crash frequencies and severity. To better understand the combined effects of contributing factors to motorcycle-related crashes in Wyoming, this study applies various statistical regression analysis using the 12 years of crash data.

3.2 Utah Descriptive Statistics

Crash frequencies, including motorcycle-related, are significantly higher in Utah than Wyoming. Therefore, this study included eight years of motorcycle crash data (2014-2021) obtained through the AASHTOWare Safety system. The data were downloaded on the crash, vehicle and person levels, and combined as needed to extract the required parameters for this study

During the eight-year period, 8,750 motorcycle-related crashes occurred in Utah. Out of those, 325 were fatal (3.7%), 1,683 suspected serious injury (19.2%), 3,867 suspected minor injury (44.2%), 1,622 possible injury (18.5%), and 1,253 no injury/property damage only (PDO) (14.3%). The breakdown of the eight-year motorcycle-related crashes in Utah, according to the number of vehicles involved and the setting is shown in Table 3.4.

Table 3.4 8-Year Motorcycle-Related Crash Frequencies in Utah

	Total	Fatal	Suspected Serious Injury	Suspected Minor Injury	Possible injury	No injury/PDO
Single	3,661	129	791	1,840	600	301
Multi	5,089	196	892	2,027	1,022	952
Rural	1,973	118	502	821	317	215
City	6,777	207	1,181	3,046	1,305	1,038
Rural Single	1,521	81	394	655	244	147
Rural Multi	452	37	108	166	73	68
City Single	2,140	48	397	1,185	356	154
City Multi	4,637	159	784	1,861	949	884

Unlike results obtained from Wyoming, in Utah the majority of all motorcycle-related crashes (58%), fatal (60%) and suspected serious injury crashes (53%) are with multi-vehicle involvement. The majority of all motorcycle-related (78%), fatal (64%), and suspected serious injury (70%) crashes occurred in urban areas. In rural areas, the majority of all (77%), fatal (59%) and suspected injury (79%) crashes were single motorcycle involved. In urban areas, the majority of all (58%), fatal (77%) and suspected injury (66%) crashes involved multiple vehicles.

The weather conditions in Utah are more favorable than in Wyoming, therefore a significant increase in motorcycle related crashes starts in April, and lasts until October. The majority of crashes occur between May and September, with little variation month-to-month. June, July and August saw almost the same number of motorcycle related crashes, and 42% of all crashes occurred during these three months. The monthly breakdown of motorcycle-related crashes in Utah for the 8-year analysis period is given in Table 3.5.

The analysis of the crash data shows the following trends:

- Helmet was not used in 41% of total, and 39% of fatal and suspected serious injury crashes.
- 14.6% of total and 23.2% of fatal and suspected serious injury crashes involved speeding.
- 12.2% of fatal and suspected serious injury crashes involved driving under influence (DUI)
- 22.2% of total and 24.6% of fatal and suspected serious injury crashes occurred in reduced visibility conditions.
- 34.5% of total and 41.8% of fatal and suspected serious injury crashes were roadway geometry related.

The data also revealed the routes with high number of motorcycle related crashes. Table 3.6 shows the routes which recorded more than 100 motorcycle crashes during the 8-year period. It is worth noting that these are crashes occurred along the entire length of the route.

Table 3.5 8-Year Utah Motorcycle-Related Crash Frequencies by Month

Month	Total	Fatal	Suspected Serious Injury	Suspected Minor Injury	Possible injury	No injury/PDO
January	111	2	18	48	27	16
February	201	5	36	86	41	33
March	466	18	93	218	78	59
April	781	29	155	346	134	117
May	1,061	38	207	457	192	167
June	1,235	49	238	549	221	178
July	1,237	41	241	562	227	166
August	1,242	44	232	568	233	165
September	1,140	45	204	494	226	171
October	778	30	164	321	152	111
November	359	21	75	148	62	53
December	139	3	20	70	29	17
Sum	**8,750**	**325**	**1,683**	**3,867**	**1,622**	**1,253**

Table 3.6 8-Year Motorcycle-Related Crash Frequencies by Route (>100)

Route	Rt. 89	I-15	Rt. 71	Rt. 68	I-80	Rt. 189	Rt. 126	Rt. 171	Rt. 39
Crash Count	677	600	114	212	144	119	115	134	150

The geo-location of motorcycle-related crashes in Utah is presented in Figure 3.2. The information is extracted from the database using the latitude/longitude coordinates coded for each crash.

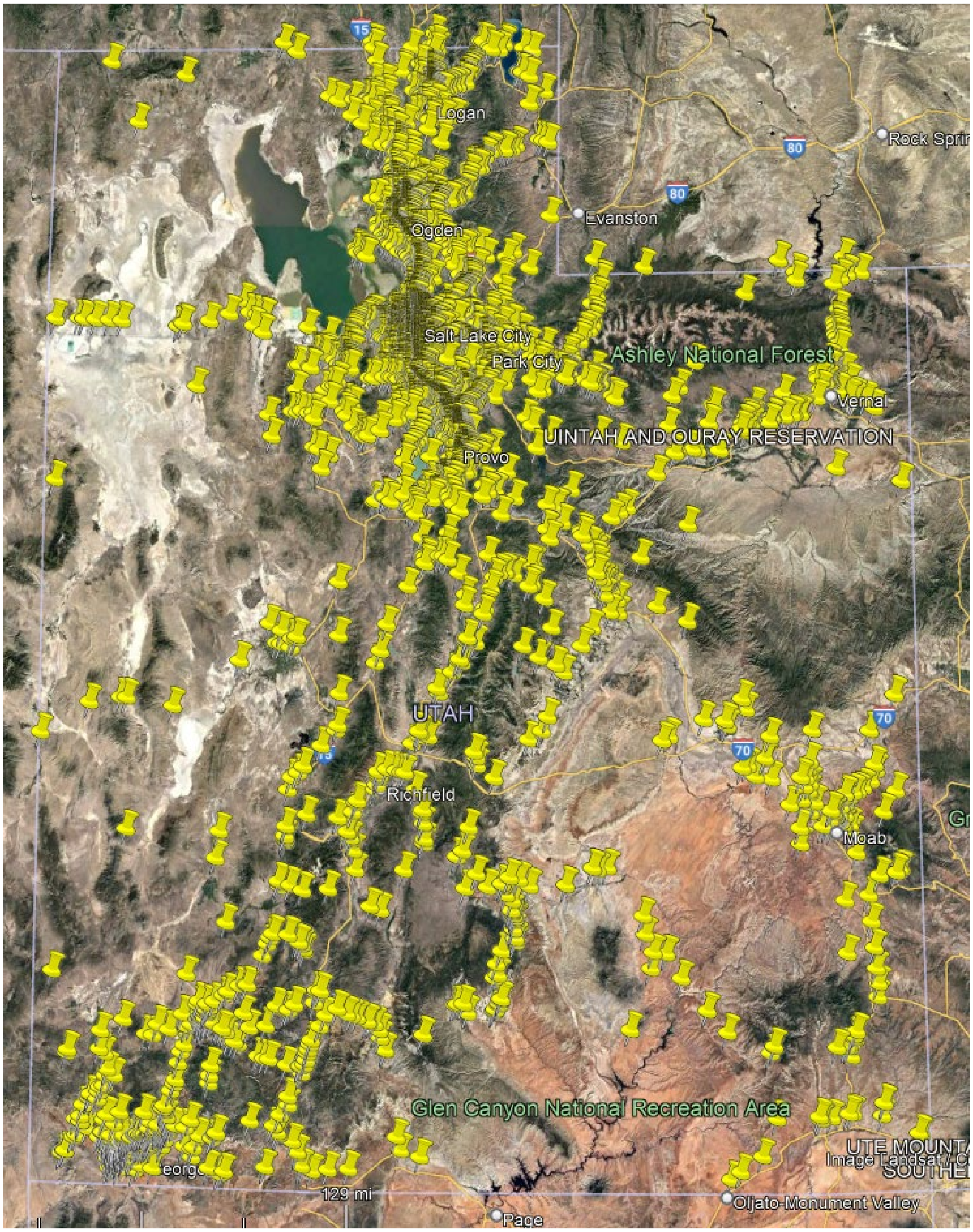

Figure 3.2 Geo-Location of Motorcycle-Related Crashes in Utah (2014 – 2021)

4. STATISTICAL ANALYSIS: MULTINOMIAL LOGISTIC REGRESSION

Multinomial logistic regression (MLN) is a promising approach in analyzing crash severities, since it does not require an assumption of the trends in the dataset and can be applied to categorical variables, which are common in safety data (Abdulhafedh, 2017). Furthermore, injury severity levels are often divided into two categories (e.g., fatal + incapacitating injury, and others), making it suitable to apply binary logit or probit models (Abdulhafedh, 2017; Kononen et al, 2011). MLN models can consider three or more discrete outcomes, which is the case with the crash database used in this study with a total of five severity outcomes (fatal, incapacitating injury, non-incapacitating injury, possible injury, and no injury). The crashes of unknown severity were not considered for inclusion in the models.

The general formulation of the MLN model is as follows (Greene, 2012):

$$p_i = P\left(Y_i = j\,|\mathbf{w_i}\right) = \frac{\exp\left(\mathbf{w_i'} \cdot \boldsymbol{\alpha}_\mathbf{j}\right)}{\sum_{j=0}^{n} \exp\left(\mathbf{w_i'} \cdot \boldsymbol{\alpha}_\mathbf{j}\right)}, \qquad j = 0, 1, 2, \ldots n \tag{1}$$

Where $p_i = P\left(Y_i = j\,|\mathbf{w_i}\right)$ is the probability of presence of an outcome of interest (i.e. crash severity on one of the five levels of the KABCO scale), $\mathbf{w_i'}$ is the vector of independent variables (e.g. for lighting: daylight, darkness lighted, darkness unlighted, dusk, dawn and uknown), and $\boldsymbol{\alpha}_\mathbf{j}$ is the vector of regression coefficients.

The odds ratio can then be defined as the probability of the event divided by the probability of non-event (Abdulhafedh, 2017; Greene, 2012):

$$\text{odds ratio} = \frac{p_i}{1 - p_i} \tag{2}$$

The logit transformation of the odds ratio is defined as the logged odds:

$$\text{logit}(p_i) = \ln\left[\frac{p_i}{1 - p_i}\right] \tag{3}$$

The MLN models use the maximum likelihood estimation (MLE) to determine the regression parameters. The probability density function (pdf) for a random variable y is conditioned on a set of vector parameters $\boldsymbol{\theta}$, denoted as $f\,(y|\boldsymbol{\theta})$, provides a mathematical description of the data that the process will produce (Abdulhafedh, 2017; Greene, 2012). The joint density of n independent and identically distributed observations from this process is the product of the individual densities, as:

$$f(y_1, \ldots, y_n|\boldsymbol{\theta}) = \prod_{\mathbf{i=1}}^{\mathbf{n}} f(y_i|\boldsymbol{\theta}) = L(\boldsymbol{\theta}|\mathbf{y}) \tag{4}$$

Where $L(\boldsymbol{\theta}|\mathbf{y})$ is the likelihood function, defined as a function of the unknown parameter vector, $\boldsymbol{\theta}$, of the vector $\mathbf{y}$ representing the collection of sample data. The likelihood function depends on the unknown parameter $\boldsymbol{\theta}$. The value of $\boldsymbol{\theta}$ for which the likelihood function is at maximum is used as an estimate of $\boldsymbol{\theta}$. This is done by maximizing the log of the likelihood function, denoted as $LL(\boldsymbol{\theta})$, as it transforms into a summation as follows (Abdulhafedh, 2017):

$$\mathrm{LL}(\boldsymbol{\theta}) = \log(\boldsymbol{\theta}) = \log \prod_{\mathbf{i=1}}^{\mathbf{n}} \mathrm{f}(\mathrm{y_i}|\boldsymbol{\theta}) = \sum_{\mathbf{i=1}}^{\mathbf{n}} \mathrm{f}(\mathrm{y_i}|\boldsymbol{\theta}) \tag{5}$$

In this study, RStudio statistical software was used to implement the MLN model on the set of 12 years of motorcycle crash data in Wyoming, and eight years of motorcycle crash data in Utah. The descriptive statistics analysis showed significant differences in crash-contributing factors and crash outcomes based on the number of vehicles involved (single or multiple), and the setting (rural or urban). To better assess the effects of different factors on injury severity, the datasets were first divided into four subsets based on the setting and number of vehicles involved in a motorcycle-related crash: rural single, rural multi-vehicle, urban single, and urban multi-vehicle crashes. For each setting/number of vehicles combination the outcome variable was the crash severity (five levels on the KABCO scale), while the independent crash variables included, among others, the manner of collision, vehicle maneuver, driver action, junction relation, lighting, weather, driver age, driver gender, alcohol, wild animal and speeding involvement, and helmet use. Some of the independent variables are categorical (e.g., manner of collision, maneuver, action etc.), while some are binary (e.g., speed, alcohol, animal involvement). RStudio was also used to calculate the correlations between the outcome variable and each independent variable, and between all pairs of independent variables (e.g., manner of collision and junction relation), to aid in the selection of predictor variables for inclusion in the models.

Previous research (Savolainen and Mannering, 2007; Geedipally et al, 2011), and the descriptive statistics from the data used in this study, show that different contributing factors and relationships exist for different settings (urban or rural), and the number of vehicles (single or multi) involved in a motorcycle-related crash. Therefore, this study assessed the four possible combinations separately to gain better insight into the factors, their relationships and resulting injury-severity outcomes: (1) rural single motorcycle crashes; (2) rural multi-vehicle, motorcycle-related crashes; (3) urban single motorcycle crashes; (4) urban multi-vehicle, motorcycle-related crashes. The strength of the associations between candidate predictors and the crash severity outcome variable were assessed to determine their inclusion in the MNL models. Chi-square (χ^2) tests were conducted for categorical predictors to determine relationship significance, and Cramer's V statistics were calculated to determine the strength of the association (McHugh, 2013). For ordinal and continuous predictors, Spearman Rank (nonparametric version of Pearson's) correlations were calculated. The magnitude of Spearman's (ρ) coefficient provided a measure of the strength of the association, and the associated p-value provided the statistical significance of the relationship. Categorical variables that possessed a moderate, strong, or very strong relationship with crash severity (Cramer's V value of 0.11 or higher) were included in the MNL models. Ordinal and continuous variables possessed only weak or very weak relationships with crash severity and were not included. However, despite the fact that the $\chi 2$ tests did not find a significant relationship between helmet use and crash severity in multi-vehicle, motorcycle-related crashes, it was still included in the models, as previous research indicated otherwise (Savolainen and Mannering, 2007; Islam, 2021; Li et al, 2021; Shaheed and Gkritza, 2014; Geedipally et al, 2011). The model fit for all four modes was determined using the McFadden's Pseudo R2 measure, which is more suitable for MLN models (McFadden, 1977). A McFadden R2 value between 0.2 and 0.4 indicates an excellent model fit. The odds ratios are computed for each of the four models, and they represent the odds of a particular outcome (crash severity level, e.g., an incapacitating crash severity) given a specific exposure (independent variables, e.g., while not wearing helmet) compared to the odds of the outcome occurring at some reference exposure (e.g., a helmet was used). The reference levels for exposures and outcome are also presented with each model.

4.1 Results and Discussion: Wyoming Dataset

4.1.1 Wyoming Rural Single MLN Model

Table 4.1 shows the MLN model results for rural, single motorcycle crashes. The exposure measures strongly associated with crash severity in this case are the road condition, weather, vehicle maneuver, alcohol, animal and speed involvement, and helmet use. Some of the odds ratios are very large, mainly due to the fact that for some crash severities the number of samples was low, resulting in overexposure for that type. The factors that increase the odds of a fatal crash compared to a no-injury crash include severe wind, cloudy/overcast weather, entering a traffic lane, overtaking/passing, making a U-turn, negotiating a curve, alcohol use (significant at the 0.05 level), animal collision, and speeding. Not wearing a helmet increases the odds of a fatal crash by about 1.3 compared to no injury. Similar relationships can be seen for incapacitating injury crashes, albeit with lower odds. Compared to no-injury crashes, the odds of non-incapacitating and possible injury crashes increase multifold for ice road conditions, entering a traffic lane, overtaking/passing, alcohol use, and animal involvement. In addition, the odds of non-incapacitating injury crashes increase for sand and snow road conditions, severe wind, making a U-turn, and stopped in traffic, compared to no-injury crashes. The odds of possible injury crashes are also increased for the presence of water on the road. Interestingly, not wearing a helmet shows lower odds for incapacitating, non-incapacitating, and possible injury crashes compared to no injury. High winds are common in Wyoming and can lead to more severe motorcycle crashes. Negotiating a curve is another common factor in single motorcycle crashes described in previous research (Savolainen and Mannering, 2007; Islam, 2021; Li et al, 2021; Shaheed and Gkritza, 2014; Geedipally et al, 2011). Wyoming is also characterized by open ranges and wild animals on the roads in rural areas, therefore animal-involved crashes can increase the odds of crash occurrence and high severity. Alcohol use and speeding are other common factors found to increase crash severities.

4.1.2 Wyoming Rural Multi-Vehicle MLN Model

The results for the rural, multi-vehicle MLN model are given in Table 4.2. In this case, the exposure measures that were strongly associated with injury severity include junction relation, vehicle maneuver, alcohol use and speeding. Helmet use did not show significant association; however, it was included in the analysis as a recommended factor from previous research (Savolainen and Mannering, 2007; Islam, 2021; Li et al, 2021; Shaheed and Gkritza, 2014; Geedipally et al, 2011).

For all levels of injury crashes, compared to no injury, the odds ratios show increased odds for interchange area intersection relation, presence of intersections (significant at the 0.01 level for incapacitating injury), presence of private road junctions, presence of ramps (except for fatal), changing lanes (except for incapacitating injury), negotiating a curve, overtaking/passing, slowing down (for incapacitating and non-incapacitating), turning right, alcohol use and speeding (except for possible injury). Not wearing a helmet shows lower odds for any injury level (except for non-incapacitating injury) compared to no injury. This shows that there are other factors that have higher significance on injury level. As expected, the vicinity of any type of intersection/interchange significantly increases the odds of injury crashes in multi-vehicle collisions with motorcycle involvement. It is interesting to see that private road junctions increase these odds multifold, much higher than other types of junctions. This can be attributed to the absence of traffic control devices and shorter sight distances. Maneuvers, such as changing lanes, overtaking/passing, and negotiating a curve, increase the interaction between the vehicles, subsequently increasing the odds of injury crashes. It is interesting to see that right turn maneuvers also have increased odds of injury crashes. Speeding and alcohol use are common factors, increasing the odds in all motorcycle-related crashes, as found in previous research.

Table 4.1 Wyoming Rural Single MLN Model and Odds Ratios

Variable	Fatal	Incapacitating Injury	Non-Incapacitating Injury	Possible Injury
Constant	0.1758*	1.9887	6.6080***	1.6182
Road Condition				
Ice or Frost	1.1964	0.2052	3.03E+07	7.46E+07
Mud or Dirt or Gravel	0.0000	1.5035	1.0295	1.7739
Oil or Fuel	0.0000	0.0000	0.0000	0.0000
Sand on Dry Pavement	0.2045	0.1037	2.67E+08	0.5034
Snow	0.4366	0.1015	5.45E+08	0.2748
Water Standing or Running	0.5580	0.0950	0.1211	6.73E+08
Wet	1.4491	0.3946	0.4783	0.0000
Weather				
Cloudy or Overcast	10.1960	5.2931	1.2495	3.4345
Fog	2.0536	8.45E+08	0.1229	0.5169
Raining	0.0000	0.2483	0.2248	0.0000
Severe Wind Only	7.30E+06	8.24E+06	1.74E+07	0.3331
Snowing	0.0000	0.0000	0.0000	0.0000
Vehicle Maneuver				
Changing Lanes	0.0000	1.0578	0.1739	0.0000
Entering a Traffic Lane	2.50E+08	1.04E+08	1.57E+17	1.47E+08
Leaving a Traffic Lane	0.0000	0.0000	0.1617	0.7109
Making a U-Turn	5.6893	0.5028	5.66E+08	0.6180
Negotiating a Curve	2.7704	2.2260	1.2311	1.1956
Other	0.5691	0.0713	0.0348	2.47E+08
Overtaking or Passing	9.39E+07	1.20E+08	1.28E+07	7.92E+07
Slowing	0.0000	0.0000	0.8307	2.2723
Stopped in Traffic	0.0996	0.0442	2.09E+08	0.3204
Turning Left	0.0000	0.0000	0.3456	0.0000
Turning Right	0.0000	0.0000	0.6460	0.0000
Alcohol Involved				
Yes	44.6847*	12.1729*	3.2619	2.9463
Animal Involved				
Yes	9.9972	7.0517	4.3466	9.3485*
Speed Involved				
Yes	4.3935	1.2799	0.9111	0.5455
Helmet				
None Used	1.2780	0.9356	0.8304	0.6547

Note. LR value = 178.4, p-value < 0.001. McFadden's $R^2 = 0.18203$.
* = significant at the 0.05 level, ** = significant at the 0.01 level, *** = significant at the 0.001 level.

Reference levels:
Crash Severity: No Injury; *Road Condition*: Dry; *Weather*: Clear; *Vehicle Maneuver*: Straight Ahead; *Alcohol Involved*: No; *Animal Involved*: No; *Speed Involved*: No; *Helmet*: Helmet Used

Table 4.2 Wyoming Rural Multi-Vehicle MLN Model and Odds Ratios

Variable	Fatal	Incapacitating Injury	Non-Incapacitating Injury	Possible Injury
Constant	0.3110	0.2783	0.9263	0.5179
Junction Relation				
Business Entrance	0.6467	2.4818	2.2455	1.9335
Driveway Related	0.0000	2.5978	1.7711	1.7821
Interchange Area Intersection	3.9637	1.49E+09	1.73E+09	10.8623
Interchange Area Intersection Related	0.0000	1.8137	0.0000	0.0000
Intersection	3.3357	9.6165**	2.6218	4.0888*
Intersection Related	0.0000	1.1067	1.0009	3.8918
Private Road Junction	3.16E+08	2.81E+09	6.85E+07	1.12E+09
Ramp	0.0000	6.6860	8.8587	2.0631
Thru Roadway	1.0996	5.35E+08	2.50E+08	5.28E+08
Vehicle Maneuver				
Changing Lanes	1.56E+09	0.5776	1.24E+09	1.7453
Entering a Traffic Lane	0.0000	1.2019	0.4799	0.0000
Making a U-Turn	0.0000	0.0000	0.0000	1.4432
Negotiating a Curve	8.2691	5.5809	4.3767	0.0000
Overtaking or Passing	1.70E+08	1.41E+07	2.77E+08	5.23E+07
Parked	0.0000	0.0000	0.3323	0.0000
Slowing	0.0000	3.0591	4.7789	0.7469
Stopped in Traffic	0.0000	0.0000	0.1145*	0.2036
Turning Left	0.0000	0.4191	0.5326	0.2368
Turning Right	6.1915	1.2775	6.97E+08	6.72E+08
Alcohol Involved				
Yes	7.05E+08	8.96E+08	1.80E+08	3.18E+08
Speed Involved				
Yes	3.60E+08	4.53E+08	1.57E+08	0.7418
Helmet				
None Used	0.7056	0.9305	1.0007	0.5362

Note. LR value = 170.19, p-value < 0.001. McFadden's $R^2 = 0.23301$.
* = significant at the 0.05 level, ** = significant at the 0.01 level, *** = significant at the 0.001 level.

Reference levels:
Crash Severity: No Injury; *Junction Relation*: Non-Junction; *Vehicle Maneuver*: Straight Ahead; *Alcohol Involved*: No; *Speed Involved*: No; *Helmet*: Helmet Used

4.1.3 Wyoming Urban Single MLN Model

The resulting coefficients and odds ratios of the MLN model for urban, single motorcycle crashes are presented in Table 4.3. In this case, the exposure variables strongly associated with crash severity include junction relation, weather, alcohol use, animal and speeding involvement, driver action, and helmet use.

Compared to no injury, the odds of any injury crash are higher for the vicinity of intersections, business entrances, alcohol, animal and speed involvement, helmet use (significant at the 0.01 and 0.001 levels), avoiding animals, avoiding non-motorists (except for fatal), disregarding road markings (except for possible injury), disregarding traffic signs (except for fatal), aggressive driving, evading law enforcement (except for possible injury), failure to keep proper lane (except for possible injury), failure to yield right-of-way (ROW) (except for incapacitating injury), improper passing (except for possible injury), improper turns (except for fatal), other improper action, running off road, and driving too fast for conditions. In addition, the odds of fatal crashes are increased for following too close, of incapacitating injury for blowing dust/sand/dirt, for over correction/over steer, and incapacitating and non-incapacitating injury for swerving. For urban single crashes, motorcyclists' improper actions and errors are present more than other contributing factors. Failure to keep proper lane was found to be significant at 0.01 and 0.05 level for fatal and incapacitating injuries, respectively. The vicinity of intersections/interchanges is a common factor in urban areas which increases the odds of motorcycle crash occurrences and subsequent higher severities. Not wearing a helmet significantly increases the odds of all injury crashes compared to no injuries in this model. An interesting finding is that rain actually reduces the odds of all injury crashes, with the relationship being significant for fatal, incapacitating and non-incapacitating crashes.

4.1.4 Wyoming Urban Multi-Vehicle MLN Model

Table 4.4 presents the results of the urban multi-vehicle MLN model. In this case, the significant measures of exposure strongly associated with crash injury severity include the manner of collision, junction relation, vehicle maneuver, alcohol use, speeding involvement and helmet use.

Angle, head-on, rear end, rear to side, and sideswipe crashes increase the odds of any injury crash compared to no injury, multifold. Business entrances, driveways, vicinity of intersections/interchanges and ramps increase the odds of any injury crash, and changing lanes, entering a traffic lane, alcohol use, and speeding (significant at the 0.05 level for fatal). Crossovers, entrance/exit rams, through roadways (at interchanges), and not wearing a helmet increase the odds of fatal and non-incapacitating crashes, compared to no injury. Negotiating a curve increases the odds of fatal and incapacitating injury, while making a U-turn increases the odds of fatal and possible injury crashes. Turning right increases the odds of all injury, with the exception of fatal crashes. Junction relation and vehicle maneuvers have significant effects on injury level in urban multi-vehicle motorcycle-related crashes. Alcohol use and speeding are typical factors increasing the odds of crash occurrences and any injury crash.

Table 4.3 Wyoming Urban Single MLN Model and Odds Ratios

Variable	Fatal	Incapacitating Injury	Non-Incapacitating Injury	Possible Injury
Constant	0.1679***	2.1885*	5.3306***	1.9203
Junction Relation				
Alley	0.3087	0.0753	1.04E+08	3.32E+08
Business Entrance	1.1650	1.96E+08	5.09E+08	3.34E+08
Driveway Related	0.6893	0.7420	1.1325	0.2483
Entrance/Exit Ramp	0.7973	3.79E+08	4.39E+08	0.2678
Interchange Area Intersection	1.1631	0.9528	0.7142	0.5000
Interchange Area Intersection Related	6.2568	0.2597	5.15E+09	0.4926
Intersection	1.8430	2.1787	5.6439	5.4728
Intersection Related	7.15E+07	7.90E+07	1.98E+08	1.59E+08
Other Non-Interchange	0.4110	1.29E+09	0.0304	0.0879
Other Parts (e.g., Gore)	9.98E+07	1.29E+08	3.91E+08	2.10E+08
Ramp	0.2884	6.79E+07	9.74E+07	3.67E+08
Thru Roadway	0.0000	8.4402	0.0000	1.8801
Weather				
Blowing Dust/Sand/Dirt	1.0142	3.77E+09	0.0452	0.1243
Blowing Snow	1.1855	0.1798	0.2456	4.04E+10
Cloudy/Overcast	1.1847	0.6422	0.6036	0.4463
Raining	0.1013*	0.1891**	0.1833**	0.4680
Severe Wind Only	0.0000	0.4275	0.2141*	0.4726
Sleet/Hail/Freezing Rain	0.0000	0.0000	0.0752	0.0000
Snowing	0.2386	0.0000	0.0000	0.0000
Alcohol Involved				
Yes	7.54E+07	5.60E+07	2.66E+07	2.58E+07
Animal Involved				
Yes	3.49E+08	4.73E+08	2.27E+08	9.96E+07
Speed Involved				
Yes	3.7058	1.8099	1.6387	1.7920
Helmet				
None Used	5.8717***	3.3512**	4.1483***	4.1883***
Driver Action				
Avoiding an Object on Road	0.9895	2.19E+08	1.51E+08	9.54E+07
Avoiding Animal	2.7073	1.5207	1.4562	1.1152
Avoiding MV	0.9518	1.7594	1.0072	1.0572
Avoiding Non-Motorist	0.7276	1.12E+08	2.80E+07	8.38E+07
Disregarded Other Road Marking	1.67E+09	2.72E+08	1.24E+08	0.3599
Disregarded Traffic Signs	0.1266	2.20E+07	1.47E+07	4.50E+07
Drove Too Fast for Conditions	1.1654	1.4739	0.6527	0.3977
Erratic/Reckless/ Aggressive	1.8481	2.5861	1.3004	1.0552
Evading Law Enforcement	8.29E+07	6.64E+07	5.92E+07	0.0357
Failed to Keep Proper Lane	6.3946**	2.9814*	1.2341	0.9583
Failed to Yield ROW	5.1200	0.4796	7.26E+09	1.0415
Following Too Close	2.0613	0.8439	0.7189	0.9324
Improper Backing	4.8093	0.4689	3.85E+08	1.30E+09
Improper Passing	1.25E+09	3.84E+08	4.22E+07	0.0827
Improper Turn/No Signal	0.7328	1.50E+08	1.26E+08	6.55E+07
Other Improper Action	8.59E+07	2.10E+08	9.14E+07	9.92E+07
Over Corrected/Over Steered	1.5795	1.3385	0.7446	0.6557
Ran Off Road	6.6279**	3.3760*	1.3458	0.9929
Ran Red Light	0.0000	0.0000	16.6459	0.0000
Speeding	6.04E+07	8.45E+07	3.60E+07	3.21E+07
Swerve Due to Wind/Slippery Surface	0.0000	1.3347	1.1675	0.6726
Wrong Side/Wrong Way	0.2903	1.26E+08	6.09E+07	0.0621

Note. LR value = 366.52, p-value < 0.001. McFadden's $R^2 = 0.10103$.
* = significant at the 0.05 level, ** = significant at the 0.01 level, *** = significant at the 0.001 level.

Reference levels:
Crash Severity: No Injury; *Junction Relation*: Non-Junction; *Weather*: Clear; *Driver Action*: No Improper Driving; *Alcohol Involved*: No; *Animal Involved*: No; *Speed Involved*: No;
Helmet: Helmet Used

Table 4.4 Wyoming Urban Multi-Vehicle MLN Model and Odds Ratios

Variable	Fatal	Incapacitating Injury	Non-Incapacitating Injury	Possible Injury
Constant	0.0000	0.7903	1.7915	0.0000
Manner of Collision				
Angle Direction not Specified	4.49E+09	8.71E+07	1.35E+08	3.00E+17
Angle Front to Side Opposing Direction	1.99E+17	1.69E+08	9.07E+07	2.00E+17
Angle Right Front to Side Includes Broadside	2.71E+09	3.7364	2.4739	4.05E+09
Angle Same Direction Front to Side	2.36E+09	3.6481	2.5434	5.84E+09
Head on Front to Front	5.97E+17	3.08E+08	1.56E+08	3.27E+17
Other	2.13E+17	0.3250	4.24E+08	2.20E+18
Rear End Front to Rear	1.44E+09	2.5424	1.7209	3.60E+09
Rear to Front Normally Backing	0.0000	0.0000	6.16E+08	0.0000
Rear to Side Normally Backing	7.67E+08	6.63E+08	5.00E+08	2.31E+18
Sideswipe Opposite Direction Meeting	4.66E+09	4.9904	1.3690	9.48E+08
Sideswipe Same Direction Passing	4.13E+08	6.6892	3.9747	5.93E+09
Junction Relation				
Business Entrance	2.5696	2.7846	4.1731	6.4326
Crossover Related	3.85E+08	0.0000	6.1574	0.0000
Driveway Related	2.2219	1.3284	0.7921	2.2876
Entrance or Exit Ramp	3.5052	0.4977	8.96E+09	0.5627
Interchange Area Intersection	5.0290	1.0413	0.5965	0.2327
Interchange Area Intersection Related	0.0000	0.0000	0.0000	0.2824
Intersection	1.00E+08	1.35E+08	2.03E+08	3.54E+08
Intersection Related	2.5208	6.1291	11.6974*	17.5232*
Other Non-Interchange	0.2630	0.0399	1.70E+08	1.78E+08
Other Parts (e.g., Gore)	0.0000	0.0000	0.3119	0.0000
Ramp	2.42E+16	2.10E+25	1.46E+25	1.49E+25
Thru Roadway	2.8378	0.1851	3.93E+09	0.3537
Vehicle Maneuver				
Backing	0.1281	0.0000	0.0000	1.2447
Changing Lanes	1.55E+08	8.29E+07	2.15E+08	1.78E+08
Entering a Traffic Lane	9.50E+07	8.50E+07	3.13E+07	6.47E+07
Leaving a Traffic Lane or Parking	0.0000	0.0000	0.0000	0.9949
Making a U-Turn	1.5030	0.9797	0.5295	1.5862
Negotiating a Curve	1.6740	1.0992	0.8504	0.4461
Other	1.7287	6.96E+08	4.26E+08	0.4369
Overtaking or Passing	1.1485	2.6255	1.3252	0.8040
Parked	0.0706	2.47E+07	3.68E+07	2.80E+07
Slowing	0.7985	4.6411	3.6621	3.7923
Stopped in Traffic	0.0000	0.2451	0.0774*	0.0914*
Turning Left	0.4028	1.4003	0.7564	0.6048
Turning Right	0.0000	8.77E+07	7.09E+07	7.84E+07
Alcohol Involved				
Yes	7.73E+07	9.64E+07	2.85E+07	5.03E+07
Speed Involved				
Yes	19.0235*	6.7013	5.5375	3.8223
Helmet				
None Used	2.1518	0.9633	1.2714	0.9221

Note. LR value = 309.68, p-value < 0.001. McFadden's R^2 = 0.14556.
* = significant at the 0.05 level, ** = significant at the 0.01 level, *** = significant at the 0.001 level.

Reference levels:
Crash Severity: No Injury; *Manner of Collision*: Not a Collision with 2 Vehicles in Transport; *Junction Relation*: Non-Junction; *Vehicle Maneuver*: Straight Ahead; *Alcohol Involved*: No; *Speed Involved*: No; *Helmet*: Helmet Used

4.2 Results and Discussion: Utah Dataset

4.2.1 Utah Rural Single MLN Model

Table 4.5 represents the coefficients and odds ratios of the Utah rural single MLN model. The significant measures of exposure strongly associated with crash injury severity include the light conditions, roadway surface, weather, vehicle maneuver, rider sex, aggressive driving, DUI, disregarding traffic control, animal involvement, collision with fixed object, intersection relation, interstate relation, roadway geometry relation, speed relation, work zone involvement, wrong way driving, older rider involvement, and helmet use. The crash severity outcome was categorized into five categories, with no injury/PDO being the reference level, and possible injury, suspected minor injury, suspected serious injury, and fatal crashes as the outcomes. Riders' age in this case was defined as a categorical variable, with older rider being defined as 55 years and older.

Compared to no injury, dusk increases the odds of all severity levels two to three times. Mud on the road increases the odds of suspected serious, minor and possible injuries multifold. Sand, dirt and gravel on the road were also found to increase the odds of fatal and suspected serious and minor injury crashes one to two times compared to no injury. Cloudy weather slightly increases the odds of fatal, suspected serious and minor injury crashes. Severe cross winds increase the odds of fatal crashes more than twice compared to no injury. Changing lanes was found to be a vehicle maneuver that increases the odds of all injury level and fatal crashes in rural single crashes more than any other maneuver. Making a U-turn increases the odds of injury crashes two to seven times compared to no injury. Overtaking other vehicles increases the odds of fatal and suspected serious injury motorcycle crashes about five and three times, respectively, compared to no injury. Slowing in the traffic lane and turning left increase the odds of injury and fatal crashes two to three times, while turning right has shown to increase the odds of injury crashes two to four times, compared to no injury. The odds of injury and fatal crashes for female riders are close to two times higher than those for male riders. Aggressive driving is another single attribute that increases the odds of fatal and all injury crashes multifold compared to no injury. Similarly, DUIs increase the odds of fatal crashes more than 17 times, and this increase is statistically significant. It also slightly increases the odds of suspected serious and minor injury crashes. Disregarding traffic control increases the odds of fatal crashes more than two times, and injury crashes multifold when compared to no injury. Collision with fixed objects increase the odds of fatal crashes more than twice. The odds of fatal crashes on interstates are more than four times higher than the odds of no injury crashes. Roadway geometry also slightly increases the odds for all fatal and injury crashes. Speed-related crashes significantly increase the odds of fatal and all injury crashes two to four times, compared to no injury. Similar results were found for work zone-related crashes. Wrong way driving increases the odds of fatal crashes multifold, compared to injury crashes. Older riders are almost seven times more likely to be involved in a fatal crash. Finally, not using a helmet increases the odds of fatal crashes more than twice compared to no injury.

Table 4.5 Utah Rural Single MLN Model and Odds Ratios

	Fatal	Suspected Serious Injury	Suspected Minor Injury	Possible Injury
Intercept	0.071***	1.584	4.389***	1.799
Light Condition				
Dark Lighted	0.000	0.245	0.199	1.532
Dark Not Lighted	0.720	0.516	0.742	0.810
Dawn	2.375	0.299	0.282	0.377
Dusk	3.133	2.013	2.089	2.489
Roadway Surface				
Mud	0.747	6.621E+08	4.372E+08	4.430E+08
Oil	0.000	0.000	0.507	0.835
Sand, Dirt, Gravel	1.296	1.391	1.184	0.595
Snow	0.000	0.000	0.032**	0.000
Wet	0.000	0.173*	0.374	0.528
Weather Condition				
Cloudy	1.251	1.206	1.008	0.944
Rain	0.000	0.851	0.393	0.557
Severe Crosswinds	2.229	0.214	0.219	1.005
Snowing	0.491	0.000	0.620	0.000
Vehicle Maneuver				
Changing Lanes	4.294E+08	1.882E+08	2.082E+08	2.109E+08
Leaving Traffic Lane	0.000	1.136	0.878	1.001
Making U-turn	0.000	2.442	1.110	7.930
Negotiating a Curve	0.000	1.099	0.667	0.000
Overtaking/Passing	4.838	2.499	1.023	0.844
Slowing in Traffic Lane	1.664	0.735	2.595	3.325
Stopped in Traffic Lane	0.000	0.265	0.000	0.820
Turning Left	1.180	2.787	1.572	1.948
Turning Right	0.000	1.222	2.234	3.823
Female Rider	1.278	2.106*	1.513	1.529
Aggressive Driving	4.794E+08	2.996E+08	2.187E+08	2.388E+08
DUI	17.236***	1.349	1.236	0.440
Disregard Traffic Control	2.308	2.780E+08	2.752E+08	1.581E+08
Animal Related	0.447	0.724	0.457**	0.625
Collision w/ Fixed Object	2.376*	1.296	0.831	0.738
Intersection Related	0.683	1.284	1.350	0.452
Interstate Related	4.242*	1.504	1.256	0.867
Roadway Geom. Related	1.815	1.136	1.137	1.172
Speed Related	3.662**	3.680*	2.809**	2.250***
Work Zone Involved	2.609	2.703	3.354	3.124
Wrong Way Driving	6.708E+08	0.389	0.232	2.110E+09
Older Driver Involved	6.801***	1.318	1.373	1.043
No Helmet	2.492*	1.649	1.318	1.017

Note. p-value < 0.001. McFadden's $R^2 = 0.0941$
* = significant at the 0.05 level, ** = significant at the 0.01 level, *** = significant at the 0.001 level.

Reference levels:
Crash Severity: No Injury; *Light Condition*: Daylight; *Weather Condition*: Clear; *Vehicle Maneuver*: Straight Ahead; *Rider Sex*: Male; *Aggressive Driving*: No; *DUI*: No; *Disregard Traffic Control*: No; *Animal Related*: No; *Collision w/ Fixed Object*: No; *Intersection Related*: No; *Interstate Related:* No; *Roadway Geometry Related*: No; *Speed Related*: No; *Work Zone Involved*: No; *Wrong Way Driving*: No; *Older Driver Involved*: No; *Helmet used*: Yes

4.2.2 Utah Rural Multi MLN Model

Table 4.6 shows the results of the Utah rural multi-MLN model. The significant variables strongly correlated with crash severity are the same as for the Utah rural single MLN model, with added commercial vehicle involvement.

In these types of motorcycle-related crashes, dark-lighted conditions were found to increase the odds of all injury crashes, while dawn increases the odds of fatal crashes more than five times, and the odds of suspected minor and possible injury crashes, compared to no injury. Sand, dirt and gravel on the road were found to increase the odds of fatal and all injury crashes multifold. Rain is another factor that increases the odds of fatal and suspected serious injury crashes. The lane-changing maneuver was found to increase the odds of all injury crashes multifold, compared to no injury. A U-turn maneuver can increase the odds of fatal crashes more than twice compared to no injury. Female riders also have higher odds for fatal (more than nine times), and all injury crashes. Driving under the influence increases the odds of fatal crashes more than 170 times, and suspected serious (more than six times) and minor injury crashes, compared to no injury. Disregarding traffic control results in increase odds of fatal and suspected serious and minor crashes multifold. Similar findings can be seen for animal-involved crashes. Collision with fixed objects increase the odds of fatal crashes almost 16 times, and the odds of suspected serious and minor injury crashes. Commercial vehicle crash involvement increases the odds of fatal crashes more than seven times and the odds of all injury crashes up to five times compared to no injury. Crashes occurring in the intersection area increase the odds of fatal crashes more than five times. Speed-related crashes increase the odds of fatal (more than four times) and all injury crashes (two to three times), compared to no injury. Wrong way driving slightly increases the odds of fatal crashes. Older riders have about four times higher odds of being involved in a fatal crash, compared to no injury crash. For this model, not using a helmet results in slightly increased odds of suspected serious and minor injury crashes.

4.2.3 Utah Urban Single MLN Model

The results of the Utah urban single MLN model are given in Table 4.7. The significant variables strongly correlated with crash severity are the same as for the Utah rural single MLN model, with the exclusion of signal/roundabout relation.

Dusk conditions are found to increase the odds of fatal (more than eight times) and all injury crashes (three to four times), compared to no injury. Wet roadway was found to slightly increase the odds of suspected minor and possible injury crashes. The lane-changing maneuver was found to increase the odds of suspected serious and minor injury crashes two to three times, compared to no injury. Negotiating a curve increases the odds of all injury crashes. Overtaking maneuvers were found to increase the odds of fatal crashes close to three times, compared to no injury. Female riders have slightly higher odds of all injury and fatal crashes. DUIs were found to increase the odds of fatal crashes more than 13 times compared to no injury, and the odds of suspected severe and minor crashes are also increased. Disregarding traffic control is a single attribute in urban single crashes that increases the odds of fatal and injury crashes multifold. Roadway geometry-related crashes slightly increase the odds of all fatal and injury crashes. Speed-related crashes increase the odds of fatal (more than three times), suspected serious injury crashes (two times) compared to no injury. Older riders have close to seven times higher odds of being involved in a fatal crash. Not using a helmet would increase the odds of fatal crashes more than twice compared to no injury.

Table 4.6 Utah Rural Multi MLN Model and Odds Ratios

	Fatal	**Suspected Serious Injury**	**Suspected Minor Injury**	**Possible Injury**
Intercept	0.116**	1.834	2.485*	1.202
Light Condition				
Dark Lighted	0.840	3.745E+08	4.999E+08	1.547
Dark Not Lighted	0.341	0.741	0.714	0.795
Dawn	5.244	0.323	2.101E+08	5.055E+08
Dusk	0.736	0.276	0.861	1.753
Roadway Surface				
Sand, Dirt, Gravel	1.734E+08	6.155E+08	1.516E+08	2.202E+08
Wet	0.000	0.000	0.139	1.202
Weather Condition				
Cloudy	0.716	0.546	1.090	1.172
Rain	1.300E+09	1.730E+08	0.730	0.000
Severe Crosswinds	0.000	1.253	0.000	0.000
Vehicle Maneuver				
Changing Lanes	0.486	1.967E+08	1.741E+08	3.433E+08
Entering Traffic Lane	0.000	0.000	0.193	0.000
Leaving Traffic Lane	0.000	0.362	0.807	2.376
Making U-turn	2.354	0.000	0.129	0.000
Negotiating a Curve	0.000	0.374	0.071	0.000
Overtaking/Passing	0.286	1.122	0.657	2.010
Parked	0.072	0.000	0.000	0.000
Slowing in Traffic Lane	0.438	0.259	0.650	0.571
Stopped in Traffic Lane	0.182	0.000	0.322	0.192
Turning Left	0.000	0.069	0.206	1.379
Turning Right	0.000	0.000	0.000	0.000
Female Rider	9.201	3.226	3.543	2.284
Aggressive Driving	2.824E+08	2.014E+08	2.796E+08	5.657E+07
DUI	173.643	6.034	2.492	0.734
Disregard Traffic Control	1.976E+08	2.147E+10	2.273	0.886
Animal Related	5.062	4.456E+08	3.623E+08	0.822
Collision w/ Fixed Object	15.674	4.020	2.425	0.595
Commercial Veh. Involved	7.431	4.566	1.258	4.619
Intersection Related	5.126	0.575	0.824	0.463
Interstate Related	1.430	0.463	1.156	0.919
Roadway Geom. Related	1.249	0.688	1.058	0.900
Roundabout/Signal	0.601	2.095	0.445	0.608
Speed Related	4.105	3.391	3.205	2.136
Work Zone Involved	0.000	0.436	0.543	3.164
Wrong Way Driving	1.286	0.549	0.787	0.919
Older Driver Involved	4.364*	1.646	1.175	0.731
No Helmet	0.517	1.134	1.276	0.377

Note. p-value < 0.001. McFadden's $R^2 = 0.2256$
* = significant at the 0.05 level, ** = significant at the 0.01 level, *** = significant at the 0.001 level.

Reference levels:
Crash Severity: No Injury; *Light Condition*: Daylight; *Weather Condition*: Clear; *Vehicle Maneuver*: Straight Ahead; *Rider Sex*: Male; *Aggressive Driving*: No; *DUI*: No; *Disregard Traffic Control*: No; *Animal Related*: No; *Collision w/ Fixed Object*: No; *Commercial Vehicle Involved*: No; *Intersection Related*: No; *Interstate Related:* No; *Roadway Geometry Related*: No; *Roundabout/Signal*: No; *Speed Related*: No; *Work Zone Involved*: No; *Wrong Way Driving*: No; *Older Driver Involved*: No; *Helmet used*: Yes

Table 4.7 Utah Urban Single MLN Model and Odds Ratios

	Fatal	Suspected Serious Injury	Suspected Minor Injury	Possible Injury
Intercept	0.098	2.492	11.167	3.209
Light Condition				
Dark Lighted	1.451	1.004	1.098	1.114
Dark Not Lighted	0.828	1.082	0.602	0.742
Dawn	0.000	0.318	0.399	0.603
Dusk	8.384	3.847	2.831	4.258
Roadway Surface				
Ice/Frost	0.000	0.000	0.223	0.633
Oil	0.000	0.105	0.170	0.311
Sand, Dirt, Gravel	0.000	0.464	0.936	0.883
Wet	0.000	0.684	1.779	1.227
Weather Condition				
Cloudy	0.878	0.916	0.909	0.620
Rain	0.000	0.125	0.209	0.304
Vehicle Maneuver				
Changing Lanes	0.000	2.454	2.387	0.694
Entering Traffic Lane	0.000	0.000	0.445	0.411
Leaving Traffic Lane	0.449	1.379	1.614	1.948
Making U-turn	0.000	0.384	0.586	0.784
Negotiating a Curve	0.720	3.439E+08	6.458E+08	2.916E+08
Overtaking/Passing	2.490	1.052	0.673	1.460
Slowing in Traffic Lane	0.000	0.981	1.463	1.316
Stopped in Traffic Lane	0.000	0.137	0.274	0.854
Turning Left	0.717	0.825	0.937	0.927
Turning Right	0.000	0.892	0.895	1.492
Female Rider	1.634	2.453	1.714	1.726
Aggressive Driving	0.921	1.288	0.826	0.680
DUI	13.489	2.397	1.189	0.730
Disregard Traffic Control	3.601E+08	4.583E+08	1.817E+08	1.552E+08
Animal Related	0.000	0.310	0.492	0.477
Collision w/ Fixed Object	3.102	1.013	0.972	0.743
Intersection Related	0.503	0.692	0.768	1.175
Interstate Related	0.469	0.471	0.507	0.704
Roadway Geom. Related	1.453	1.372	1.073	1.102
Speed Related	3.025	2.136	1.147	0.967
Work Zone Involved	0.779	0.648	0.903	0.894
Older Driver Involved	6.600	1.610	0.989	0.792
No Helmet	2.047	1.405	1.130	0.818

Note. p-value < 0.001. McFadden's $R^2 = 0.0735$
* = significant at the 0.05 level, ** = significant at the 0.01 level, *** = significant at the 0.001 level.

Reference levels:
Crash Severity: No Injury; *Light Condition*: Daylight; *Weather Condition*: Clear; *Vehicle Maneuver*: Straight Ahead; *Rider Sex*: Male; *Aggressive Driving*: No; *DUI*: No; *Disregard Traffic Control*: No; *Animal Related*: No; *Collision w/ Fixed Object*: No; *Intersection Related*: No; *Interstate Related:* No; *Roadway Geometry Related*: No; *Speed Related*: No; *Work Zone Involved*: No; *Older Driver Involved*: No; *Helmet used*: Yes

4.2.4 Utah Urban Multi-MLN Model

The MLN model coefficient and odds ratios for the Utah urban multi-model are shown in Table 4.8. The significant variables strongly correlated with crash severity are the same as for the Utah urban single MLN model, with added commercial vehicle and roundabout/signal relation.

When it comes to lighting, dusk increases the odds of fatal crashes about two times, with a slight increase in odds of all injury crashes, compared to no injury. Dark, not lighted, and dawn conditions slightly increase the odds of fatal crashes. Severe crosswinds increase the odds of fatal crashes about 16 times, with a multifold increase in the odds for suspected serious and possible injury crashes. Snowing also increases the odds of suspected minor and possible injury crashes. In this type of crashes, merging was found to increase the odds of fatal crashes about 22 times compared to no injury, with also a multifold increase in odds of suspected minor and possible injury crashes. Negotiating a curve results in a 19 times increase in odds of fatal crashes and a multifold increase in suspected minor injury crashes compared to no injury. Female riders are about twice more likely to be involved in fatal and all injury crashes, compared to no injury. Aggressive driving increases the odds of fatal crashes almost six times and the odds of injury crashes two to four times. Driving under the influence is a major factor that significantly increases the odds of fatal crashes (about 50 times), and the odds of injury crashes two to three times. Disregarding traffic control increases the odds of fatal crashes close to five times, and the odds of suspected serious and minor crashes two to three times, compared to no injury. Collisions with fixed objects slightly increase the odds of fatal and all injury crashes. Collisions with commercial vehicles increase the odds of motorcycle fatal crashes about four times when compared to no injury. Roadway geometry and roundabout/signal-related crashes increase the odds of fatal and injury crashes about two times. Speed-related crashes were found to increase the odds of fatal crashes more than nine times and the odds of injury crashes two to four times. Work-zone related crashes can double the odds of fatal crashes compared to no injury. In this type of crash, wrong way driving significantly increases the odds of fatal crashes (almost 42 times), and the odds of suspected serious and minor injury crashes, compared to no injury. Older riders are about twice more likely to be involved in fatal crashes. Not using a helmet in this type of crash does not change the odds of fatal or injury crashes.

Table 4.8 Utah Urban Multi MLN Model and Odds Ratios

	Fatal	Suspected Serious Injury	Suspected Minor Injury	Possible Injury
Intercept	0.031***	0.513***	2.114***	1.149
Light Condition				
Dark Lighted	0.952	1.254	1.085	1.054
Dark Not Lighted	1.465	0.831	0.936	0.870
Dawn	1.290	0.566	0.509	1.383
Dusk	2.203	1.569	1.530	1.175
Roadway Surface				
Sand, Dirt, Gravel	0.000	0.274	0.739	0.431
Slush	0.314	0.309	0.000	3.902
Wet	0.945	0.715	0.770	0.455
Weather Condition				
Cloudy	0.801	1.166	1.145	1.236
Rain	1.175	2.259	1.332	2.892
Severe Crosswinds	16.002	1.688E+09	0.554	3.786E+08
Snowing	4.316	0.803	1.850E+08	3.341E+08
Vehicle Maneuver				
Changing Lanes	0.178	0.806	0.812	0.649
Entering Traffic Lane	0.000	0.851	0.499	0.509
Leaving Traffic Lane	0.207	0.716	1.300	0.611
Making U-turn	1.280	0.142	0.567	0.436
Merging	22.096	1.357	8.722E+07	2.615E+08
Negotiating a Curve	19.469	1.047	1.284E+09	0.641
Overtaking/Passing	0.547	0.688	0.864	0.570
Slowing in Traffic Lane	0.845	0.710	0.681	0.788
Starting in Traffic Lane	0.000	0.000	1.463	1.040
Stopped in Traffic Lane	0.086**	0.147***	0.207***	0.418***
Turning Left	0.044***	0.291***	0.363***	0.738
Turning Right	0.155	0.256**	0.407*	0.439*
Female Rider	2.272*	2.411***	1.820***	1.916***
Aggressive Driving	5.642***	4.131***	2.234*	1.819
DUI	50.009***	3.171**	2.222*	1.779
Disregard Traffic Control	4.575***	3.033***	2.083**	1.316
Collision w/ Fixed Object	1.275	2.254*	1.519	1.593
Commercial Veh. Involved	4.094**	0.635	1.081	0.697
Intersection Related	0.772	0.959	0.901	1.014
Interstate Related	0.318*	0.589*	0.554***	0.618*
Roadway Geom. Related	2.207**	1.593**	1.316*	1.218
Roundabout/Signal	2.385**	1.951***	1.495*	1.581*
Speed Related	9.721***	3.863***	2.089***	2.054**
Work Zone Involved	1.958	0.879	0.859	1.183
Wrong Way Driving	41.650***	4.996	2.706	1.416
Older Driver Involved	2.254***	0.893	1.108	1.043
No Helmet	1.084	0.880	0.808*	0.680***

Note. p-value < 0.001. McFadden's $R^2 = 0.0804$
* = significant at the 0.05 level, ** = significant at the 0.01 level, *** = significant at the 0.001 level.

Reference levels:
Crash Severity: No Injury; *Light Condition*: Daylight; *Weather Condition*: Clear; *Vehicle Maneuver*: Straight Ahead; *Rider Sex*: Male; *Aggressive Driving*: No; *DUI*: No; *Disregard Traffic Control*: No; *Animal Related*: No; *Collision w/ Fixed Object*: No; *Commercial Vehicle Involved*: No; *Intersection Related*: No; *Interstate Related:* No; *Roadway Geometry Related*: No; *Roundabout/Signal*: No; *Speed Related*: No; *Work Zone Involved*: No; *Wrong Way Driving*: No; *Older Driver Involved*: No; *Helmet used*: Yes

4.3 Conclusions

Multinomial logistic models were applied to the crash data obtained from Wyoming (2008-2019) and Utah (2014-2021) to assess the significance of crash variables and contributing factors on crash severity levels. This type of analysis was performed to capture the combined effects of various contributing factors (exposure measures) on crash severity (outcome variable), given on KABCO scale. Furthermore, to better understand the manner of setting (urban or rural) and the number of vehicles involved in a motorcycle-related crash (single or multi-vehicle) and their impacts on crash severity, four different models were developed and analyzed: (1) rural single motorcycle crashes; (2) rural, multi-vehicle motorcycle-related crashes; (3) urban single motorcycle crashes; (4) urban, multi-vehicle motorcycle-related crashes. For each model, the significant exposure measures were first determined, and then their odd ratios were computed to determine the association between the exposure and outcome, using no injury as the outcome reference level.

In the case of Wyoming, in all four models, it was found that speeding and alcohol involvement increase the odds of any injury crash multifold. Additionally, for single motorcycle crashes, vehicle maneuver and driver action exposure measures were found to have significant effects on injury level. Helmet use can reduce the odds of fatal and serious injuries in single motorcycle crashes. For multi-vehicle crashes, it was found that junction relation and vehicle maneuver exposure measures have significant effects on odds ratios of injury crashes compared to no injury. Additionally, road and weather conditions impact injury severity level in single rural motorcycle crashes, while weather also impacts the severity level in single urban motorcycle crashes. Manner of collision factors have additional effects on the severity of urban multi-vehicle motorcycle related crashes. Helmet use is found to reduce the odds of fatality and non-incapacitating injuries in urban multi-vehicle crashes.

In Utah, the common factors that increase the odds of fatal and injury crashes include unlighted environment, changing lane and U-turn maneuvers, overtaking in traffic, aggressive driving, DUI, disregard for traffic control, collisions with fixed objects, speeding, wrong-way driving and older riders. Involvement of commercial vehicles in motorcycle related crashes increases the odds in multi-vehicle crashes. Roadway geometry was found to increase the odds of fatal and injury single motorcycle crashes. Wrong-way driving increases the odds of fatal and injury crashes in single rural and urban multi-vehicle crashes. Not wearing a helmet increases the odds of fatal and serious injury crashes in single motorcycle crashes, while it does not have a significant effect in multi-vehicle crashes.

The results obtained from the MLN models can provide guidance on selecting proper engineering, education and enforcement measures, which have the potential to reduce the occurrence and severity of motorcycle-related crashes. Combined with the descriptive statistics and location-specific conditions, this analysis can contribute to the selection of correct measures.

5. STATISTICAL ANALYSIS: BAYESIAN MULTILEVEL MODELS

Bayesian statistical models have been used extensively in traffic safety research. The main advantage of Bayesian regression (BR) modeling is that it treats model variables as random, and the data are used to simulate the behavior of the variables to assess their distributional properties (Haq et al., 2020). The modeling process starts with the selection of the prior distribution of the parametric family. Three types of priors used in BM models include: 1) informative prior, which uses the results of previous similar studies; 2) weak informative prior, which restrict the posterior distribution to be at a sensible range and allows the models to converge; 3) non-informative prior, which allows the information to be drawn from the likelihood. In this study, the weak informative prior was used due to the fact that no previous studies were found to include all the parameters used in modeling of motorcycle-related crashes.

The probability of a parameter in Bayesian data analysis is defined as (Haq et al., 2020; Nalborczyk et al., 2019):

$$p(\theta|y) = \frac{p(y|\theta) \cdot p(\theta)}{p(y)} \tag{6}$$

Where θ = parameters to be estimated, $p(\theta \mid y)$ is the probability distribution to be estimated, also known as the posterior distribution, $p(y \mid \theta)$ is the likelihood function, $p(\theta)$ is prior information of the parameters, also known as the prior distribution, and $p(y)$ is the marginal likelihood.

The predictor variables used in the BR models are the same ones used in the MLN models. However, in this case, the crash severity (response variable) was defined as binary, with two levels: fatal/severe, which contains fatal and serious injury crashes; and other, which includes minor injury, possible injury, and no injury crashes. The statistical modeling was performed in RStudio, using BRMS (Bayesian Regression Modeling with Stan) functionality.

5.1 Results and Discussion: Wyoming Dataset

The BR modeling was performed in R studio using motorcycle-related safety data from the WYDOT CARE database. However, due to the recommendations that more than 10 years of data can introduce too much variability in the results, only eight years (2012–2019) of data were used to develop the BR models. Furthermore, the response variable was defined as binary (fatal/severe, or not), with non-fatal/severe being the reference level, and the age was defined as young (30 years or less), middle (30-50 years), and older (more than 50), with middle age as the reference level. Each model using the Wyoming dataset was run for four Markov chains, 1,000 iterations for warm-up, and 2,000 iterations for sampling, resulting in a total of 8,000 samplings. The coefficient estimation is read as follows: if it is positive, the predictor increases the odds of fatal/severe crashes, the higher the value, the higher the impact; if the coefficient is negative, the predictor reduces the odds of fatal/severe crashes.

5.1.1 Wyoming Rural Single BR Model

The BR model results for rural single motorcycle crashes in Wyoming are given in Table 5.1. For junction relation, majority of junction-related location can increase the odds of fatal and severe crashes. Private road junctions, intersections, other parts, and ramps, respectively, are the locations that significantly increase the severity of single motorcycle-related crashes in rural areas, compared to non-junction locations.

Table 5.1 Wyoming Rural Single BR Model and Estimates

Variable	Estimate
Intercept	2,306.1
Junction Relation	
Thru Roadway	696.7
Interchange Area Intersection	-4,876.7
Driveway	15.1
Intersection	4,176.2
Other (e.g. gore)	3,347.3
Business Entrance	-203.9
Entrance/Exit Ramp	2,339.3
Intersection Related	-377.2
Ramp	2,449.5
Interchange Area Int. Related	-5,542.9
Private Road Junction	17,264.4
Road Condition	
Wet	4,853.2
Mud, Dirt, Gravel	1,843.7
Sand on Dry Pavement	1,533.6
Ice or Frost	140.2
Snow	-656.1
Water	-2,525.2
Other	1,533.2
Weather Condition	
Cloudy	518.7
Raining	-1,097.9
Severe Wind Only	24.3
Snowing	190.3
Sleet, Hail, Freezing Rain	10,685.1
Vehicle Maneuver	
Negotiating a Curve	2,688.2
Turning Right	967.7
Turning Left	4,388.6
Changing Lanes	1,888.3
Making a U-Turn	720.0
Slowing	4,352.3
Overtaking/Passing	-447.2
Other	380.6
Leaving Traffic Lane	749.6
Backing	238.3
Driver Age	
Young	-8,553.4
Old	273.7
Female Rider	449.4
Driver Action	
Failed to Keep Proper Lane	660.4
Ran off Road	-83.9
Over Corrected/Steered	-4,247.1
Drove Too Fast for Conditions	-15.4
Avoiding Animal	2,534.3
Swerve due to Wind/Slippery Surface	-523.6
Speeding	-245.5
Other Improper Action	-1,347.2
Following too Close	34.8
Avoiding Motor Vehicle	834.1
Avoiding Object	6,060.1
Aggressive/Reckless	-2,567.5
Improper Turn	-2,453.9
Avoiding Non-Motorist	-101.5
Disregard Road Markings	-611.0
Disregard Traffic Signs	475.3
Improper Passing	399.1
Wrong Side/Wrong Way	-417.3
Evading Law Enforcement	-251.8
Improper Backing	114.4
Alcohol Involved	1,000.1
Wild Animal	303.1
Speed Involved	-286.0
Helmet Not Used	35.5

Reference levels:
Crash Severity: Not Fatal/Severe; *Junction Relation*: Not Junction; *Road Condition*: Dry; *Weather*: Clear; *Vehicle Maneuver*: Straight Ahead; *Driver Age*: Middle; *Female Rider*: Male; *Driver Action*: No Improper Action; *Alcohol Involved*: No; *Wild Animal*: No; *Speed Involved*: No; *Helmet*: Helmet Used

Wet and roadways covered with mud, dirt, gravel and sand increase the odds of fatal and severe crashes, compared to dry roadways. Snow and water on the roadway can reduce the odds of fatal and severe crashes, mainly due to the fact that riders avoid these types of conditions. For weather conditions, sleet, hail, and freezing rain have a major potential to increase the severity of crashes. Vehicle maneuvers that significantly increase the odds of fatal and severe crashes include turning left, slowing, and negotiating a curve, in that order, compared to riding straight ahead. Old riders have higher odds to be involved in fatal and severe crashes, while for young riders these odds reduce. Female riders also have higher odds to be involved in fatal and severe crashes. Compared to no improper action, driver actions that significantly increase the odds of fatal and severe crashes include avoiding objects in the road, animals and other vehicles, failure to keep proper lane, disregard for traffic signs and improper passing. Alcohol use, wild animals, and no helmet are also found to increase the odds of severe and fatal crashes. Speed, in this case, was not found to increase the severity of crashes.

5.1.2 Wyoming Rural Multi BR Model

The results of the BR model for rural multivehicle crashes are presented in Table 5.2. Dusk and dark, unlighted conditions significantly increase the odds of fatal and severe crashes. As far as junction relation, in the rural multi models, only ramps, trail crossings, private junctions, and other parts were found to have significant effects in increasing the severity of crashes. Mud, dirt and gravel, followed by water on the roadway surface, can significantly increase the odds of fatal and severe injury crashes. For weather conditions, only sleet, hail, and freezing rain were found to increase the odds of severe motorcycle crashes. The vehicle maneuver that significantly increases the odds of fatal and severe injury crashes is slowing, followed by entering a traffic lane and negotiating a curve. Old riders have higher odds of being involved in fatal and severe injury crashes, while, for young riders, these odds reduce, compared to middle-age riders. The odds of fatal and severe injury crashes for female riders are higher than for male riders. Driver actions that significantly increase the odds of fatal and severe crashes include avoiding motor vehicle, aggressive driving, following too close, and improper turns. Alcohol use and wild animal involvement also significantly increase the odds of fatal and severe crashes. Speed involvement was not found to be a significant factor in this case. No helmet increases the odds of fatal and severe crashes.

5.1.3 Wyoming Urban Single BR Model

The BR model results for urban single motorcycle crashes in Wyoming are shown in Table 5.3. Dawn is a lighting condition that contributes to increase in odds of fatal and severe injury crashes. For junction relation predictors, the most significant one increasing the odds of fatal and severe crashes is alley location, followed by ramps and other parts of junctions. Ice and frost are the road conditions that have major effects on increasing the odds of fatal and severe crashes, followed by oil on the surface. Fog and severe winds can increase the odds of fatal/severe crashes in urban single motorcycle crashes. For vehicle maneuvers, turning right, overtaking, entering traffic lane and negotiating a curve increase the odds of severe crashes, in that order. Young riders have less chances of being involved in fatal and severe crashes compared to the middle age group, while for older riders the increase in odds is not significant. Driving too fast for conditions is the driver action that would increase the odds of fatal and severe crashes the most, followed by failure to yield ROW, swerving, following too close, improper passing, running off road, disregarding road markings, and over-correction. Alcohol use can slightly increase the odds of fatal and severe crashes, while this effect is significant for animal-related crashes. Not using a helmet also slightly increases the odds of severe crashes. Speed was not found to be a significant predictor for fatal and severe crashes.

Table 5.2 Wyoming Rural Multi BR Model and Estimates

Variable	Estimate
Intercept	4914.30
Lighting	
Dusk	3,010.2
Darkness Unlighted	275.3
Dawn	47.2
Junction Relation	
Thru Roadway	-812.5
Intersection	-549.6
Driveway	-926.4
Interchange Area Intersection	-688.8
Business Entrance	-53,156.4
Interchange Area Int. Related	-46.1
Trail/School X-ing	5,434.3
Intersection Related	-1,340.2
Other parts (e.g. gore)	105.1
Ramp	9,222.9
Private Road Junction	403.6
Road Condition	
Wet	-1,543.7
Water	1,565.0
Mud, Dirt, Gravel	4,506.6
Weather Condition	
Cloudy	-114.8
Raining	-4,766.6
Fog	-2,645.9
Severe Wind Only	-1,074.9
Sleet, Hail, Freezing Rain	3,230.5
Vehicle Maneuver	
Turning Left	-786.2
Stopped in Traffic	-127.1
Turning Right	886.5
Slowing	5,589.8
Overtaking/Passing	-422.5
Entering Traffic Lane	2,542.2
Backing	-1,216.4
Making a U-Turn	-1,404.3
Changing Lanes	-761.9
Negotiating a Curve	362.2
Other	-604.0
Driver Age	
Young	-115.7
Old	15.9
Female Rider	109.5
Driver Action	
Failed to Keep Proper Lane	-398.5
Speeding	-9,620.3
Improper Passing	-10,665.9
Following too Close	1,514.7
Improper Turn	705.8
Ran Off Road	-557.2
Improper Backing	-861.0
Swerve Due to Wind/Slippery Surface	-240.1
Other Improper Action	425.5
Avoiding Motor Vehicle	8,731.1
Disregarded Traffic Signs	182.1
Wrong Side/Wrong Way	-711.1
Drove too Fast for Conditions	-161.5
Disregarded Road Marking	-703.0
Evading Law Enforcement	506.7
Over Correctedor/Steered	-3,780.9
Avoiding Animal	-1,228.2
Failed to Yield ROW	-4,640.3
Aggressive/Reckless	3,398.4
Alcholod Involved	440.8
Wild Animal	4,622.4
Speed Involved	-167.8
Helmet Not Used	149.2

Reference levels:
Crash Severity: Not Fatal/Severe; *Lighting*: Daylight; *Junction Relation*: Not Junction; *Road Condition*: Dry; *Weather*: Clear; *Vehicle Maneuver*: Straight Ahead; *Driver Age*: Middle; *Female Rider*: Male; *Driver Action*: No Improper Action; *Alcohol Involved*: No; *Wild Animal*: No; *Speed Involved*: No; *Helmet*: Helmet Used

Table 5.3 Wyoming Urban Single BR Model and Estimates

Variable	Estimate
Intercept	782.3
Lighting	
Darkness Lighted	0.9
Dusk	-0.2
Darkness Unlighted	0.0
Dawn	1,331.2
Junction Relation	
Thru Roadway	1,055.0
Intersection Related	-345.7
Intersection	-348.5
Other Parts (e.g. gore)	1,821.1
Business Entrance	-346.2
Interchange Area Intersection	-343.7
Alley	50,063.6
Driveway Related	-346.1
Interchange Area Intersection Related	-347.7
Ramp	9,363.7
Road Condition	
Wet	-1.8
Sand on Icy Road	-1.5
Mud, Dirt, Gravel	-7.2
Oil	8,243.1
Sand on Dry Pavement	-2.3
Ice or Frost	32,738.2
Snow	-66,193.5
Other	1,157.2
Weather Condition	
Cloudy	3.6
Raining	-30,192.8
Severe Wind Only	2,317.4
Snowing	-1.5
Fog	7,597.4
Vehicle Maneuver	
Negotiating a Curve	1,745.5
Turning Right	12,056.9
Turning Left	-224.2
Changing Lanes	-53,906.1
Make U-Turn	-218.9
Slowing	-223.7
Overtaking/Passing	3,120.1
Stopped in Traffic	16.1
Entering Traffic Lane	2,170.6
Other	-218.3
Leaving Traffic Lane	-222.2
Driver Age	
Young	-16,040.4
Old	1.0
Female Rider	-1.5
Driver Action	
Ran Off Road	5,742.1
Over Corrected/Steered	1,025.5
Drove too Fast for Conditions	15,498.3
Following too Close	6,780.0
Failed to Keep Proper Lane	-214.4
Avoiding Motor Vehicle	-213.0
Speeding	923.6
Aggressive/Reckless	-214.1
Swerve Due to Wind/Slippery Surface	8,991.7
Other Improper Action	1,565.8
Ran Red Light	-11,509.2
Failed to Yield ROW	13,084.0
Evading Law Enforcement	-215.0
Avoiding Object on Road	-213.4
Avoiding Animal	-214.8
Improper Turn	-213.4
Disregarded Traffic Signs	-212.0
Improper Passing	5,943.8
Disregarded Road Marking	3,129.3
Alcohol Involved	1.4
Wild Animal	776.2
Speed Involved	-0.6
Helmet Not Used	0.7

Reference levels:
Crash Severity: Not Fatal/Severe; *Lighting*: Daylight; *Junction Relation*: Not Junction; *Road Condition*: Dry; *Weather*: Clear; *Vehicle Maneuver*: Straight Ahead; *Driver Age*: Middle; *Female Rider*: Male; *Driver Action*: No Improper Action; *Alcohol Involved*: No; *Wild Animal*: No; *Speed Involved*: No; *Helmet*: Helmet Used

5.1.4 Wyoming Urban Multi BR Model

Table 5.4 shows the BR model results for Wyoming urban multi-vehicle crashes. Crossovers and business entrances can significantly increase the odds of fatal and severe injury crashes. Roadway and weather conditions were not found to have significant effects on fatal and severe crashes. Leaving a lane and changing lanes were found to significantly increase the odds of fatal and severe injury crashes. Rider age and sex do not have significant effects on injury severity.

Table 5.4 Wyoming Urban Multi BR Model and Estimates

Variable	Estimate
Intercept	-38.0
Junction Relation	
Thru Roadway	-113,921.6
Intersection Related	-0.2
Intersection	-1.4
Business Entrance	7,270.4
Interchange Area Intersection	-1.2
Driveway Related	-1.9
Interchange Area Intersection Related	-0.7
Ramp	-2.9
Crossover Related	18,835.8
Road Condition	
Wet	-5.1
Mud, Dirt, Gravel	-1.7
Sand on Dry Pavement	-72,416.0
Ice or Frost	-20,432.3
Snow	2.4
Weather Condition	
Cloudy	-0.9
Raining	-4.6
Vehicle Maneuver	
Turning Left	1.6
Stopped in Traffic	-0.2
Turning Right	-117,538.2
Slowing	1.8
Leaving Traffic Lane	36,335.7
Overtaking or Passing	2.2
Entering Traffic Lane	1.8
Backing	-37,125.6
Making U-Turn	5.1
Changing Lanes	14,863.8
Parked	3.7
Negotiating Curve	1.9
Overtaking/Passing	3.1
Driver Age	
Young	-2.5
Old	0.2
Female Rider	0.9
Driver Action	
Failed to Keep Proper Lane	4,906.9
Speeding	113,177.9
Improper Passing	6,031.5
Following too Close	36.3
Improper Turn	9,529.4
Ran Off Road	35.6
Improper Backing	53,619.3
Ran Red Light	38.6
Swerve Due to Wind/Slippery Surface	36.3
Avoiding Motor Vehicle	36.4
Disregarded Traffic Signs	36.2
Wrong Side/Way	34.0
Avoiding Non Motorist	36.4
Drove too Fast for Conditions	37.4
Disregarded Road Marking	36.9
Evading Law Enforcement	38.1
Over Corrected/Steered	-23,793.5
Avoiding Animal	36.2
Failed to Yield ROW	35.9
Aggressive/Reckless	37.9
Other Improper Action	15,739.9
Alcohol Involved	1.2
Wild Animal	2,152.1
Speed Involved	0.2
Helmet Not Used	-0.2

Reference levels:
Crash Severity: Not Fatal/Severe; *Lighting*: Daylight; *Junction Relation*: Not Junction; *Road Condition*: Dry; *Weather*: Clear; *Vehicle Maneuver*: Straight Ahead; *Driver Age*: Middle; *Female Rider*: Male; *Driver Action*: No Improper Action; *Alcohol Involved*: No; *Wild Animal*: No; *Speed Involved*: No; *Helmet*: Helmet Used

As for driver action, speeding was found to cause the most significant increase in the odds of fatal and severe injury crashes. It is followed by improper backing, improper turn, improper passing, and failure to keep a proper lane. Most of other improper actions can increase the odds of severe crashes. Alcohol use has minor effects on injury severity, while animal-related collision significantly increase the odds of severe crashes. Speed and helmet use do not have significant effects on injury severity levels.

5.2 Results and Discussion: Utah Dataset

The Utah BRM models were developed in R studio using the same eight years (2014–2021) of motorcycle-related safety data from the AASHTOWare Safety system. The response variable was defined as binary (fatal/severe, or not), with non-fatal/severe being the reference level. Lighting conditions, roadway surface conditions, weather conditions, and vehicle maneuvers were coded as categorical variables. Other predictors were defined as binary only. Older rider in this model is defined as being 55 or more years. Each Utah BR model was run for four Markov chains, 1,000 iterations for warm-up and 3,000 iterations for sampling, resulting in a total of 12,000 samplings. The coefficient estimation is read as follows: if it is positive, the predictor increases the odds of fatal/severe crashes, the higher the value, the higher the impact; if the coefficient is negative, the predictor reduces the odds of fatal/severe crashes.

5.2.1 Utah Rural Single BR Model

The Utah BR model results for rural single motorcycle crashes is given in Table 5.5. Light conditions, except dark unlighted, slightly increase the odds of fatal and severe injury crashes. Roadway surface conditions were not found to impact the odds of fatal and severe crashes. Severe crosswinds significantly increase the odds of fatal and severe injury crashes, and other adverse weather conditions, albeit to a much lesser effect. Most vehicle maneuvers have similar effects on the increase of the odds of severe crashes, while turning maneuvers stopping in traffic lane and parking actually reduce the odds of severe crashes. Female riders have slightly lower odds of being involved in fatal and severe crashes. Aggressive driving, DUI, disregard of traffic control, animal involvement, collisions with fixed objects, interstate, roadway geometry, speed and older riders all cause small increases in the odds of fatal and severe injury crashes. Right and left turns significantly increase the odds of severe and fatal crashes. Work zone, wrong-way driving, and no helmet slightly reduce the odds of severe crashes.

5.2.2 Utah Rural Multi BR Model

Table 5.6 shows the results of the Utah BR models for rural crashes with multiple vehicles involvement. Reduced visibility, with the exception of dark unlighted conditions, increase the odds of fatal and severe injury crashes. Mud was found to be the only road surface condition to increase the odds of higher severity crashes. Severe crosswinds are a significant contributor to fatal and severe injuries. The majority of vehicle maneuvers, other than going straight, result in an increase in the odds of fatal and severe crashes. Female riders have lower odds of being involved in fatal and severe crashes. Driving under the influence results in higher severity levels. In these types of crashes, disregard for traffic control devices significantly increases the odds of fatal and severe crashes. Animal involvement, collisions with fixed objects, commercial vehicles, and intersections all increase the odds of severe crashes. Not using a helmet also results in an increase in odds of high-level injury and fatal crashes.

Table 5.5 Utah Rural Single BR Model and Estimates

Variable	Estimate
Intercept	-440.2
Lighting	
Dark - Not Lighted	-5,185.4
Dark - Lighted	0.8
Dusk	1.3
Dawn	1.0
Roadway Surface	
Ice/Frost	-2,382.2
Sand, Dirt, Gravel	-0.3
Mud	-1.0
Wet	-1,419.8
Oil	-1.0
Slush	0.3
Snow	-10,708.6
Water	-4,212.1
Other	-4,875.5
Weather	
Cloudy	242.4
Rain	242.6
Severe Crosswinds	57,776.9
Snowing	242.7
Blowing Snow	242.5
Fog, Smog	242.1
Vehicle Maneuver	
Overtaking/Passing	195.9
Changing Lanes	195.7
Leaving Traffic Lane	197.5
Slowing in Traffic Lane	196.1
Making U-turn	196.5
Parked	196.8
Stopped in Traffic Lane	-13,500.8
Parking Maneuvers	-3,878.0
Backing	194.5
Negotiating Curve	195.1
Entering Traffic Lane	195.7
Other	-484.1
Sex (Female)	-0.3
Aggressive Driving	0.6
DUI	1.2
Disregard Traffic Control	0.1
Animal Related	0.2
Collision With Fixed Object	0.5
Intersection Related	0.0
Interstate Highway	0.4
Right Turn Involved	352.4
Left Turn Involved	680.1
Roadway Geometry Related	0.1
Speed Related	0.4
Work Zone Involved	-0.2
Wrong Way Driving	-0.6
Older Driver Involved	0.4
Helmet Not Used	-0.6

Reference levels:
Crash Severity: No Injury; *Lighting*: Daylight; *Roadway Surface*: Dry; *Weather*: Clear; *Vehicle Maneuver*: Straight Ahead; *Rider Sex*: Male; *Aggressive Driving*: No; *DUI*: No; *Disregard Traffic Control*: No; *Animal Related*: No; *Collision with Fixed Object*: No; *Intersection Related*: No; *Interstate Related:* No; *Right Turn Involved*: No; *Left Turn Involved*: No; *Roadway Geometry Related*: No; *Speed Related*: No; *Work Zone Involved*: No; *Wrong Way Driving*: No; *Older Driver Involved*: No; *Helmet used*: Yes

Table 5.6 Utah Rural Multi BR Model and Estimates

Variable	Estimate
Intercept	-216.1
Lighting	
Dusk	1.6
Dark - Not Lighted	-11,702.6
Dark - Lighted	1.2
Dawn	0.1
Roadway Surface	
Sand, Dirt, Gravel	-19,425.1
Wet	-1,736.5
Oil	-82,945.2
Ice/Frost	-23,741.4
Mud	1.2
Weather	
Cloudy	-0.9
Rain	-3,000.3
Severe Crosswinds	6,872.7
Vehicle Maneuver	
Stopped in Traffic \Lane	213.4
Slowing in Traffic Lane	-6,599.0
Backing	212.7
Overtaking/Passing	214.1
Leaving Traffic Lane	214.1
Making U-turn	212.4
Entering Traffic Lane	-18,717.2
Parking Maneuvers	213.1
Parked	212.1
Changing Lanes	214.2
Negotiating Curve	211.3
Sex (Female)	-0.4
Aggressive Driving	-0.2
DUI	3.1
Disregard Traffic Control	176,389.8
Animal Related	0.8
Collision With Fixed Object	0.9
Commercial Vehicle Involved	1.3
Intersection Related	0.2
Interstate Highway	-0.6
Right Turn Involved	-0.5
Left Turn Involved	-0.3
Roadway Geometry Related	-0.3
Roundabout/Signal	1.2
Speed Related	0.2
Work Zone Involved	-2.2
Wrong Way Driving	0.7
Older Driver Involved	0.6
Helmet Not Used	0.2

Reference levels:
Crash Severity: No Injury; *Lighting*: Daylight; *Roadway Surface*: Dry; *Weather*: Clear; *Vehicle Maneuver*: Straight Ahead; *Rider Sex*: Male; *Aggressive Driving*: No; *DUI*: No; *Disregard Traffic Control*: No; *Animal Related*: No; *Collision with Fixed Object*: No; *Commercial Vehicle Involved*: No; *Intersection Related*: No; *Interstate Related:* No; *Right Turn Involved*: No; *Left Turn Involved*: No; *Roadway Geometry Related*: No; *Roundabout/Signal*: No; *Speed Related*: No; *Work Zone Involved*: No; *Wrong Way Driving*: No; *Older Driver Involved*: No; *Helmet used*: Yes

5.2.3 Utah Urban Single BR Model

The Utah BR model results for urban single motorcycle crashes are presented in Table 5.7. In this case, it was found that the predictors that increase the odds of fatal and severe injury crashes include dark-lighted and dawn lighting conditions, cloudy weather, aggressive driving, DUI, disregard for traffic control, collision with fixed objects, left turns, roadway geometry, speed, and older riders. Other predictors were not found to increase the odds of fatal and severe injury crashes.

Table 5.7 Utah Urban Single BR Model and Estimates

Variable	Estimate
Intercept	-0.3
Lighting	
Dark - Not Lighted	-1.4
Dark - Lighted	0.6
Dusk	-0.3
Dawn	0.3
Roadway Surface	
Oil	-3,034.8
Sand, Dirt, Gravel	29,190.6
Wet	-0.8
Mud	-2.2
Ice/Frost	-0.7
Snow	-4,079.5
Water	-2,167.7
Weather	
Cloudy	0.2
Rain	-7,622.7
Severe Crosswinds	-0.2
Snowing	-1.1
Fog, Smog	16,073.6
Vehicle Maneuver	
Entering Traffic Lane	-1,338.7
Slowing in Traffic Lane	-563.7
Changing Lanes	-4,799.9
Leaving Traffic Lane	-0.6
Stopped in Traffic Lane	-1.9
Overtaking/Passing	-0.5
Making U-turn	-2,896.9
Parked	-1.5
Negotiating Curve	-2,046.9
Backing	-2.9
Merging	-1.0
Starting to Move in Traffic Lane	-563.0
Sex (Female)	-0.3
Aggressive Driving	0.4
DUI	1.1
Disregard Traffic Control	1.0
Animal Related	-0.6
Collision With Fixed Object	0.3
Commercial Vehicle Involved	-3,792.9
Intersection Related	-0.2
Interstate Highway	-0.2
Right Turn Involved	-1,560.3
Left Turn Involved	561.8
Roadway Geometry Related	0.2
Speed Related	0.7
Work Zone Involved	-0.3
Wrong Way Driving	-0.4
Older Driver Involved	0.6
Helmet Not Used	-0.3

Reference levels:
Crash Severity: No Injury; *Lighting*: Daylight; *Roadway Surface*: Dry; *Weather*: Clear; *Vehicle Maneuver*: Straight Ahead; *Rider Sex*: Male; *Aggressive Driving*: No; *DUI*: No; *Disregard Traffic Control*: No; *Animal Related*: No; *Collision with Fixed Object*: No; *Commercial Vehicle Involved*: No; *Intersection Related*: No; *Interstate Related:* No; *Right Turn Involved*: No; *Left Turn Involved*: No; *Roadway Geometry Related*: No; *Speed Related*: No; *Work Zone Involved*: No; *Wrong Way Driving*: No; *Older Driver Involved*: No; *Helmet used*: Yes

5.2.4 Utah Urban Multi BR Model

Table 5.8 presents the BR model results for Utah urban crashes with multiple vehicle involvement. In these types of crashes, the environmental conditions were not found to have significant effects on injury severity levels, with the exception of severe crosswinds and fog/smog. Slowing in a traffic lane is a vehicle maneuver that significantly increases the odds of fatal and severe injury crashes. Maneuvers, other than going straight, generally increase the odds of higher level severity crashes. Animal involvement is not a significant factor in this case. Aggressive driving, DUI, collisions with fixed objects, left turns, roadway geometry, roundabouts/signals, speed involvement, work zones, and wrong-way driving all increase the odds of fatal and severe injury crashes. Other analyzed factors did not show significant effects in increasing the odds of higher level and fatal injuries.

Table 5.8 Utah Urban Multi BR Model and Estimates

Variable	Estimate
Intercept	-174.6
Lighting	
Dark - Lighted	-0.8
Dark - Not Lighted	-0.1
Dusk	-0.4
Dawn	-0.2
Roadway Surface	
Wet	-122,192.0
Oil	-22,615.8
Sand, Dirt, Gravel	-1.5
Mud	-17,463.7
Slush	-98,180.8
Water	-0.3
Weather	
Cloudy	-0.1
Rain	-171,406.4
Snowing	-40,492.4
Severe Crosswinds	0.7
Fog, Smog	3.1
Vehicle Maneuver	
Leaving Traffic Lane	173.0
Parked	172.5
Stopped in Traffic Lane	172.0
Slowing in Traffic Lane	12,927.0
Changing Lanes	-67,312.5
Overtaking/Passing	172.8
Entering Traffic Lane	-108,697.3
Making U-turn	173.0
Mechanically Disabled in Traffic Lane	-166,460.7
Backing	173.0
Parking Maneuvers	-22,442.5
Starting to Move in Traffic Lane	172.2
Negotiating Curve	173.1
Merging	172.5
Sex (Female)	-0.3
Aggressive Driving	0.8
DUI	1.4
Disregard Traffic Control	0.6
Animal Related	-42,658.5
Collision With Fixed Object	0.5
Commercial Vehicle Involved	0.0
Intersection Related	0.0
Interstate Highway	-0.3
Right Turn Involved	-0.2
Left Turn Involved	0.9
Roadway Geometry Related	0.3
Roundabout/Signal	0.3
Speed Related	0.9
Work Zone Involved	0.1
Wrong Way Driving	1.5
Older Driver Involved	0.0
Helmet Not Used	-0.3

Reference levels:
Crash Severity: No Injury; *Lighting*: Daylight; *Roadway Surface*: Dry; *Weather*: Clear; *Vehicle Maneuver*: Straight Ahead; *Rider Sex*: Male; *Aggressive Driving*: No; *DUI*: No; *Disregard Traffic Control*: No; *Animal Related*: No; *Collision with Fixed Object*: No; *Commercial Vehicle Involved*: No; *Intersection Related*: No; *Interstate Related:* No; *Right Turn Involved*: No; *Left Turn Involved*: No; *Roadway Geometry Related*: No; *Roundabout/Signal*: No; *Speed Related*: No; *Work Zone Involved*: No; *Wrong Way Driving*: No; *Older Driver Involved*: No; *Helmet used*: Yes

5.3 Conclusions

Bayesian regression modeling is being increasingly used in traffic safety analysis due to its advantages over traditional factor models. Bayesian models were applied to eight years of crash data in Wyoming (2012–2019), and eight years of crash data in Utah (2014–2021). In these types of models, the outcome variable (crash severity) was defined as binary, fatal/severe injury, and other. The predictor variables are a mix of categorical and binary variables, depending on how they were coded in the used databases. As in the case of the MLN approach, four different BR models were developed and analyzed: (1) rural single motorcycle crashes; (2) rural multi-vehicle motorcycle-related crashes; (3) urban single motorcycle crashes; (4) urban multi-vehicle motorcycle-related crashes.

In the case of Wyoming, in all four models, it was found that alcohol involvement, animal involvement, certain reduced lighting, inclement weather, roadway surface condition, and majority of driver actions other than going straight increase the odds of fatal and severe injury crashes. Not wearing a helmet was found to significantly increase the odds of severe and fatal crashes in rural areas and urban single motorcycle crashes. Interestingly, the BR models did not find speed to be a significant contributor to severe and fatal outcomes in Wyoming.

Utah BR models found that speed, aggressive driving, DUI, disregard for traffic control, collisions with fixed objects, involvement of commercial vehicles, and certain reduced lighting, inclement weather, roadway surface condition, and the majority of driver actions (other than going straight) increase the odds of fatal and severe injury crashes. Not wearing a helmet increases the odds of severe and fatal crashes in rural single motorcycle crashes, while it was not found a significant factor in other types of crashes. Wrong way driving and intersection relation increase the odds of severe crashes in multiple vehicle collisions.

The results obtained from the BR models show a lot of similarities with the MLN models when it comes to variables that have significant effects on fatal and severe injury crash outcomes. Therefore, more engineering, education, enforcement and roadway infrastructure maintenance efforts should be conducted to provide countermeasures that directly affect the severe crash contributing factors.

6. COUNTERMEASURES

Various countermeasures can be implemented to reduce the frequency and severity of motorcycle-related crashes. They can incorporate roadway design, traffic control, construction, maintenance practices, and strategies to increase awareness, reduce crashes due to impairment, increasing the visibility of motorcycles, and similar strategies (Potts et al., 2008). The selection of countermeasures to be implemented at certain location in Wyoming and Utah is based on the results of the safety analysis to address the contributing factors resulting in fatal and severe motorcycle crashes.

6.1 Roadway Design Countermeasures

6.1.1 Motorcycle-Friendly Guardrails

Guardrails are installed to protect errant vehicles from leaving the roadway and encroaching on fixed objects in the roadside (Potts et al., 2008). However, the needs of motorcycles are often overlooked, and most of the used barrier designs could not completely prevent a motorcycle and the rider from sliding under the barrier. The barrier itself can present a serious hazard for the rider. Due to the fact that many single motorcycle crashes in rural areas include negotiating a curve and running off road, this is one strategy that should be considered for locations with horizontal curves that experience higher than average motorcycle related crashes.

A motorcycle-friendly guardrail design includes a lower portion of the guardrail free of sharp edges and posts, which prevent motorcycles and riders from sliding under. Examples of this type of guardrail is shown in Figure 6.1.

a) Biker Shield Motorcycle Barrier (Source: Safe Direction Crash Barrier Solutions)

b) System Euskirchen Plus Guardrail (Source: Nicol et al., 2012)

Figure 6.1 Motorcycle-friendly Crash Barriers

These guardrails should be considered for implementation first along horizontal curves with narrow roadway, and where the shoulders are absent or narrower than two feet. The expected effectiveness of this countermeasure is in the reduction of motorcyclists' exposure to serious injury due to collisions with roadside barriers or objects in the roadside (Potts et al., 2008).

6.1.2 High-traction Pavement Materials and Markings

Motorcycles maintain contact with the road through two tires (or three, in the case of three-wheelers). Therefore, there are much more susceptible to the loss of traction than other vehicles, especially if the pavement friction factor is reduced due to the inadequate materials, pavement markings, wet roadway, or the presence of dirt, gravel, and other debris. This can cause a loss of control over the motorcycle, resulting in a crash. A motorcycle's traction can be significantly compromised by surface treatments that include bituminous rubberized asphalt sealer (creating so-called "road or tar snakes," shown in Figure 6.2), plasticized adhesive pavement marking tape, manhole covers and raised pavement markers (Potts et al., 2008). These treatments lose much of the friction when wet, some also being slippery when dry (such as the road snakes).

Figure 6.2 Road (Tar) Snakes (Source: Reddit)

In rural areas in horizontal curves, the application of bituminous, rubberized asphalt sealer should be avoided, especially in the longitudinal direction. This material can cause a motorcycle to lose traction on contact, depending on the speed and lean angle in curves. Bridge joints treated with this material can also present problems for motorcycles. Road snakes can be significantly more dangerous to motorcycles in wet pavement and hot temperature conditions.

Manhole covers cause a loss of friction especially when they are wet, because they blend with the pavement, are hard to see at night. They should be treated with non-slip material and made more visible using edging and contrasting color (Potts et al., 2008). Raised pavement markings, applied frequently at intersections, can also cause motorcycles to lose traction, mainly during turning maneuvers. In the absence of other ways to minimize impacts, intersections with high motorcycle traffic are recommended to leave portions of the pavement free of markings (e.g., pedestrian crossings) that motorcycles can use to traverse the intersection.

6.1.3 Roadway Maintenance

Routes with high motorcycle traffic and locations with high motorcycle crash frequencies, should be inspected and maintained in more frequent intervals. Surface irregularities, such as potholes, rutting, surface drop-offs or rises, deteriorating pavement and similar, can present serious issues for motorcycles (Potts et al., 2008). They should be attended to in a timely manner.

Dirt, gravel, sand, and other debris on the roadway can pose a significant problem for motorcycles. Highway maintenance personnel, law enforcement, and other agency personnel should look for debris routinely as they travel along roadways and request maintenance as needed. This is particularly important for routes with a high percentage of motorcycle traffic or locations with historically high motorcycle-related crash frequencies.

6.1.4 Motorcycle Signage

Warning signs aimed at motorcycle riders can be successful in preventing potentially dangerous riding and maneuvers at certain locations, such as sharp curves, gravel on the roadway, grooving and similar. Warning signs from the Manual on Uniform Traffic Control Devices (MUTCD) (FHWA, 2012) can be adapted for motorcyclists and used at these locations. Some examples of the signage design are shown in Figure 6.3.

Figure 6.3 Warning Signs Adapted for Motorcycles (Adapted from MUTCD)

6.1.5 Other Measures

Education and enforcement are also measures that can be implemented with the aim to reduce the frequency and severity of motorcycle-related crashes. Through studies, such as the one presented in this report, motorcycle riders can be made aware of the different contributing factors and ways to protect themselves from being involved in crashes. All states run various motorcycle safety programs, and riders should be encouraged to participate. Furthermore, this study found that DUI, speeding and various improper and illegal driver actions significantly contribute to frequency and severity of motorcycle crashes. Some of these factors can be addressed through enforcement aimed at motorcycle riders.

7. CONCLUSIONS

Motorcycle fatalities comprise a large percentage of traffic fatalities in the United States, in excess of 15%, and are closely followed by serious injuries. The mean fatality crash rate for motorcycles is more than six times higher than that for passenger cars, and motorcycle account for about 0.6% of all Vehicle Miles Traveled (VMT).

Various factors affect the frequency and severity of motorcycle crashes. Roadway geometry, road, weather, environmental and traffic conditions, setting (urban or rural), the number of vehicles involved, relation to a junction, helmet use, driver condition and action (e.g., riding under the influence or speeding), are some of the most common factors attributed to motorcycle crashes. It is generally accepted that motorcycle crashes result in higher severity due to the exposure of the riders and the lack of construction and restrain elements, which exist in other vehicle types. Even though efforts are being made to improve motorcycle safety, a more proactive and collaborative approach is needed to address this issue. This study assessed the correlation between different characteristics and factors and their individual and mutual effects on motorcycle crash severities in Wyoming and Utah. Four types of motorcycle-related crashes were analyzed in this research, depending on the setting and the number of vehicles involved: (1) rural single motorcycle crashes; (2) rural multi-vehicle motorcycle-related crashes; (3) urban single motorcycle crashes; (4) urban multi-vehicle motorcycle-related crashes. The separate assessment was performed as it was initially found that the characteristics and contributing factors differ based on the setting (urban or rural), and the number of vehicles involved in a motorcycle crash (single or multi-vehicle).

In addition to the descriptive statistics of motorcycle-related crashes in Wyoming and Utah, this study developed and implemented two types of statistical models to analyze the effects of various contributing factors, with a focus on fatal and severe injury crashes: multinomial logistic regression and Bayesian multilevel regression models.

The application of MLN models in Wyoming found that speeding and alcohol involvement increases the odds of any injury crash multifold, in all types of motorcycle-related crashes. For single motorcycle crashes, vehicle maneuver and driver action exposure measures were found to have significant effects on injury level. Helmet use can reduce the odds of fatal and serious injuries in single motorcycle crashes. For multi-vehicle crashes, it was found that junction relation and vehicle maneuver exposure measures have significant effects on odds ratios of injury crashes compared to no injury. Additionally, road and weather conditions impact injury severity level in single rural motorcycle crashes, while weather also impacts the severity level in single urban motorcycle crashes. Manner of collision factors have additional effects on the severity of urban multi-vehicle motorcycle related crashes. Helmet use is found to reduce the odds of fatality and non-incapacitating injuries in urban multi-vehicle crashes.

The application of MLN models in Utah found that the most common factors that increase the odds of fatal and injury crashes include unlighted environment, changing lane and U-turn maneuvers, overtaking in traffic, aggressive driving, DUI, disregard for traffic control, collisions with fixed objects, speeding, wrong way driving and older riders. Involvement of commercial vehicles in motorcycle related crashes increases the odds in multi-vehicle crashes. Roadway geometry was found to increase the odds of fatal and injury single motorcycle crashes. Wrong-way driving increases the odds of fatal and injury crashes in single rural and urban multi-vehicle crashes. Not wearing a helmet increases the odds of fatal and serious injury crashes in single motorcycle crashes, while it does not have a significant effect in multi-vehicle crashes.

BR modeling application in Wyoming found that alcohol involvement, animal involvement, certain reduced lighting, inclement weather, roadway surface condition and majority of driver actions other than going straight increase the odds of fatal and severe injury crashes, in all types of analyzed crashes. Not wearing a helmet was found to significantly increase the odds of severe and fatal crashes in rural areas, and in urban single motorcycle crashes. The BR models did not find speed to be a significant contributor to severe and fatal outcomes in Wyoming.

Utah BR models found that speed, aggressive driving, DUI, disregard for traffic control, collisions with fixed objects, involvement of commercial vehicles, and certain reduced lighting, inclement weather, roadway surface condition and majority of driver actions other than going straight increase the odds of fatal and severe injury crashes. Not wearing a helmet increases the odds of severe and fatal crashes in rural single motorcycle crashes, while it was not found a significant factor in other types of crashes. Wrong-way driving and intersection relation increase the odds of severe crashes in multiple vehicle collisions.

The study also recommends certain roadway, maintenance, education and enforcement countermeasures that should be implemented to reduce the frequency and severity of motorcycle-related crashes. This study is generalized, meaning it does not focus on specific locations and types of crashes. In future studies, the analysis should be expanded and provide more detailed analysis for certain locations, and more information from the vehicle and person crash databases. The approach and results of this study would present a good starting point for future motorcycle safety studies in Wyoming and Utah and in other states.

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