FINAL REPORT WY2301F

ASSESSMENT OF MOTORCYCLE SAFETY IN WYOMING: FATAL AND SEVERE CRASHES, CONTRIBUTING FACTORS AND POTENTIAL COUNTERMEASURES

Source: Milan Zlatkovic, personal archive

November 2022

Prepared by:
Milan Zlatkovic, Ph.D., P.E., PTOE
Isaac Baah
Zorica Cvijovic, Ph.D.

Department of Civil and Architectural Engineering and Construction Management
University of Wyoming
1000 E University Ave.
Laramie, WY 82071

1. Report No. WY2301F	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Assessment of Motorcycle Safety in Wyoming: Fatal and Severe Crashes, Contributing Factors and Potential Countermeasures		5. Report Date November 2022 6. Performing Organization Code
7. Author(s) Milan Zlatkovic, Ph.D., P.E., PTOE, https://orcid.org/0000-0002-6777-230X Isaac Baah, https://orcid.org/0000-0003-1596-5633 Zorica Cvijovic, Ph.D., https://orcid.org/0000-0003-3558-7967		8. Performing Organization Report No. 1005517
9. Performing Organization Name and Address University of Wyoming College of Engineering and Physical Sciences 1000 E University Ave Laramie, WY 82071		10. Work Unit No. 11. Contract or Grant No. RS04222
12. Sponsoring Agency Name and Address Wyoming Department of Transportation 5300 Bishop Blvd. Bldg. 6100 Cheyenne, WY 82009		13. Type of Report and Period Covered Final Report (March 2022 – November 2022) 14. Sponsoring Agency Code
15. Supplementary Notes WYDOT Contact: Jennifer Goodrich		

16. Abstract

Motorcycle riders and passengers are much more likely to be killed or severely injured in a crash, and on average about 15 percent of all traffic fatalities include motorcyclists. The study uses 12 years of motorcycle crash data (2008-2019) from Wyoming on crash, vehicle and person levels, and applies multinomial logistic and Bayesian regression modeling to determine the effects of various exposure measures on injury severity. On the crash level 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, 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. On the vehicle level, the most significant factors contributing to fatal and severe crash outcomes include horizontal curves, sag vertical curves, vehicle disabling damage, slowing and parked vehicles, overtaking/passing, and damages to the left and front areas of the motorcycle. On the person level, the significant factors were found to be riding under the influence, out-of-state riders, and young or old riders. The motorcycle operator survey results show education and training, road maintenance, and riding gear to be the most important strategies to prevent motorcycle crashes and their severity. The proper education is also needed for the operators of other vehicles and raising their awareness about the presence of motorcycles on the road. The study also analyzes locations in rural and urban areas in Wyoming that experience high frequencies of motorcycle related crashes and recommends potential mitigation countermeasures.

17. Key Words	18. Distribution Statement
Motorcycle Safety; Multinomial Logistic Regression; Bayesian Logit Regression; Crash Severity Outcome; Crash Contributing Factors; Wyoming	This document is available through the National Transportation Library and the Wyoming State Library.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Non-Classified	Non-Classified	87	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

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

APPROXIMATE CONVERSIONS FROM SI UNITS

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

Table of Contents

List of Figures

List of Tables

List of Abbreviations

AADT	Annual Average Daily Traffic
BAC	Blood Alcohol Concertation
BR	Bayesian Binary Regression Models
BRM	Bayesian Regression Multilevel Models
BRMS	Bayesian Regression Modeling with Stan
CARE	Critical Analysis Reporting Environment
DUI	Driving Under the Influence
FHWA	Federal Highway Administration
IIHS	Insurance Institute for Highway Safety
KABCO	Injury Severity Scale
MCCS	Motorcycle Crash Causation Study
MLE	Maximum Likelihood Estimation
MNL	Multinomial Logistic Regression Models
MP	Milepost
MUTCD	Manual on Uniform Traffic Control Devices
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
RDFO	Roadside Fixed Object
ROW	Right of Way
RPNB	Random Parameters Negative Binomial
SPF	Safety Performance Function
USDOT	United States Department of Transportation
VMT	Vehicles Miles Travelled
WHP	Wyoming Highway Patrol
WYDOT	Wyoming Department of Transportation

Executive Summary

More than 15 percent of all traffic fatalities in the U.S. involve motorcycle riders. The National Highway Traffic Safety Administration (NHTSA) estimates that the mean fatality crash rate for motorcycle riders is more than five times higher than the mean fatality crash rate for passenger car occupants. From 2008 to 2019, Wyoming experienced an average of 286 motorcycle related crashes per year, with an average of 17 fatalities and 73 incapacitating injuries per year. Majority of motorcycle-related crashes and fatalities in Wyoming occur during the summer months, with the peak in August.

A number of factors influence the frequency and severity of motorcycle-related crashes. This research performs a comprehensive analysis of motorcycle safety in Wyoming, and identifies the most significant contributing factors leading to fatal and severe motorcycle crashes. It uses 12 years of safety data on the crash level, vehicle level and person level. Furthermore, the study identifies locations in rural and urban areas in Wyoming that experience a higher number of motorcycle-related crashes and recommend potential countermeasures for safety improvements.

The study first performs statistical analyses using the crash data obtained from the Wyoming Department of Transportation (WYDOT), and assesses various characteristics and factors, as well as their individual and mutual effects on the motorcycle crash severity outcomes. The analyses are performed on crash, vehicle and person levels. On the crash level, 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 As different factors were found to be significant to crash outcomes on vehicle and person levels, these analyses were performed for all motorcycle crashes, regardless off the setting and the number of vehicles involved.

The study 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 (MNL), Bayesian multilevel regression (BRM) and Bayesian binary regression (BR) models.

The application of MNL models on the crash level 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 impacts injury severity level in single rural motorcycle crashes, while weather 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. On the vehicle level, the MNL model shows a significant increase in the odds of fatal crashes for horizontal curves (especially curves to the right), sag vertical curves, vehicle disabling damage, slowing and parked vehicles, overtaking/passing, and damages to the left and front areas of the motorcycle. The person-level MNL model shows increased odds of fatal and severe injury crashes where drugs and alcohol are involved, or the rider is distracted. The injury areas resulting in the highest odds of fatal and severe crashes include head, neck, and chest.

The BRM models on the crash level found that alcohol and animal involvement, reduced lighting conditions, 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 was found to significantly increase the odds of severe and fatal crashes in rural areas, as well as urban single motorcycle crashes. The BRM models did not find speed to be a significant contributor to severe and fatal outcomes in Wyoming. The BR models on the vehicle level show that the level of the damage of the vehicle corresponds to the crash severity level. On the person level, the BR models show a significant increase in the odds of fatal and severe injury outcomes for young and old riders, alcohol and drug use, rider distraction, and out-of-state riders.

The motorcycle operator survey results show education and training, road maintenance, and riding gear to be the most important strategies to prevent motorcycle crashes and their severity. The proper education is also needed for the operators of other vehicles and raising their awareness about the presence of motorcycles on the road.

The study performs a locational crash cluster analyses to identify locations in rural and urban areas in Wyoming that experience high frequencies of motorcycle related crashes, and recommends potential location-specific mitigation measures. 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. The approach and results of this study would present a good starting point for future motorcycle safety studies in Wyoming, as well as in other states.

1. Introduction

Motorcycle fatalities represent a large portion of traffic fatalities in the U.S., in excess of 15 percent (National Motorcycle Institute, n.d.), 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 motorcycle account for about 0.6 percent of all Vehicle Miles Traveled (VMT) (NHTSA, 2021). Between 2015 and 2019, the average number of motorcycle fatalities in the U.S. was 5,129 per year, with the peak in 2016 (5,337). From 2015 onwards, the 5-year rolling average of fatal motorcycle crashes per million population in Wyoming has been increasing, from 26 in 2015, to 32 in 2018 (National Motorcycle Institute, n.d.). There were 13 motorcycle fatalities in Wyoming in 2019, representing 9 percent 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 aged 17 or younger, with the exception of mopeds (IIHS, 2022). Of all motorcycle fatalities in Wyoming, it is estimated that 57 percent were not using a helmet (NHTSA, 2021).

Various factors affect the frequency and severity of motorcycle crashes. Roadway geometry, road conditions, 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 that 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. The safety analyses are performed on crash, vehicle and person levels. On the crash level, 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; 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). As different factors were found to be significant to crash outcomes on vehicle and person levels, these analyses were performed for all motorcycle crashes, regardless of the setting and the number of vehicles involved.

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). 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, and driver condition and action (e.g. riding under the influence or speeding) are some of the most common factors attributed to motorcycle crashes.

1.1. Study goal and methodology

The goal of this study was to assess the characteristics of motorcycle safety in Wyoming, 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 defined as follows:

1) Summarize motorcycle crash characteristics for Wyoming.
2) Develop statistical models for motorcycle safety assessment on crash, vehicle and person levels, using multiple years of crash data.
3) Determine the major contributing factors for severe and fatal motorcycle crashes.
4) Develop recommendations for countermeasures.

The study first presents the descriptive statistics of motorcycle crash characteristics in Wyoming, including 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 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 that 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 in Wyoming. Finally, the study recommend potential countermeasures for the reduction of severe and fatal motorcycle crashes. Findings from this study will help WYDOT and local traffic safety engineers with developing strategies for motorcycle safety improvement. Furthermore, the models and results developed in this research could be transferred to other locations across the nation.

2. Literature Review

In the U. S. 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 U. S. is negligible. In the developing countries, especially in Asia, motorcycling is the predominant transportation mode (Jittrapirom et al., 2017). Due to the lower use of resources and less required space, motorcycles can contribute to more sustainable transportation systems (Jittrapirom et al., 2017; Rose et al., 2012). The motorcycle can utilize up to five times less space than a car, consumes less energy in production and operation, and emits less carbon dioxide (Bakker, 2018; 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 the 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 U.S., which accounted for 14 percent of all traffic fatalities. No systematic motorcycle transportation policy exists, although steps have been taken to develop an active motorcycle safety agenda.

Motorcycle crashes result in more fatalities and serious injuries, therefore many research efforts have been focused on analyzing motorcycle crash severities and contributing factors using various methods. A 2006 study using crash data from Indiana assessed 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 study on single motorcycle crashes explored the effects of motorcyclists' age in combination with other factors using 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 to assess the 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 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 of more than 25, not using a helmet, and riding under the influence. A study using motorcycle crash data from Texas analyzed 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 recent 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. A study by Dadashova et al (2022) found that motorcycle crashes involving fixed objects have a higher tendency of resulting in a fatality and serious injury compared to passenger vehicles hitting the same objects. A total of 7,057 roadside fixed object (RDFO) crashes were identified in the Texas Department of Transportation database from 2010 to 2017. The majority of the crashes resulted in fatal or injury while a few resulted in no injury crashes. Also, bridges and guardrails were found to have a higher association with fatal crashes than possibly injury crashes compared to other fixed roadside objects. Urban highways were found to be more associated with higher motorcycle crash severities.

Various factors cause motorcycle-related crashes, including but not limited to 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 found in 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; weather the motorcyclist was riding in a group of the motorcyclist or alone. Further collected information is related to motorcyclist impaired and what was the blood alcohol concentration (BAC).

Based on a study by Chaudhuri et al., 2019, the fatality rate per 100,000 population consistently increased in the period from 2000 to 2016. The study also found that fatality rates for those older than the age of 60 have risen notably in this period. Considering the age-and-sex standardized state fatality, Wyoming, South Dakota, and South Carolina consistently have the highest rates. 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 percent 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 percent each of total crashes). Motorcycles rear-ending other vehicles were represented by 7 percent of all motorcycle-related crashes. Other crash types were represented by 3 percent 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 percent) were fatal, 269 crashes (76.6 percent) involved multiple vehicles, and 22 fatalities (26.8 percent) were single vehicle cases. Close to 80 percent of multi-vehicle crashes were intersection-related. The absence of traffic control, horizontal curves, roadside fixed objects, 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 percent of fatal motorcycle crashes occur at intersections (Scopatz et al, 2018).

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 easier head injuries as well as traumatic brain injury during crashes. In the U.S., less than half of states (19) have a law that proposes mandatory wearing of protective helmets during riding of motorcycles for both 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 U.S. increased by over 20 percent (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 Wyoming, the license could be issued to an individual at the age of 16 or older, if they pass the vision, writing, and skill tests.

A study by Wali et al (2018) showed that riders with partial helmet coverage have lower risk of injury crash involvement. This is because, partial helmet coverage does not interfere with the riders hearing and vision capabilities when riding. Also, a rider's motorcycle-oriented lower clothing that cannot get stuck in the machinery lowers the tendency of crash involvement. Drowsy riding (drivers with less sleep before riding) and riding under the influence of alcohol or drugs lead to higher risks of crash involvement. Drivers who have had traffic convictions in the past are less likely to be involved in a crash. This is because these drivers are more cautious to prevent penalties. The result also showed that drivers who received training were less likely to be involved in motorcycle crashes. Trip destinations also influence the incident of motorcycle crashes. Trips from home to work and from work to home have very little propensity of being involved in a crash unlike trips from home to a friend or relatives place.

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 percent of all vehicle miles traveled (VMT) in the U.S., with narrowly three percent 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 percent of all traffic fatalities. In the previous 10 years, the fatalities increased by 20 percent in the U.S., while from 2019 to 2020 fatalities increased by 11 percent (Motorcycles - Injury Facts, n.d.). Using data from the 2016 Motorcycle Crash Causation Study (MCCS), the National Transportation Safety Board (NTSB) analyzed factor that lead to motorcycle crashes throughout the nation (National Transportation Safety Board, 2018). The study found that 65 percent of motorcycle crashes occur in urban areas and arterial roadways. Considering the weekly crash distribution, more than half of crashes, as well as half of the fatal crashes, occur on Fridays, Saturdays, and Sundays. Most motorcycle crashes include at least one additional motor vehicle (81 percent), while only 19 percent are single motorcycle crashes. Half of the single motorcycle crashes are fatal, which is not a surprise considering that 38 percent 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 percent of crashes. Based on crash data from 2007, 27 percent of riders involved in motorcycle-related fatal crashes in the U.S. were intoxicated (Fell et al., 2009). From 2010 to 2020, almost 95 percent 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). Appropriate motorcycle apparel has a significant impact on crash prevention. Motorcycle riders with appropriate apparel (boots and retroreflective jackets) had the tendency to significantly reduce their Injury Severity Score (ISS) score, which is also true for lightly colored helmets (Wali et al, 2019). The same study explored riders experience, finding that if a rider had gaps in between their riding, they were more likely to sustain severe injuries. Riders with experience who attended a rider's course significantly decreased their ISS.

Currently, Wyoming has about 30,000 registered motorcycles which are about 1 percent 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 percent. 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 percent of fatalities and 55 percent of injuries. Based on a study by Rezapour et al., 2020 34 percent 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.

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. This study is using the multinomial logistic, and Bayesian multilevel and binomial regression to determine the individual and mutual effects of different characteristics and factors on motorcycle crash severities in Wyoming.

3. Data Collection and Descriptive Statistics

The data used in this study were obtained from the WYDOT's CARE system and 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, categorized as Fatal (K), Incapacitating (A), Non-incapacitating (B), Possible (C), and No injury (O).

3.1. Descriptive Statistics

This study uses 12 years of Wyoming crash data (2008-2019) obtained through WYDOT's CARE crash database. There were a total of 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 breakdown of 12-year motorcycle crashes is provided in Table 1.

Table 1. 12-year motorcycle-related crash statistics for Wyoming.

	Total	Fatal (K)	Incapacitating (A)	Non-incapacitating (B)	Possible (C)	No injury (O)	Unknown
12-Year Sum (crashes)	3,429	202	875	1,356	508	186	302
Annual Avg. (crashes/yr)	285.8	16.8	72.9	113.0	42.3	15.5	25.2
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 percent involved a single motorcycle, and 40 percent were multi-vehicle crashes with motorcycle involvement. 57 percent of fatal and 67 percent of incapacitating injury crashes were with single motorcycle involvement. Even though more than 53 percent of all motorcycle-related crashes occurred in urban environments, the majority of fatal (71 percent) and incapacitating injury crashes (64 percent) were recorded in rural areas. In rural areas, the majority of total (77 percent), fatal (64 percent) and incapacitating injury (77 percent) crashes involved a single motorcycle. In urban areas, most of the total (54 percent), fatal (59 percent) and incapacitating injury (52 percent) crashes involved multiple vehicles.

The number of total motorcycle-related crashes had a decreasing trend from 2008 to 2019. However, the total number of fatal (K) and incapacitating injury (A) crashes remained relatively stable over time. Overall, the percentage of (K) and (A) crashes combined varied between 25 percent and 37 percent of total motorcycle-related crashes during the 12 year period, as shown in Figure 1, with the average of 31.2 percent.

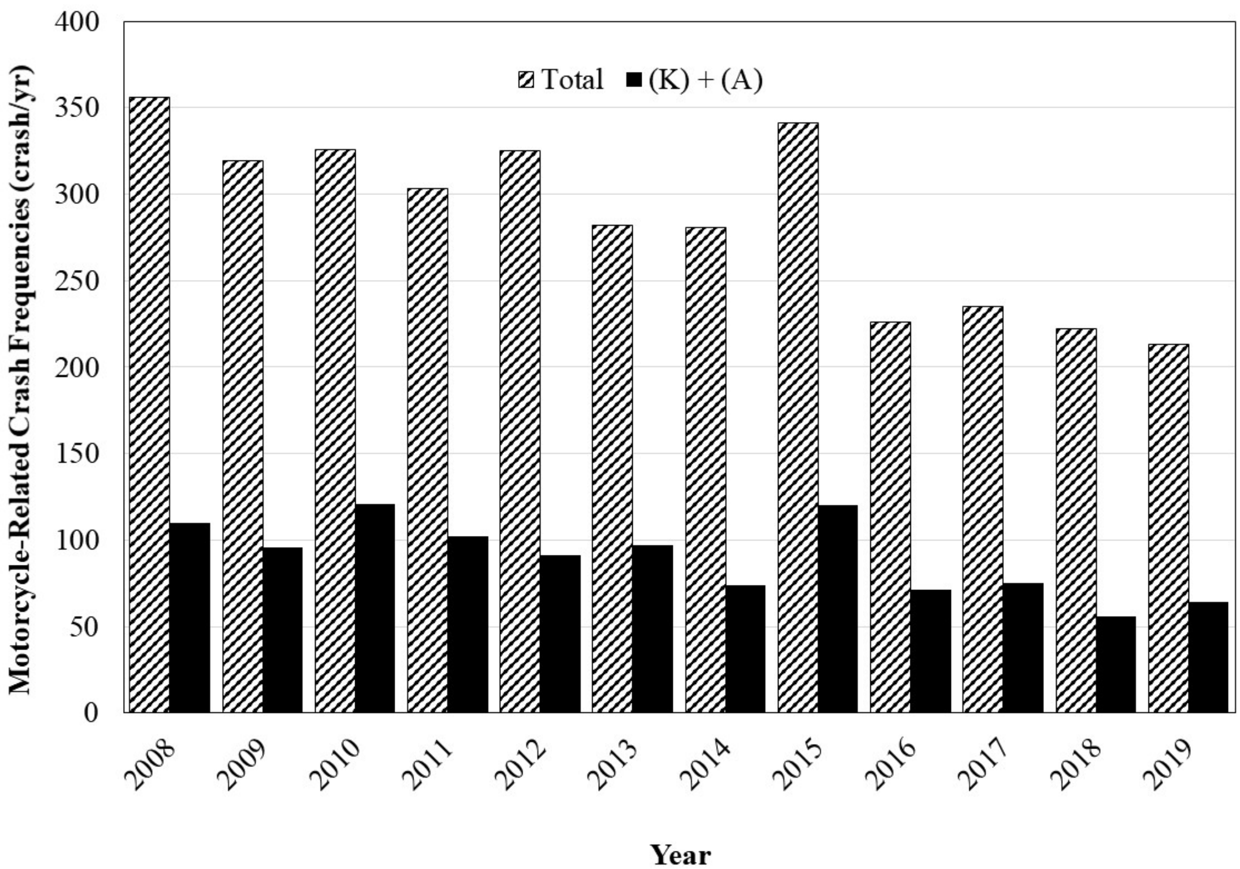


Figure 1. Graph. Total and (K) + (A) motorcycle-related crashes in WY 2008 - 2019.

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 2. The majority of the total (20 percent), fatal (29 percent) and injury (28 percent) crashes occurred in August.

Table 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**	**1356**	**508**	**186**	**302**
Annual Avg.	**285.8**	**16.8**	**72.9**	**113.0**	**42.3**	**15.5**	**25.2**

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

- Close to 60 percent of fatalities and incapacitating injuries occurred in motorcycle riders and passengers who were not wearing a helmet
- 21 percent of single rural motorcycle crashes involved run-off-road
- 20 percent of total motorcycle crashes occurred while negotiating a curve
- 69 percent of multi-vehicle urban crashes with motorcycle involvement were intersection/interchange/driveway related
- 19 percent of all motorcycle crashes occurred during reduced visibility conditions
- Of all motorcycle-related crashes, 18.4 percent involved speeding, 10.7 percent involved alcohol, and 6.4 percent 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. It is worth noting that these are crashes occurred along the entire length of the route.

Table 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

The crashes in the CARE database are geo-located, and this information was used to plot the crash locations for the covered 12-year period, as shown in Figure 2.

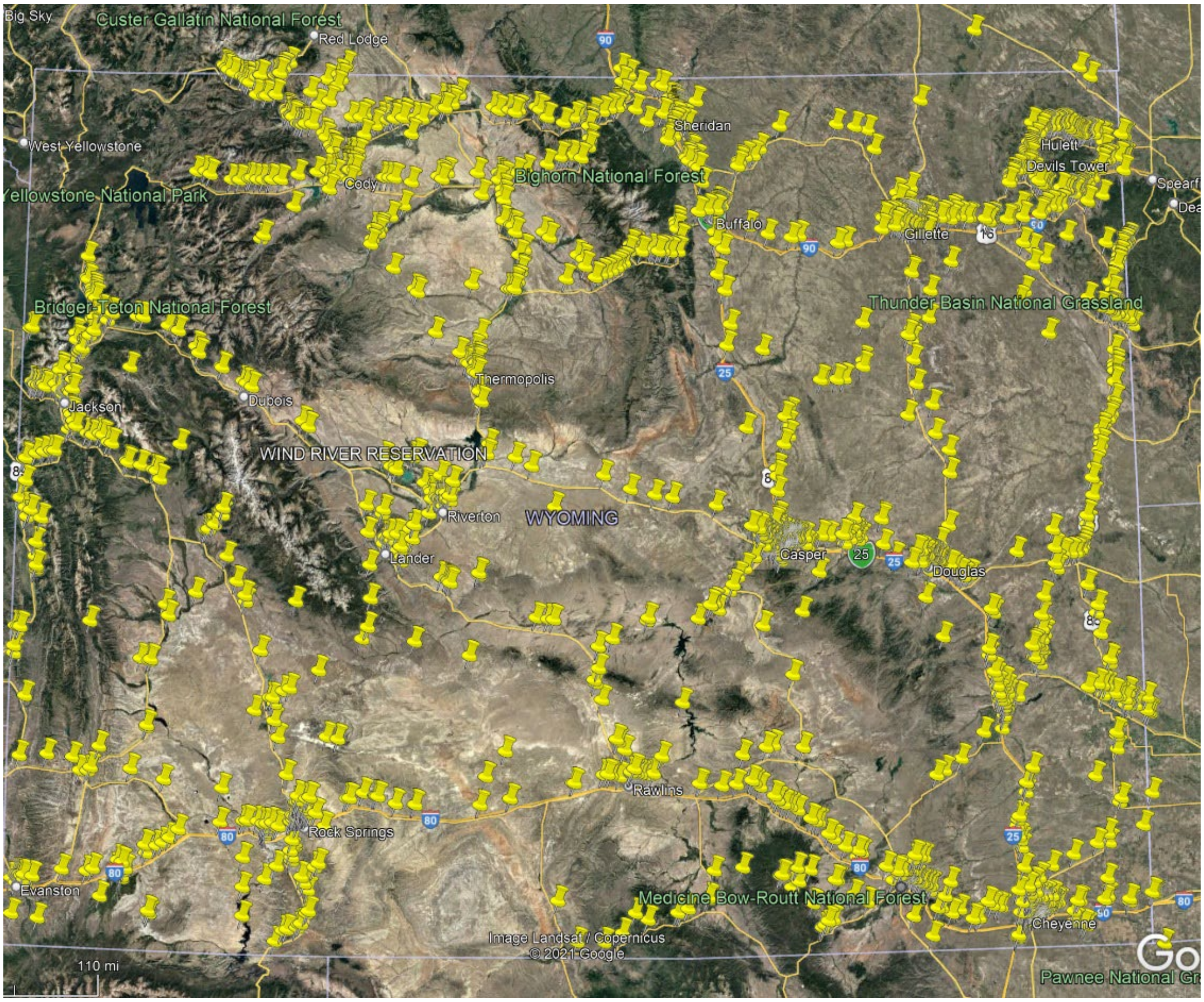


Figure 2. Illustration. Geo-location of motorcycle-related crashes in Wyoming (2008 – 2019). Source: Google Earth, modified from source.

Motorcycle crashes typically involve more than one contributing factor; therefore, there are combined effects which 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 analyses using the 12 years of crash data.

4. Statistical Models

This study applied three types of statistical models widely used in traffic safety research, Multinomial Logit Models (MNL), Bayesian multilevel models (BRM) and Bayesian binary regression models (BR). The models were implemented in RStudio statistical software, using the 12-year motorcycle safety data on the crash, vehicle and person levels. The results of the statistical models are used to determine the odds ratios of various variables and their significance on crash severity outcomes. This in turn would provide information on roadway, control, maintenance, education and enforcement characteristics that might need improvement in order to reduce the frequency and severity of motorcycle-related crashes in Wyoming.

4.1. Multinomial logit models

The MNL regression modeling is a widely used 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). MNL 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 MNL model, adapted from (Greene, 2012), is shown in Figure 3:

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

Where $p_i = P(Y_i = j \,|\mathbf{w_i})$ 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 $\boldsymbol{\alpha}_j$ 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), as shown in Figure 4:

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

The logit transformation of the odds ratio is defined as the logged odds, as shown in Figure 5:

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

The MNL 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 **θ**, denoted as f(y|**θ**), 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 shown in Figure 6:

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

Where L(**θ** | **y**) is the likelihood function, defined as a function of the unknown parameter vector, **θ**, of the vector **y** representing the collection of sample data. The likelihood function depends on the unknown parameter **θ**. The value of **θ** for which the likelihood function is at maximum is used as an estimate of **θ**. This is done by maximizing the log of the likelihood function, denoted as LL(**θ**), as it transforms into a summation as presented in Figure 7 (Abdulhafedh, 2017):

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

Previous research (Savolainen and Mannering, 2007; Geedipally et al, 2011), as well as the descriptive statistics from the data used in this study, show that different contributing factors and relationships are involved in a motorcycle-related crash. Therefore, this study assessed various combinations of variables to gain a better insight into the factors, their relationships and resulting injury-severity outcomes. 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 R^2 measure, which is more suitable for MNL models (McFadden, 1977). A McFadden R^2 value between 0.2 and 0.4 indicates an excellent model fit. The odds ratios are computed for each model on the crash, vehicle and person levels.

4.2. Bayesian multilevel and binary regression models

Bayesian statistical models have been used extensively in traffic safety research. The main advantage of Bayesian regression 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; Nalborczyk et al., 2019). The modeling process starts with the selection of the prior distribution of the parametric family. Three types of priors used in Bayesian 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; and 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 shown in Figure 8:

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

Figure 8. Equation. Bayesian parameter probability.

Where θ are the parameters to be estimated, $p(\theta | y)$ is the probability distribution to be estimated, also known as the posterior distribution, $p(y | \theta)$ 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 Bayesian models are the same ones used in the MNL 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 difference between the Bayesian multilevel models (BRM) and Bayesian binary regression models (BR) is in the level of descriptive variables: in the BRM models, these were defined as categorical; in the BR models, they are defined as binary. The BRM models are used for analysis on the crash level, while the BR models were used for the analyses on vehicle and person levels. The statistical modeling was performed in RStudio, using BRMS (Bayesian Regression Modeling with Stan) functionality.

5. Results and Discussion: Crash-Level Analysis

Multinomial logistic models were applied to the 12 years of crash-level data to assess the significance of crash variables and contributing factors on crash severity levels. This type of analysis was performed in order 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; and (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.

The crash-level BRM modeling was performed using eight years (2012-2019) of data, as recommendations from the literature suggest that more than 10 years of data can introduce too much variability in the results. 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 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. Rural single MNL model

Table 4 shows the MNL model results for rural single motorcycle crashes. The exposure measures strongly associated with crash severity in this case are found to be 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, and 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 very 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 which are found to increase crash severities.

Table 4. Rural single MNL model results.

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

5.2. Rural multi-vehicle MNL model

The results for the rural multi-vehicle MNL model are given in Table 5. In this case, the exposure measures that were strongly associated with injury severity include junction relation, vehicle maneuver, alcohol use, and speeding. Hemet 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, and 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 5. Rural multi-vehicle MNL model results.

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

5.3. Urban single MNL model

The resulting coefficients and odds ratios of the MNL model for urban single motorcycle crashes are presented in Table 6. 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, of both for over correction/over steer, and of both 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.

Table 6. Urban single MNL model results.

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

5.4. Urban multi-vehicle MNL model

Table 7 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, as well as 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 7. Urban multi-vehicle MNL model results.

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

5.5. Rural single BRM model

The BRM model results for rural single motorcycle crashes in Wyoming are given in Table 8. 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. 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.

Table 8. Rural single BRM model results.

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

5.6. Rural multi-vehicle BRM model

The results of the BRM model for rural multivehicle crashes are presented in Table 9. 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.

Table 9. Rural multi-vehicle BRM model results.

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

5.7. Urban single BRM model

The BR model results for urban single motorcycle crashes in Wyoming are shown in Table 10. 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 is the road condition that has 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 right of way (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 effects 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 10. Urban single BRM model results.

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

5.8. Urban multi vehicle BRM model

Table 11 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. 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.

Table 11. Urban multi-vehicle BRM model results.

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

5.9. Crash-level analysis: conclusions

In all four MNL 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 the four BRM 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, as well as urban single motorcycle crashes. Interestingly, the BRM models did not find speed to be a significant contributor to severe and fatal outcomes in Wyoming.

The results obtained from the crash-level MNL and BRM models can provide guidance on selecting proper engineering, education and enforcement measures which have the potential to reduce the frequency 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. More engineering, education, enforcement and roadway infrastructure maintenance efforts should be put to provide countermeasures that directly affect the severe crash contributing factors.

6. Results and Discussion: Vehicle-Level Analysis

The statistical analyses on the vehicle-level were performed for all motorcycle-related crashes in Wyoming for the 12-year period, without splitting them based on the setting and the number of vehicles involved. The reason for this is in the fact that for the vehicle (and person levels, presented in the next chapter), other types of crash characteristics are significant when compared to the crash-level characteristics. The MNL model setup is the same as in the crash-level analysis, while the Bayesian modeling used binary models, as there were found to be more accurate than the multilevel models on the crash dataset. All the variables used in the analysis were defined as binary (Y/N). The response variable was also defined as binary (fatal/incapacitating (Y), or not (N)), with non-fatal/incapacitating as the reference level. Young in the model is defined as all ages below or equal to 30, and old is defined as all ages greater or equal to 50. Summer in the model is also defined as the period between June and August inclusive. The Wyoming 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 defined as follows: if it is positive, the predictor increases the odds of fatal/incapacitating crashes, the higher the value, the higher the impact; if it is negative, the predictor decreases the odds of fatal/incapacitating crashes.

6.1. Vehicle-level MNL model

Table 12 represents the coefficients and odds ratios of the vehicle-level MNL Model. The significant measures of exposure strongly associated with crash severity include Horizontal Alignment, Vertical Alignment, Vehicle Damage, Vehicle year, Vehicle Maneuver, and Vehicle Most Damaged Area.

Compared to no injury, the odds ratio shows increased odds of any injury crash for curve to the left (two to five times), curve to the right (two to six times), and overtaking/passing (two to twenty-four times). For vehicle maneuvers, it was found that parked vehicles and other maneuvers have multifold odds of increase in fatal and possible injury compared to no injury. Slowing (more than three times), vehicle movement on sag vertical curve, disabling vehicle damage, damage to the left front (more than six times), top, undercarriage, right front, and left side areas increased the odds of fatal injury almost two to six times compared to no injury. Vehicle movement on crest vertical curves, functional and minor vehicle damage (both fatal and possible injury), vehicle year greater than 10 years old (for all injuries except incapacitating), right rear fender damaged area all increased the odds of fatal injury compared to no injury. Negotiating a curve, entering a traffic lane (more than eight times), right rear and right end damaged area are other factors that increase the odds of incapacitating injury compared to no injury. Backing (except for possible injury), turning left and right, moving downhill and uphill, leaving a traffic lane (except for non-incapacitating injury and possible injury), making a U-turn (except for non-incapacitating injury) and stopping in traffic all have low odds of increased fatal injury compared to no injury..

Table 12. Vehicle-level MNL model results.

	Fatal Injury (K)	Incapacitating Injury (A)	Non-Incapacitating Injury (B)	Possible Injury (C)
Intercept	1.282E-31	3.186E-20	1.101E-12	3.583E-31
Horizontal Alignment				
Curve Left	3.582	3.058	2.098	5.170
Curve Right	6.382	2.703	2.197	4.240
Vertical Alignment				
Downhill	0.881	0.639	1.186	2.042
Crest	1.215	0.330	1.068	0.120
Sag	4.238	0.512	0.513	1.037
Uphill	0.531	0.760	0.810	1.126
Vehicle Damage				
Disabling	2.200	0.033	1.061	1.451
Functional	1.539	0.024	0.993	1.529
Minor	1.599	0.030	0.903	2.063
Vehicle Year				
Between 6-10	0.278	0.421	0.739	0.658
Greater than 10	1.189	0.963	1.000	1.382
Vehicle Maneuver				
Slowing	3.016	0.280	0.436	1.464
Negotiating a Curve	0.256	1.111	0.704	0.176
Parked	2.08E+08	0.020	0.320	1.77E+08
Stopped in Traffic	0.856	0.057	0.082	0.484
Other	3.19E+08	0.300	0.105	3.571E+07
Backing	0.972	0.140	0.443	1.741E+09
Changing Lanes	7.099E-17	0.939	0.442	1.042E-08
Overtaking/Passing	10.162	24.688	2.116	4.024
Turning Right	0.332	2.150E-09	0.889	0.359
Turning Left	0.149	3.295E-09	0.802	0.725
Making a U-Turn	3.087E-16	1.302E-09	1.882	1.627E-08
Leaving a Traffic Lane/Parking	6.286E-09	8.071E-09	1.503	2.513
Entering a Traffic Lane	5.745E-09	8.307	0.446	0.277
Vehicles Most Damaged Area				
Front Right Fender	0.777	0.500	1.101	1.986
Left Front Area	6.079	0.722	1.685	0.307
Front Left Fender	0.714	0.116	0.205	0.761
Front Head On	0.987	0.420	0.586	0.611
Top	2.420	0.351	0.591	2.024
Undercarriage	3.037	0.106	5.238E-10	0.367
Right Front Area	2.064	0.850	1.724	0.780
Right Side	0.996	1.049	2.218	1.092
Right Rear Area	0.925	0.626	1.117	0.379
Rear Right Fender	1.067	8.181E-10	0.094	0.043
Rear End	0.110	1.041	0.312	0.072
Rear Left Fender	0.251	0.148	0.257	0.387
Left Rear Area	0.377	1.321E-08	1.043	0.121
Left Side	3.176	0.701	1.852	0.454

Note. p.value < 0.001, McFadden $R^2 = 0.3965$

Reference Levels:

Crash Severity: No Injury; *Horizontal Alignment*: Straight; *Vertical Alignment*: Level; *Vehicle Damage*: None; *Vehicle Year*: Less than or equal to 5 years; *Vehicle maneuver*: Straight Ahead; *Vehicle Most Damaged Area*: Non-Collision.

6.2. Vehicle-level BR model

Table 13 shows the estimates of BR model for vehicle level crashes in Wyoming. The results show that vehicle area damaged was the only predictor that has a slight odd of increased fatal and/or incapacitating injury. The rest of the predictors, more than one vehicle involved, vehicle age greater than 5 years, vehicle damaged, vehicle maneuver straight, crash on level grade, crash on straight horizontal alignment, vehicle most harmful event overturn, and vehicle occupants greater than one have low odds of fatal and/or incapacitating injury.

Table 13. Vehicle-level BR model results.

Variable	Estimate
Intercept	-1.69
More than One Vehicle Involved	
Yes	-0.68
Vehicle Age =5 years	
No	-0.68
Vehicle Damaged	
Yes	-0.55
Vehicle Area Damaged	
Yes	1.15
Vehicle Maneuver Straight	
No	-0.8
Level Grade	
No	-0.47
Straight Horizontal Alignment	
No	-1.82
Vehicle Most Harmful Event Overturn	
No	-1.39
Occupants Greater than One	
Yes	-0.96

Reference Levels:

Crash Severity: Non-Incapacitating/Possible/No Injury; *More than One Vehicle Involved*: No; *Vehicle Age less than or equal to 5 years*: No; *Vehicle Damaged*: No; *Vehicle Maneuver Straight*: Yes; *Level Grade*: Yes; *Straight Horizontal Alignment*: Yes; *Vehicle Most Harmful Event Overturn*: Yes; *Occupants Greater than One*: No.

6.3. Vehicle-level analysis: conclusions

On the vehicle level, the MNL model shows a significant increase in the odds of fatal crashes for horizontal curves (especially curves to the right), sag vertical curves, vehicle disabling damage, slowing and parked vehicles, overtaking/passing, and damages to the left and front areas of the motorcycle. The BR models on the vehicle level show that the level of the damage of the vehicle corresponds to the crash severity level. These results complement the findings from the crash level analyses, and identify additional factors which need more attention for safety improvements and management.

7. Results and Discussion: Person-Level Analysis

The person-level analysis follows the same approach as the vehicle-level analysis and applies MNL and BR models to determine the odds of fatal and severe injury crashes of predictor variables. In this case, certain variables from the person-level crash database were selected based on their significance and the recommendations from the literature, and the statistical models were run using RStudio software.

7.1. Person-level MNL model

Table 14 shows the results of the person-level MNL model. The significant measures of exposure strongly associated with crash severity include riders' age, riders' sex, alcohol and drugs use, safety equipment use, driver distraction, and injury area.

In all motorcycle-related crashes, the use of drugs (more than four times for fatal injury), alcohol (except for non-incapacitating injury), other distraction (more than three times for fatal injury) were found to increase the odds of all injury types compared to no injury. Driver injury areas: head, face, neck, thorax (chest/back), abdomen/pelvis, spine, upper extremity (arms, hand, shoulder, etc.), lower extremity (legs, feet, etc.), multifold increase the odds of any injury crash compared to no injury. Helmet use and other safety equipment (more than six times for incapacitating injury) are factors that have increased odds of incapacitating and non-incapacitating injury compared to no injury. Young and old riders, female riders have low odds of any injury compared to no injury. All safety equipment use has low odds of fatal and possible injury compared to no injury. Electronic communication devices and other distractions have low odd of fatal injury compared to no injury, which is reasonable comparing that motorcycle riders cannot use electronic devices while operating a motorcycle.

Table 14. Person-level MNL model results.

	Fatal Injury (K)	Incapacitating Injury (A)	Non-Incapacitating Injury (B)	Possible Injury (C)
Intercept	0.549	5.430E-10	8.477E-16	2.851
Drivers Age				
Young	0.569	0.320	0.354	0.550
Old	0.678	0.376	0.288	0.615
Drivers Sex				
Female	0.608	0.411	0.353	0.526
Alcohol Suspected				
Yes	1.201	1.256	0.898	1.656
Drugs Suspected				
Yes	4.434	3.394	2.327	1.176
Safety Equipment Use				
Helmet Used	0.722	1.085	1.147	0.754
Other	4.167E-09	6.514	7.089	1.360E-09
Shoulder and Lap Belt Used	7.877E-17	1.088E-07	1.338E-07	7.290E-18
Lap Belt Only Used	4.261E-11	0.077	4.436E+04	8.491E-12
Driver Distraction				
El. Communication Device	0.305	6.585E-10	4.711E-10	0.194
Other Electronic Devices	4.96E+09	1.698	1.97E+09	3.06E+09
Other Distraction Inside MV	0.021	6.72E+05	3.476E+14	4.60E+07
Other Distraction Outside MV	3.084	1.270	1.141	2.207
Injury Area				
Head	9.476E+14	2.697E+24	2.313E+30	2.413E+14
Face	2.058E+09	2.906E+09	2.470E+25	2.539E+09
Neck	5.391E+09	2.854E+19	7.644E+24	6.343E+08
Thorax (Chest/Back)	3.021E+09	7.290E+18	7.768E+24	1.314E+09
Abdomen/Pelvis	2.764E+09	9.351E+18	2.850E+25	2.624E+09
Spine	1.517E+09	1.726E+19	6.436E+24	2.547E+09
Upper Extremity (Arms, Hand, Shoulder etc.)	1.043E+09	8.877E+18	4.980E+25	3.273E+09
Lower Extremity (Legs, Feet, etc.)	1.315E+09	1.377E+19	1.593E+25	1.335E+09

Note. p.value < 0.001, McFadden $R^2 = 0.3743$

Reference Levels:

Crash Severity: No Injury; *Driver Age*: Middle; *Driver Sex*: Male; *Alcohol Suspected*: No; *Drugs Suspected*: No; *Safety Equipment Use*: None Used; *Driver Distraction*: Not Distracted; *Injury Area*: No Injury.

7.2. Person-level BR model

Table 15 shows the results of the BR model and estimates for person level analysis. Young and older drivers have multifold odd of increased fatality and/or incapacitating injury compared to non-incapacitating, possible and/or no injury. For young riders, this is predominantly due to a lack of experience and riding distraction that is more prominent among ages less than 30, as the literature shows. Driving under the influence of alcohol and drugs caused a slight increase in the odds of fatal and/or incapacitating injury crash outcomes. Riders from out of Wyoming, riders' distraction, and riders' injury all had a small odd of increased fatal and/or incapacitating injury outcomes. The result also showed that female motorcycle riders have significantly lower odds of being involved in fatal and incapacitating injury crashes.

Table 15. Person-level BR model results.

Variable	Estimate
Intercept	-3.95
Driver Age	
Young/Old	1,240,449.32
Driver Sex	
Female	-58,805.14
Alcohol Suspected	
Yes	0.03
Drugs Suspected	
Yes	0.68
Helmet Used	
No	-0.22
State of Residence Wyoming	
No	0.77
Driver Distracted	
Yes	0.75
Driver Injured	
Yes	0.67
Improper Driver Action	
Yes	-0.96

Reference Levels:

Crash Severity: Non-Incapacitating/Possible/No Injury; *Driver Age*: Middle; *Driver Sex*: Male; *Alcohol Suspected*: No; *Drugs Suspected*: No; *Helmet Used*: Yes; *State of Residence Wyoming*: Yes; *Driver Distraction*: No; *Driver Injured*: No; *Improper Driver Action*: No.

7.3. Person-level analysis: conclusions

The person-level MNL model shows increased odds of fatal and severe injury crashes where drugs and alcohol are involved, or the rider is distracted. The injury areas resulting in the highest odds of fatal and severe crashes include head, neck and chest. On the person level, the BR models show a significant increase in the odds of fatal and severe injury outcomes for young and old riders, alcohol and drug use, rider distraction, and out-of-state riders. These results further complement the findings from the crash and vehicle level analyses, and identify additional factors which need more attention for safety improvements and management.

8. Motorcycle Operators Survey

As a part of this study, the researchers created and distributed a survey aimed at motorcycle riders, instructors and law enforcement officers. The survey was distributed through WYDOT contacts and local motorcycle societies.

The survey consist of 14 questions, aimed to assess the background, motorcycle ownership and experience, safety perception and riders' opinions on safety improvement strategies. The complete survey is provided in Appendix A, and can be assessed online at https://uwyo.sjc1.qualtrics.com/jfe/form/SV_0JJkeQWimB9C9fw. Table 16 summarizes the survey questions.

Table 16. Rider survey questions summary.

1	Rider's residence
2	Rider's age group (≤19, 20-39, 40-59, ≥60)
3	Level of riding experience (motor officer, motorcycle safety instructor, regular/frequent rider, occasional rider, law enforcement (non-motorcycle)
4	Years of riding experience
5	Miles ridden in the past three years
6	Type of motorcycle ridden the most (touring, cruiser, standard, sport, adventure…)
7	Engine size (cc) of motorcycle ridden the most (≤249, 250-649, 650-1,199, ≥1,200)
8	Maintaining and improving riding proficiency (motorcycle safety courses, individual practice, motorcycle operator manuals, online resources and videos, other)
9	Personal involvement in a motorcycle crash (yes, no, abstain)
10	Most significant factors affecting single motorcycle crashes
11	Most significant factors affecting multiple-vehicle motorcycle crashes
12	Strategies to reduce frequency and severity of motorcycle crashes
13	Preventive measures for riders to reduce frequency and severity of motorcycle crashes
14	Additional comments

As of the closure of this report, there are five responders, which can be considered as a low response rate. However, the survey will remain open after the conclusion of this study, and any new information and responses will be shared with WYDOT.

8.1. Summary of survey results

The complete survey results are provided in Appendix B. Overall, the responders agree on majority of causes and remedies related to the state of motorcycle safety in Wyoming.

All responders are local riders from Cheyenne and Laramie, four of them in the 40 to 59 age group, and one in the 20 to 39 age group. All except one responders are regular riders, with many years of experience (one over 40 years, two over 20, one approximately 10, and one approximately 4 years of riding experience). On average, the responders rode more than 10,000 miles in the past three years, with two of them riding more than 20,000 miles. The types of motorcycles they are riding includes cruisers (two responders), standard, dual sport and adventure (one responder each).

All responders maintain their riding proficiency through individual practice. The next strategies in line include motorcycle safety courses and online resources, followed by the motorcycle operator manuals. Two of the responders were involved in a motorcycle-related crash.

For factors causing single motorcycle crashes, there is an agreement among the responders that the motorcycle operator state and actions (aggressiveness, lack of skill, disregard of traffic control) are the most significant factors. They are followed by speeding, the quality of the roadway surface, weather, and visibility. When it comes to multiple-vehicle crashes with motorcycle involvement, there is an even stronger agreement among the responders that the operators of other vehicles represent the most significant factors leading to a crash (their aggressiveness, lack of skill, and disregard for traffic control), followed by the motorcycle operator and the failure of drivers of other vehicles to identify the motorcyclist. The next in line is speeding (by any vehicle), followed by the roadway quality, weather and visibility.

When it comes to general strategies to reduce the frequency and severity of motorcycle crashes, the responders agree that education and training for riders is the most important factor. Road maintenance is the next most important strategy, followed by enforcement, helmet use requirement, upgrades to traffic control, and lastly the installation of motorcycle safety devices. As for the motorcycle rider related strategies, the responders agree that the continuous educations is the most important, followed by wearing proper gear and a helmet, regular and proper motorcycle maintenance, and lastly respect of traffic control.

For their personal recommendation, the responders advise motorcycle operators to be vigilant at all times, and the inclusion of awareness training for automobile operators. In conclusion, the survey results show education and training, road maintenance, and riding gear are the most important strategies to prevent motorcycle crashes and their severity. The proper education is also needed for the operators of other vehicles and raising their awareness about the presence of motorcycles on the road.

9. Measures for Improving Motorcycle Safety

Various countermeasures for reducing the frequency and severity of motorcycle related crashes have been explored in research and practice. This measures incorporate roadway design, traffic control, construction, maintenance practices, as well as 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 is mainly location-specific, and results from location characteristics.

9.1. Roadway design countermeasures

9.1.1. 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 which experience higher than average motorcycle related crashes.

Motorcycle-friendly guardrail design includes a lower portion of the guardrail free of sharp edges and posts gthat prevent motorcycles and riders to slide under. An examples of this type of guardrails is shown in Figure 9.

Figure 9. Photo. Motorcycle-friendly crash barriers. Source: Safe Direction Crash Barrier Solutions.

These types of 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.

9.1.2. 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 10), 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 slipper when dry (such as the road snakes).

Figure 10. Photo. 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 loose traction on contact, depending on the speed and the lean angle in curves. Bridge joints that are 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 loose friction especially when they are wet, and due to fact that they blend with the pavement, they 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 loose traction, mainly during turning maneuvers. In the absence of other ways to minimize their impacts, for intersections with high motorcycle traffic it is recommended to leave portions of the pavement free of markings (e.g. pedestrian crossings) that motorcycles can use to traverse the intersection.

9.1.3. 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 high percentage of motorcycle traffic, or locations with historically high motorcycle-related crash frequencies.

9.1.4. 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 example of the signage design is shown in Figure 11.

Figure 11. Illustration. Motorcycle warning signs. Source: MUTCD, modified from source.

9.1.5. Pavement markings

Many motorcycle related crashes occur due to the loss of traction resulting from wet pavement markings. Furthermore, recessed pavement markings and rumble strips can result in motorcyclists loosing balance while traversing them, especially during turning maneuvers. In intersection areas which are frequented by motorcyclists, it is recommended to avoid using recessed markings (such as stop lines or pedestrian crossings), and using paint which has better wet friction properties.

9.1.6. 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 need to 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.

10. Crash Clusters Locational Analysis

By nature, traffic crashes are random. However, there are many external factors that can increase the probability of crash occurrence, and/or crash severity at certain locations. Through the data analysis, this study identified certain locations in Wyoming where motorcycle-related crashes are more common, and share same or similar crash contributing factors. These clusters are shown in Figure 12. Some crashes are in rural, some in urban areas.

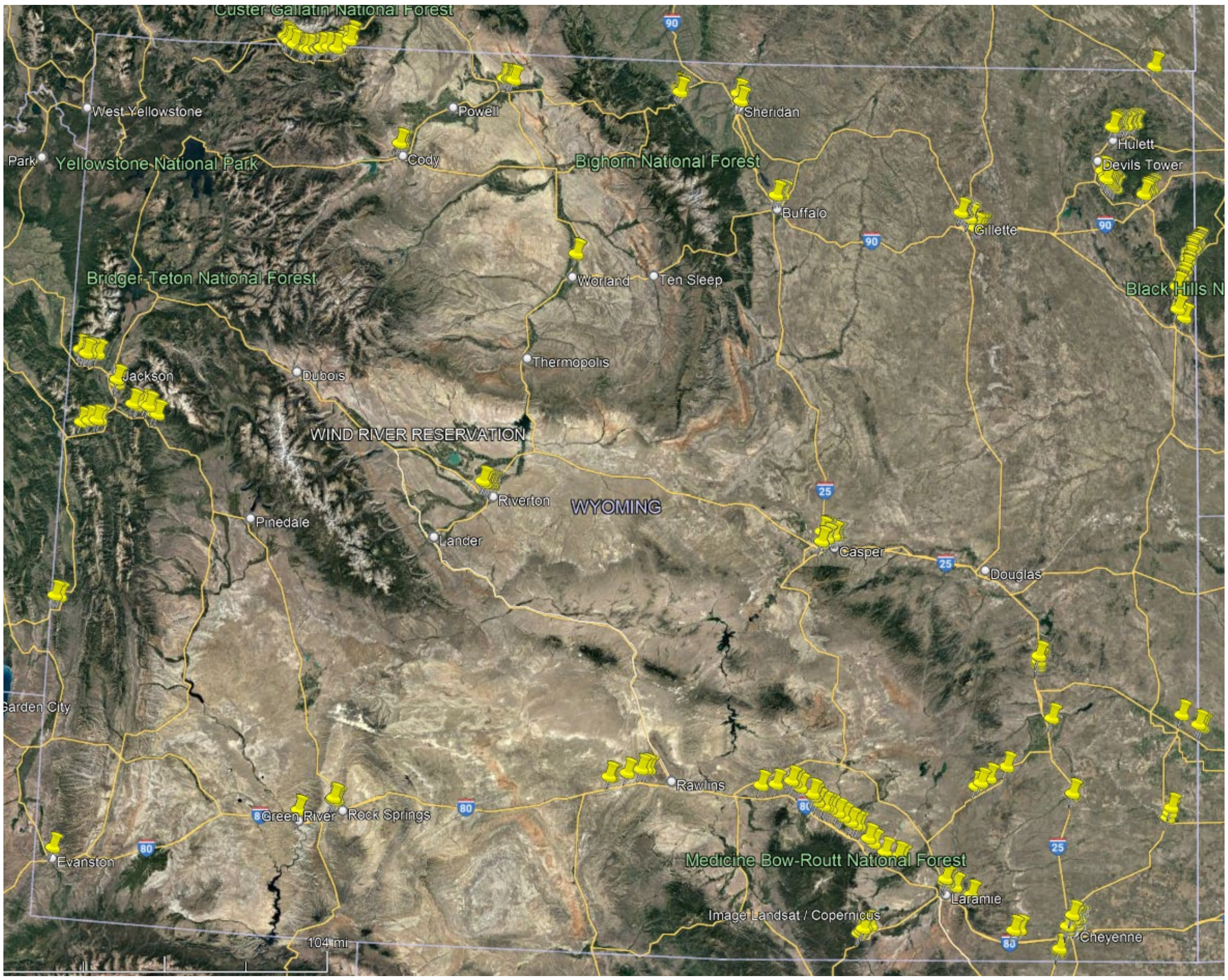


Figure 12. Illustration. Motorcycle crash clusters in Wyoming. Source: GoogleEarth, modified from source.

The interactive GoogleEarth (.kml) map, titled "2008-2019_MC_crash_clusters", is included in addition to this report. For each crash, it shows the ID number, junction relation status, vehicle maneuver, driver action, animal and speeding involvement, and crash severity, as illustrated in Figure 13.

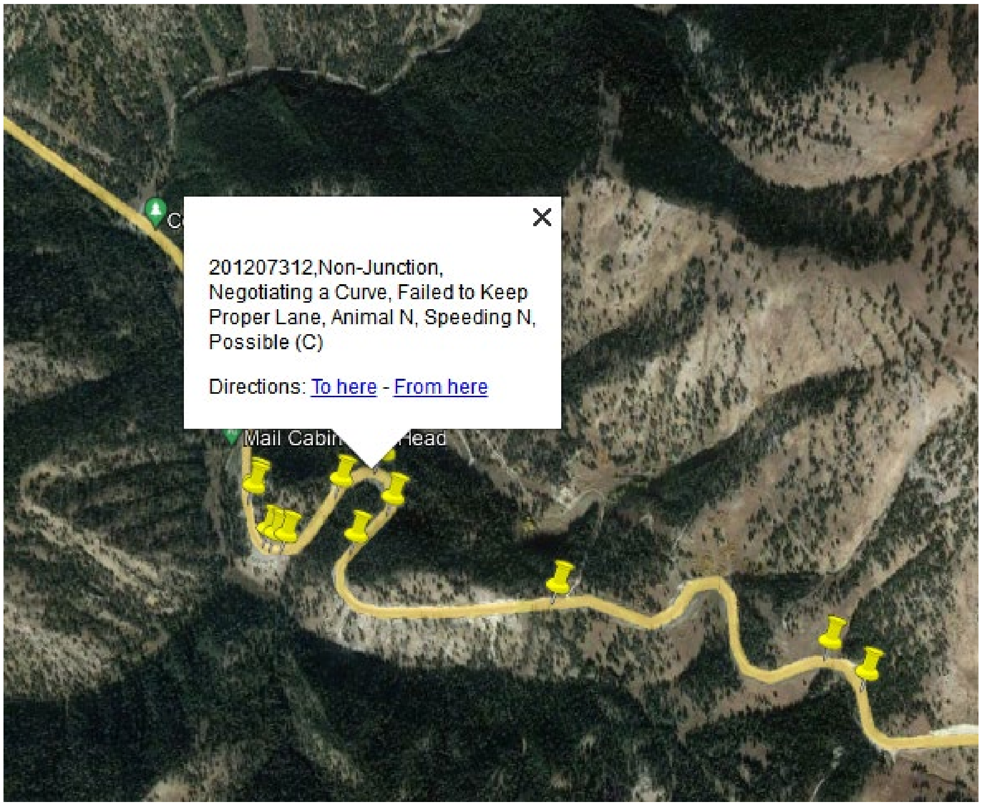


Figure 13. Illustration. Motorcycle crash clusters interactive information. Source: GoogleEarth, modified from source.

10.1. Cluster 1: WY 22, Teton Pass Highway, MP 6 – MP 15

WY 22, Teton Pass Highway, was found to be one of the highways experiencing the highest motorcycle-related crash rates in the State. Of a particular attention is the section between milepost (MP) six and MP 15, a portion of which is shown in Figure 13. Close to 80 percent of crashes that occurred along this section of the roadway included negotiating a curve maneuver, with riders failing to keep proper lane, or running of road. Speeding was found to be a factor in relatively low number of crashes. Therefore, along this section geometric features of the roadway are the most significant factors contributing to motorcycle crashes. The recommendations for this section are as follows:

- Upgrade the warning signs, with an emphasis on motorcycles (e.g. a variation of curve warning and advisory speed warning signs similar to those shown in Figure 11).
- Provide curve widening, especially in curves with lower curve radius, to the maximum extent possible.
- Install motorcycle-friendly crash barriers in curve sections.
- Keep the clear zone free of obstructions.
- Maintain the roadway surface in good condition, and free of debris.
- Provide more frequent enforcement along this section.

10.2. Cluster 2: WY 212, access to Yellowstone National Park

Access to the Yellowstone National Park, as well as the park itself, see a lot of motorcycle-related crashes. WY 212 on the north-east side is one of the critical routes in this area. Negotiating a curve, running of road and speeding are the major contributing factors along this route. The remedy recommendations are the same as for Cluster 1 (WY 22), however enforcement should be emphasized along this route.

10.3. Cluster 3: US Highway 14, MP 72 – MP 79

US 14 is one on the roadways in Wyoming which generally experiences high overall crash frequencies, mainly due to its challenging geometrical characteristics. The section between MP 72 and MP 79 is particularly dangerous for motorcycles, as many crashes occur at this section. Almost all motorcycle-related crashes along this section occurred within horizontal curves. The most common rider actions include failure to keep a proper lane and speeding. Therefore, the recommended strategies are the same as for the previous two clusters.

10.4. Cluster 4: WY 189, MP 143 – MP 146

This particular section of WY 189 experiences high motorcycle-related crash frequencies. Turning, following too close, and riders failing to yield the right of way (accounting for about 70 percent of crashes on this section) are some factors that contribute to motorcycle related crashes. Along this section, erratic and/or careless behaviors are the main contributing factors leading to crashes. The following countermeasures are strongly recommended:

- Road signs should be checked regularly to make sure they are replaced when faded or displaced.
- Provide more frequent enforcement along this section.
- Increase public awareness regarding this section.

10.5. Cluster 5: US Highway 85, MP 231 – MP 256

This road was also found to be one of the highways in Wyoming experiencing some of the highest motorcycle-related crash frequencies, particularly the section between MP 231 and MP 256. About 30 percent of crashes on this section included negotiating a curve, while about 37 percent of the crashes involved animal collisions. Crashes that involved speeding were found to be moderately low. The recommendation for this section of roadway is the same for Cluster 1, with an addition of animal presence warning signs, improved roadside fences, and potentially providing animal crossings.

10.6. Cluster 6: Interstate 80, MP 242 – MP 296

The section of I-80 between MP 242 and MP 296, experienced one of the highest motorcycle-related crashes in the state. Close to 70 percent of all motorcycle-related crashes along this section included negotiating a curve, overtaking/passing, running of road, and failing to keep proper lane. Geometric features of the highway and erratic behavior of riders are factors resulting in crashes on this road section. Speed control and enforcement should be increased along this section of I-80, with an addition in rising riders' awareness of dangerous geometric and traffic conditions.

10.7. Cluster 7: US 87 (Greeley Highway), Fox Farm Road to I-80 interchange, Cheyenne

This section of US 87 in Cheyenne, especially the intersection between US 87 and Fox Farm Road, experienced very high frequencies of motorcycle-related crashes. The majority of crashes are intersection and business access related, and involve turning maneuvers. Speeding was also found to be a contributing factor along this section of the highway. One of the mitigation strategies for this section would include improvements in visibility and intersection sight distances, and increased speed control and enforcement.

10.8. Cluster 8: WY 24, access to Devils Tower, MP 14 – MP 25

WY 24 was found to be one of the highways experiencing the highest motorcycle-related crash rates in the State, particularly the section between MP 14 and MP 25. About 50 percent of crashes that occurred along this section of the roadway included negotiating a curve maneuver, with riders failing to keep proper lane, or running of road. Speeding and crashes involving animals were found to be a factor in relatively low number of crashes. Therefore, the recommended strategies are the same as for Cluster 1, with an addition of animal presence warning signs, and improvements in roadside fences.

10.9. Cluster 9: Lincoln Highway, Downtown to Nationway, Cheyenne

This section is characterized by the highest motorcycle-related crash frequencies in urban areas anywhere in Wyoming, especially the section between Downtown and Nationway intersection. Lane changing maneuvers, erratic, reckless, careless and aggressive, following too close, disregard of traffic control were found to be the most contributing factors leading to crashes on this section of the road. Therefore, it could be seen that bad driver behavior is the predominant main crash contributing factor. The following countermeasures are highly recommended:

- Provide more frequent enforcement along this section.
- Increase the visibility of traffic control devices.
- Increase the intersection sight distances.

10.10. Cluster 10: US Highway 14, access to Devils Tower, MP 183 – MP 194

WY 14, specifically the section between MP 183 and MP 194 experienced significantly high motorcycle-related crashes. About 60 percent of crashes on this road included negotiating a curve, running off road, and failing to keep proper lane. Speeding and crashes that involved animals was not a contributing factor that led to crashes; however, road geometric features and inappropriate driver behavior were leading contributing factors. Therefore, the recommended strategy to be adopted on this road is the same as for Cluster 6.

10.11. Cluster 11: Westover Road and Douglas Highway, Gillette

The most predominant factors leading to crashes along Westover Road included negotiating a curve, turning maneuvers, and running of road, accounting for more than 60 percent of crashes. It was followed by speeding, attributing to about 30 percent of the crashes. Speed control and enforcement should be increased along this road. Majority of crashes along Douglas Highway are intersection and driveway related, therefore a special attention should be given to visibility and sight distances.

10.12. Cluster 12: 2nd Street, Casper

This street experienced highest motorcycle-related crash frequencies in the City of Casper. Most of the entrances on this section of roadway are business entrances. The majority of factors contributing to crashes on this section included turning movements and failing to yield the right of way. The recommendations for this section are as follows:

- Upgrade the warning signs, with an emphasis on motorcycles (e.g., advisory speed warning signs like those shown in Figure 11).
- Increase public education on matters regarding motorcycle safety.
- Provide more frequent enforcement along this section.

11. Conclusions

Motorcycle fatalities represent a large portion of traffic fatalities in the U.S., in excess of 15 percent. According to the National Highway Traffic Safety Administration, the mean fatality crash rate for motorcycles is about five times higher than that for passenger cars. From 2015 onwards, the 5-year rolling average of fatal motorcycle crashes per million population in Wyoming has been increasing, from 26 in 2015, to 32 in 2018. In 2018, there were 15 motorcycle fatalities in Wyoming. Most fatal and serious injury motorcycle crashes happen between April and September, with the peak occurring in August. Wyoming does not have a comprehensive helmet law, and requires helmets only for riders/passengers aged 17 or younger, with the exception for mopeds.

This research performed a comprehensive motorcycle safety assessment for Wyoming, using twelve years of detailed crash data. It analyzed crash characteristics, severities, types and contributing factors on crash, vehicle and person levels. The study also recommended countermeasures which have the potential to reduce the frequency and severity of motorcycle crashes.

This study assessed the correlation between different characteristics and factors, and their individual and mutual effects on motorcycle crash severities in Wyoming. The analyses were performed on crash, vehicle and person levels. On the crash level, 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). As different factors were found to be significant to crash outcomes on vehicle and person levels, these analyses were performed for all motorcycle crashes, regardless of the setting and the number of vehicles involved.

In addition to the descriptive statistics of motorcycle related crashes, 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, on crash, vehicle and person levels: multinomial logistic regression (MNL), Bayesian multilevel regression (BRM), and Bayesian binary regression (BR) models.

The application of MNL models on the crash level 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. On the vehicle level, the MNL model shows a significant increase in the odds of fatal crashes for horizontal curves (especially curves to the right), sag vertical curves, vehicle disabling damage, slowing and parked vehicles, overtaking/passing, and damages to the left and front areas of the motorcycle. The person-level MNL model shows increased odds of fatal and severe injury crashes where drugs and alcohol are involved, or the rider is distracted. The injury areas resulting in the highest odds of fatal and severe crashes include head, neck and chest.

The BRM models on the crash level found that alcohol and animal involvement, reduced lighting conditions, 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, as well as urban single motorcycle crashes. The BRM models did not find speed to be a significant contributor to severe and fatal outcomes in Wyoming. The BR models on the vehicle level show that the level of the damage of the vehicle corresponds to the crash severity level. On the person level, the BR models show a significant increase in the odds of fatal and severe injury outcomes for young and old riders, alcohol and drug use, rider distraction, and out-of-state riders.

The motorcycle operator survey results show education and training, road maintenance and riding gear to be the most important strategies to prevent motorcycle crashes and their severity. The proper education is also needed for the operators of other vehicles and raising their awareness about the presence of motorcycles on the road.

The study performs a locational crash cluster analyses to identify locations in rural and urban areas in Wyoming that experience high frequencies of motorcycle related crashes, and recommends potential location-specific mitigation measures. 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. The approach and results of this study would present a good starting point for future motorcycle safety studies in Wyoming, as well as in other states.

References

1. Abdulhafedh, A. (2017). Incorporating the Multinomial Logistic Regression in Vehicle Crash Severity Modeling: A Detailed Overview. *Journal of Transportation Technologies*, Vol. 7, pp. 279-303. https://doi.org/10.4236/jtts.2017.73019

2. Bakker, S. (2018). Electric Two-Wheelers, Sustainable Mobility and the City. *Sustainable Cities - Authenticity, Ambition and Dream*. http://dx.doi.org/10.5772/intechopen.81460

3. Broughton, P., and L. Walker. (2019). *Motorcycling and Leisure: Understanding the Recreational PTW Rider*. CRC Press, ISBN 9780367385606.

4. Byrd, R. N., and R. F. Parenti. (1978). Factors related to head injury severity of motorcyclists involved in traffic crashes. *Accident Analysis and Prevention*, 10(1), pp. 1–4.

5. Chaudhuri, U., K. L. Ratnapradipa, S. Shen, T. M. Rice, G. A. Smith, and M. Zhu. (2019). Trends and patterns in fatal US motorcycle crashes, 2000–2016. *Traffic Injury Prevention*, Vol. 20(6), pp. 641–647.

6. Cook, L. J., Kerns, T. J., Burch, C. A., Thomas, A., & Bell, E. (2009). *Motorcycle helmet use and head and facial injuries: Crash outcomes in CODES-linked data*. National Highway Traffic Safety Administration (NHTSA), Report No. HS-811 208.

7. Dadashova, B., C. Silvestri-Dobrovolny, J. Chauhan, M. Perez, and R. Bligh. (2022). Hot-spot analysis of motorcyclist crashes involving fixed objects using multinomial logit and data mining tools. *Journal of Transportation Safety & Security*, Vol. 14:7, pp. 1201-1219. 10.1080/19439962.2021.1898070

8. *Dangerous States for Motorcycle Riders | QuoteWizard.* https://quotewizard.com/news/posts/dangerous-states-for-motorcycles. Accessed May 9, 2022.

9. Farid, A., and K. Ksaibati. (2021). Modeling severities of motorcycle crashes using random parameters. *Journal of Traffic and Transportation Engineering (English Edition)*, Vol. 8-2, pp. 225-236. https://doi.org/10.1016/j.jtte.2020.01.001

10. Farid, A., S. Nazneen, K. Ksaibati, and M. Mashhadi. (2022). *Enhancing Crash Data Reporting to Highway Safety Partners in Wyoming by Utilizing Big Data Analysis and Survey Techniques*. Wyoming Department of Transportation, Report No. WY-2202F.

11. Farid, A., M. Rezapour, and K. Ksaibati. (2019). *Modeling Severities of Motorcycle Crashes on Low-Volume Roadways*. 12th International Conference on Low-Volume Roads, pp. 479.

12. Fatalities Crash Statistics, Utah Department of Public Safety's Highway Safety Office. https://highwaysafety.utah.gov/crash-data/. Accessed March 15, 2022.

13. Fatal motorcycle crashes per mileage in U.S. | Statista. https://www.statista.com/statistics/191547/fatal-motorcycle-crashes-in-the-us/. Accessed May 21, 2022.

14. Federal Highway Administration. (2012). *Manual on Uniform Traffic Control Devices (MUTCD).*

15. Fell, J. C., A. S. Tippetts, and R. B. Voas. (2009). *Fatal traffic crashes involving drinking drivers: what have we learned?* Annals of Advances in Automotive Medicine/Annual Scientific Conference, pp. 53-63.

16. Geedipally, S. R., P. A. Turner, and S. Patil. (2011). Analysis of Motorcycle Crashes in Texas with Multinomial Logit Model. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2265, pp. 62-69. DOI: 10.3141/2265-07

17. Greene, W. H. Econometric Analysis, 7th Edition. (2012). Pearson Education, Boston, MA. ISBN 978-0-273-75356-8.

18. Haq, M., Zlatkovic, M., and Ksaibati, K. (2020). Occupant Injury Severity in Passenger Car-Truck Collisions on Interstate 80 in Wyoming: A Hamiltonian Monte Carlo Markov Chain Bayesian Inference Approach. *Journal of Transportation Safety & Security*, Taylor & Francis, https://doi.org/10.1080/19439962.2020.1786872

19. Insurance Institute for Highway Safety (IIHS). *Motorcycle helmet use laws by state*. https://www.iihs.org/topics/motorcycles/motorcycle-helmet-laws-table. Accessed February 25, 2022.

20. Islam, M. (2021). The effect of motorcyclists' age on injury severities in single-motorcycle crashes with unobserved heterogeneity. *Journal of Safety Research*, Vol. 77, pp. 125-138. https://doi.org/10.1016/j.jsr.2021.02.010

21. Jittrapirom, P., H. Knoflacher., and M. Mailer. (2017). The conundrum of the motorcycle in the mix of sustainable urban transport. *Transportation Research Procedia,* Vol. 25, pp. 4869-4890.

22. Kononen, D. W., C. A. C. Flannagan, and S. C. Wang. (2011). Identification and Validation of a Logistic Regression Model for Predicting Serious Injuries Associated with Motor Vehicle Crashes. *Accident Analysis and Prevention*, Vol. 43(1). https://doi.org/10.1016/j.aap.2010.07.018

23. Kvasnes, S., et al. (2021). Safety Effects of Horizontal Curve Design and Lane and Shoulder Width on Single Motorcycle Accidents in Norway. *Journal of Advanced Transportation*, Vol. 2021, pp. 1-11. https://doi.org/10.1155/2021/6684334

24. Li, X., et al. (2021). A spatiotemporal analysis of motorcyclist injury severity: Findings from 20 years of crash data from Pennsylvania. *Accident Analysis and Prevention*, Vol. 151, pp. 1-17. https://doi.org/10.1016/j.aap.2020.105952

25. McFadden, D. (977). *Quantitative Methods for Analyzing Travel Behavior of Individuals: Some Recent Developments*. Cowles Foundation for Research in Economics, Yale University.

26. McHugh, M. L. (2013). *The Chi-square test of independence*. Biochemia Medica Vol. 23(2), pp. 143-149.

27. Nalborczyk L., C. Batailler, H. Lœvenbruck, A. Vilain, and P. C. Burkner. (2019). An Introduction to Bayesian Multilevel Models Using brms: A Case Study of Gender Effects on Vowel Variability in Standard Indonesian. *Journal of Speech, Language, and Hearing Research*, Vol. 62(5), pp. 1225-1242. DOI: 10.1044/2018_JSLHR-S-18-0006. PMID: 31082309

28. National Highway Traffic Safety Administration (NHTSA) (2021). *Traffic Safety Facts: 2019 Data: Motorcycles*. US Department of Transportation, DOT HS 813 112.

29. National Motorcycle Institute Fatality Reporting System, National Motorcycle Institute. https://motorcyclefatalities.org/

30. National Transportation Safety Board. (2018). *Select Risk Factors Associated with Causes of Motorcycle Crashes: Safety Report*. Report No. NTSB/SR-18/01.

31. Nazametz, J. W. et al. (2019). *Motorcycle Crash Causation Study: Final Report*. Federal Highway Administration, Report No. FHWA-HRT-18-064.

32. Nicol, D., et al. (2012). *Infrastructure Countermeasures to Mitigate Motorcyclist Crashes in Europe*. FHWA, AASHTO and NCHRP. Report No. FHWA-PL-12-028.

33. Perrin, J. (2003). *Animal-vehicle accident analysis*. Utah Department of Transportation, Research Division.

34. Pfaffenbichler, P., and G. Circella. (2009). *The role of motorized two-wheelers in an energy efficient transport system*. Proceedings of the Act! Innovate! Deliver! Reducing energy demand sustainably conference, European Council for an Energy Efficient Economy, pp. 1345-1354.

35. Potts, I., S. Garets, T. Smith, R. Pfefer, T. Neuman, K. Slack, K. Hardy, and J. Nichols (2008). *A Guide for Addressing Collisions Involving Motorcycles*. National Cooperative Highway Research Program (NCHRP), Report No. 500.

36. Rezapour, M., A. Molan, and K. Ksaibati. (2020). Analyzing injury severity of motorcycle at-fault crashes using machine learning techniques, decision tree and logistic regression models. *International Journal of Transportation Science and Technology*, Vol. 9(2), pp. 89-99.

37. Rose, G., R. Thompson, B. Amani, and R. McClure. (2012). *Understanding Ownership and Use of Powered Two Wheelers in Melbourne*. Proceedings of the Australasian Transport Research Forum.

38. Rossheim, M. E., F. Wilson, S. Suzuki, M. Rodriguez, S. Walters, and D. L. Thombs. (2014). Associations between drug use and motorcycle helmet use in fatal crashes. *Traffic Injury Prevention*, Vol. 15(7), pp. 678-684.

39. Savolainen, P., and F. Mannering. (2007). Probabilistic models of motorcyclists' injury severities in single- and multi-vehicle crashes. Accident Analysis and Prevention, Vol. 39(5), pp. 955-963. https://doi.org/10.1016/j.aap.2006.12.016

40. Schultz, G., C. Lunt, T. Pew, R. L. Warr, and M. J. Heaton. (2020*). Segment and Intersection Crash Analysis Methodologies for Utah Highways*. Utah Department of Transportation, Research Division.

41. Scopatz, B., J. DeFisher, and C. Lyon. Emerging Practices for Addressing Motorcycle Crashes at Intersections. Federal Highway Administration, FHWA-SA-18-045, 2018.

42. Shaheed, M. S., and K. Gkritza. A latent class analysis of single-vehicle motorcycle crash severity outcomes. Analytic Methods in Accident Research, Vol. 2, 2014, pp. 30-38. https://doi.org/10.1016/j.amar.2014.03.002

43. Shinkle, D., and A. Teigen. (2012). *Transportation review: Motorcycle Safety*. National Conference of State Legislatures, Denver, Colorado.

44. UDPS. *Motorcycle Involved - Portals*. https://udps.numetric.net/motorcycle-involved#/. Accessed May 18, 2022.

45. Utah SHSP. https://www.udot.utah.gov/shsp/motorcyclesafety.html. Accessed May 10, 2022.

46. Wali, B., A. J. Khattak, and A. Khattak.(2018). A Heterogeneity Based Case-Control Analysis of Motorcyclist Injury Crashes: Evidence from Motorcycle Crash Causation Study. *Accident Analysis & Prevention*, Vol. 119, pp. 202-214. https://doi.org/10.48550/arXiv.1808.06999

47. Wali, B., A. J. Khattak, N. Ahmad. (2019). Examining correlations between motorcyclist's conspicuity, apparel related factors and injury severity score: Evidence from new motorcycle crash causation study. *Accident Analysis & Prevention*, Vol. 131, pp. 45-62. https://doi.org/10.1016/j.aap.2019.04.009.

48. Wigan, M. (2002). Motorcycles as a Full Mode of Transportation. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 1818, pp. 39-46.

49. Williams, V., S. McLaughlin, J. Atwood, and T. Buche. (2016). *Factors that Increase and Decrease Motorcyclist Crash Risk*. Motorcycle Safety Foundation.

50. Wyoming Department of Transportation. Traffic Data Portal. http://www.dot.state.wy.us/home/planning_projects/Traffic_Data.html. Accessed February 25, 2022.

51. Wyoming Department of Transportation. *Motorcycle Safety*. https://www.dot.state.wy.us/MotorcycleSafety. Accessed May 18, 2022.

52. Wyoming Report on Traffic Crashes. http://www.dot.state.wy.us/home/dot_safety/crash-data/standard-crash-data.html. Accessed May 11, 2022.

53. Xin, C., et al. (2017). Safety Effects of Horizontal Curve Design on Motorcycle Crash Frequency on Rural, Two-Lane, Undivided Highways in Florida. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2637, pp. 1-8.

Appendix A: Motorcycle Operator Survey

Motorcycle Safety in Wyoming: A Survey

This survey is conducted as part of the project RS04222 “Assessment of Motorcycle Safety in Wyoming: Fatal and Severe Crashes, Contributing Factors and Potential Countermeasures”, sponsored by the Wyoming Department of Transportation (WYDOT)

Project link: https://rip.trb.org/view/1922380

Take this survey online (scan the code or link):

https://uwyo.sjc1.qualtrics.com/jfe/form/SV_0JJkeQWimB9C9fw

Contact: Dr. Milan Zlatkovic, University of Wyoming
mzlatkov@uwyo.edu

1. What is your residence (City/State, or zip): ______________________________

2. Which age category do you belong to:

   ☐ 19 years old or less
   ☐ 20 – 39 years
   ☐ 40 – 59 years
   ☐ 60 years or older

3. What is the level of motorcycle riding experience that best describes you (check all that apply):

   ☐ Motor officer

   ☐ Motorcycle safety instructor

   ☐ Regular / frequent rider

   ☐ Occasional (“weekend”) rider

   ☐ Law enforcement (non-motorcycle)
   (if not riding a motorcycle, skip to questions 10 – 14)

4. Approximately how many years of riding experience do you have? _________

5. In the past 3 (three) years, approximately how many miles have you ridden?
   ____

6. What best describes the motorcycle type you ride the most:

☐ Touring

☐ Cruiser

☐ Standard

☐ Sport

☐ Adventure

☐ Off-road / Trail

☐ Dual sport

☐ Scooter / moped

☐ Trike

☐ Other (please explain): ________________________

7. What is the engine size of the motorcycle you ride the most:

☐ 249 cc or less

☐ 250 – 649 cc

☐ 650 – 1,199 cc

☐ 1,200 cc or more

8. How do you maintain / improve your riding proficiency (check all that apply):

☐ Motorcycle safety courses

☐ Individual practice

☐ Motorcycle operator manuals

☐ Online resources and videos (YouTube, readings, blogs, personal materials, etc.)

☐ Other (please explain): __________________________________

9. Have you ever been personally involved in a motorcycle crash:

☐ Yes

☐ No

☐ Decline to answer

10. Based on your experience / opinion, what would be the most significant factors causing SINGLE motorcycle crashes (check all that apply):

☐ Motorcycle operator (aggressiveness, lack of skills, disregard for traffic control, etc.)

☐ Motorcycle failure (brakes, tires, steering, other systems)

☐ Speeding

☐ Roadway: curves

☐ Roadway: upgrades / downgrades

☐ Roadway: pavement quality / debris

☐ Weather (rain, hail, strong winds, etc.)

☐ Inadequate traffic control / signage / pavement markings

☐ Sight distances / visibility

☐ Animals on the road

11. Based on your experience / opinion, what would be the most significant factors causing MULTIPLE VEHICLE crashes with motorcycle involvement (check all that apply):

☐ Motorcycle operator (aggressiveness, lack of skills, disregard for traffic control, etc.)

☐ Drivers of other vehicles (aggressiveness, lack of skills, disregard for traffic control, etc.)

☐ Failure of the motorcycle operator to notice other traffic

☐ Failure of the vehicle driver to notice the motorcycle

☐ Motorcycle failure (brakes, tires, steering, other systems)

☐ Other vehicle(s) failure

☐ Speeding

☐ Roadway: curves

☐ Roadway: upgrades / downgrades

☐ Roadway: pavement quality / debris

☐ Weather (rain, hail, strong winds, etc.)

☐ Inadequate traffic control / signage / pavement markings

☐ Sight distances / visibility

12. Based on your experience / opinion, on the scale of 1 (most important) to 6 (least important), rank the STRATEGIES that could reduce the number and severity of motorcycle crashes:

Strategy:	Rank (1 to 6):
Education and training	
Enforcement	
Helmet use requirement	
Road maintenance	
Upgrades to traffic control / signage / markings	
Installation of motorcycle safety devices on the road (e.g. motorcycle crash barriers)	

13. Based on your experience / opinion, on the scale of 1 (most important) to 5 (least important), rank the preventive measures that MOTORCYCLE RIDERS should take to reduce the probability of crashes and severity of injuries:

Preventive measure:	Rank (1 to 5):
Continuous education and training	
Wearing proper riding gear	
Wearing a helmet	
Regular and proper motorcycle maintenance	
Respecting traffic control and rules of the road	

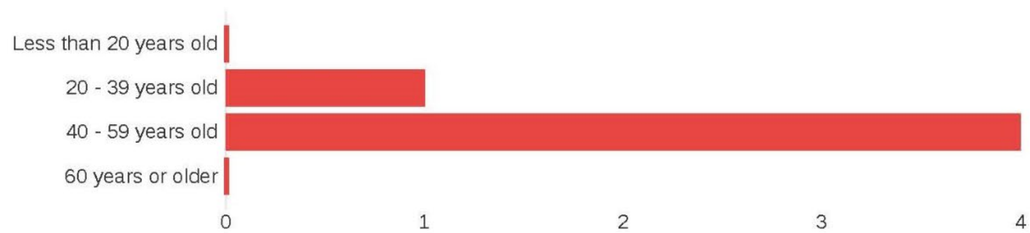
14. Please provide any additional comments you might have that could help improve motorcycle safety in Wyoming.

Appendix B: Motorcycle Operator Survey Results

Q1 - 1. What is your residence (City/State, or zip code)

1. What is your residence (City/State, or zip code)
82001
82001
Cheyenne way 82007
82072
82070

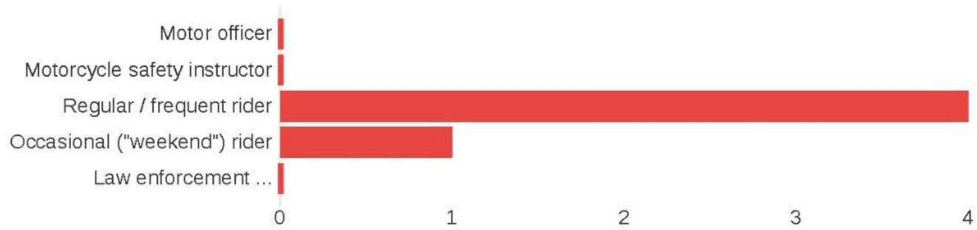
Q2 - 2. Which age category do you belong to?



Field	Min	Max	Mean	Standard Deviation	Variance	Responses
2. Which age category do you belong to?	2	3	3	0	0	5

Field	Choice Count
Less than 20 years old	0
20 - 39 years old	1
40 - 59 years old	4
60 years or older	0
Total	5

Q3 - 3. What is the level of motorcycle riding experience that best describes you (check all that apply):



Field	Choice Count
Motor officer	0
Motorcycle safety instructor	0
Regular / frequent rider	4
Occasional ("weekend") rider	1
Law enforcement (non-motorcycle) (if not riding a motorcycle, skip to Questions 10 - 14)	0
Total	5

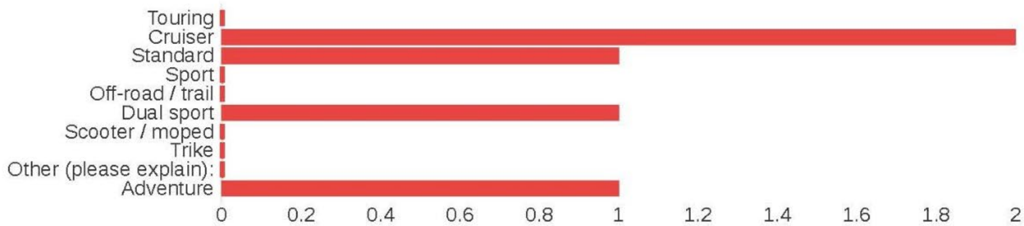
Q4 - 4. Approximately how many years of riding experience do you have?

4. Approximately how many years of riding experience do you have?
20
4
40
20
10

Q5 - 5. In the past 3 (three) years, approximately how many miles have you ridden a motorcycle?

5. In the past 3 (three) years, approximately how many miles have you ridden a motorcycle?
20,000
1200
6000
20,000
4000

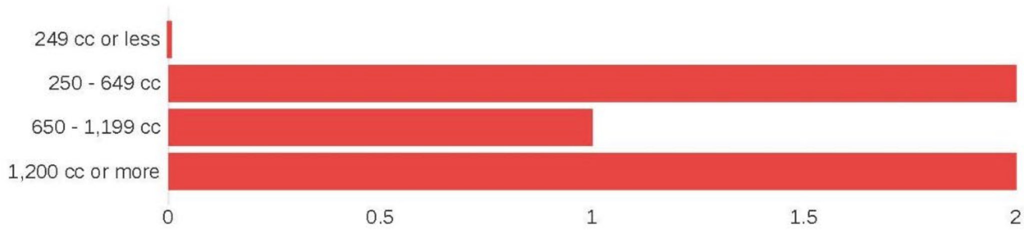
Q6 - 6. What best describes the type of the motorcycle you ride the most:



Field	Min	Max	Mean	Standard Deviation	Variance	Responses
6. What best describes the type of the motorcycle you ride the most: - Selected Choice	2	10	5	3	9	5

Field	Choice Count
Touring	0
Cruiser	2
Standard	1
Sport	0
Off-road / trail	0
Dual sport	1
Scooter / moped	0
Trike	0
Other (please explain):	0
Adventure	1
Total	5

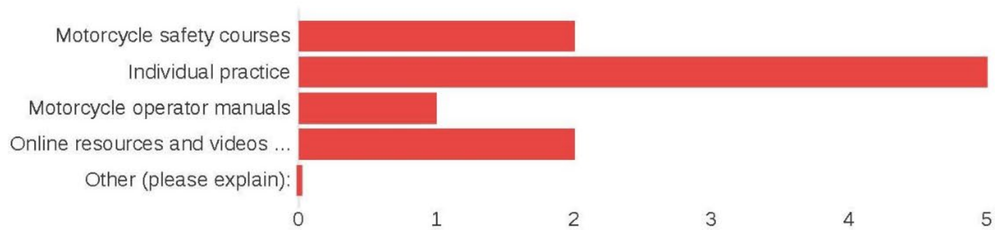
Q7 - 7. What is the engine size of the motorcycle you ride the most:



Field	Min	Max	Mean	Standard Deviation	Variance	Responses
7. What is the engine size of the motorcycle you ride the most:	2	4	3	1	1	5

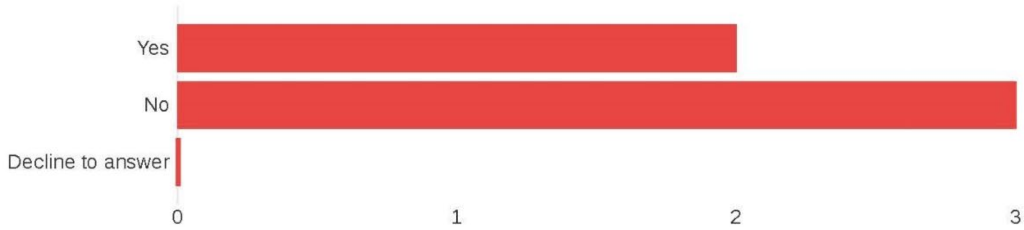
Field	Choice Count
249 cc or less	0
250 - 649 cc	2
650 - 1,199 cc	1
1,200 cc or more	2
Total	5

Q8 - 8. How do you maintain / improve your riding proficiency (check all that apply):



Field	Choice Count
Motorcycle safety courses	2
Individual practice	5
Motorcycle operator manuals	1
Online resources and videos (YouTube, readings, blogs, personal materials, etc.)	2
Other (please explain):	0
Total	10

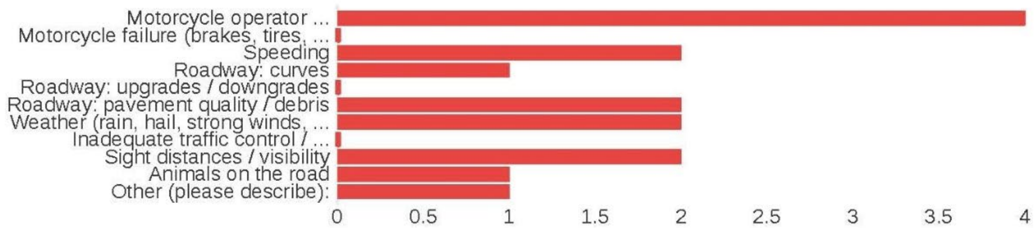
Q9 - 9. Have you ever been personally involved in a motorcycle crash:



Field	Min	Max	Mean	Standard Deviation	Variance	Responses
9. Have you ever been personally involved in a motorcycle crash:	1	2	2	0	0	5

Field	Choice Count
Yes	2
No	3
Decline to answer	0
Total	5

Q10 - 10. Based on your experience / opinion, what would be the most significant factors causing SINGLE motorcycle crashes (check all that apply):

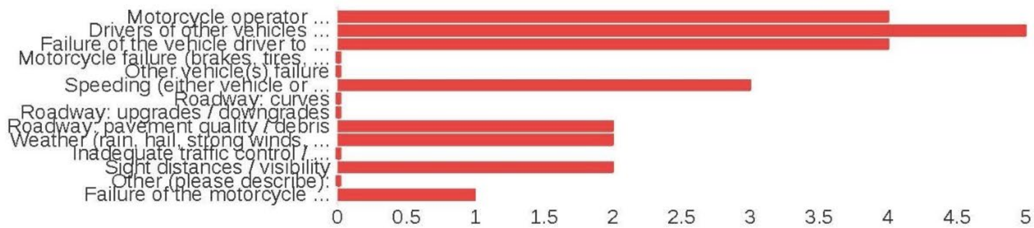


Field	Choice Count
Motorcycle operator (aggressiveness, lack of skills, disregard for traffic control, etc.)	4
Motorcycle failure (brakes, tires, steering, other systems)	0
Speeding	2
Roadway: curves	1
Roadway: upgrades / downgrades	0
Roadway: pavement quality / debris	2
Weather (rain, hail, strong winds, etc.)	2
Inadequate traffic control / signage / pavement markings	0
Sight distances / visibility	2
Animals on the road	1
Other (please describe):	1
Total	15

Other (please describe): - Text

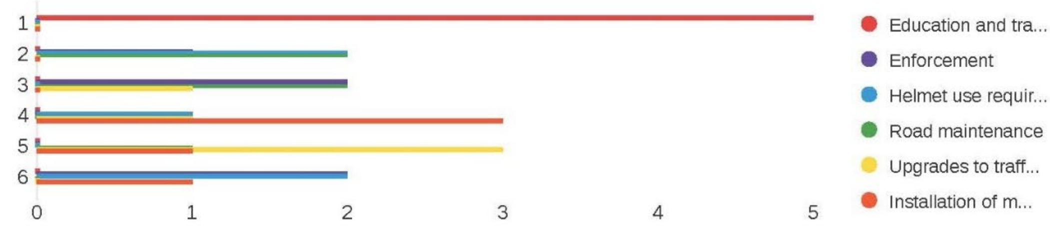
Motorvehcicles, other drivers lack of attention

Q11 - 11. Based on your experience / opinion, what would be the most significant factors causing MULTIPLE VEHICLE crashes with motorcycle involvement (check all that apply):



Field	Choice Count
Motorcycle operator (aggressiveness, lack of skills, disregard for traffic control, etc.)	4
Drivers of other vehicles (aggressiveness, lack of skills, disregard for traffic control, etc.)	5
Failure of the vehicle driver to notice the motorcycle	4
Motorcycle failure (brakes, tires, steering, other systems)	0
Other vehicle(s) failure	0
Speeding (either vehicle or motorcycle)	3
Roadway: curves	0
Roadway: upgrades / downgrades	0
Roadway: pavement quality / debris	2
Weather (rain, hail, strong winds, etc.)	2
Inadequate traffic control / signage / pavement markings	0
Sight distances / visibility	2
Other (please describe):	0
Failure of the motorcycle operator to notice other traffic	1
Total	23

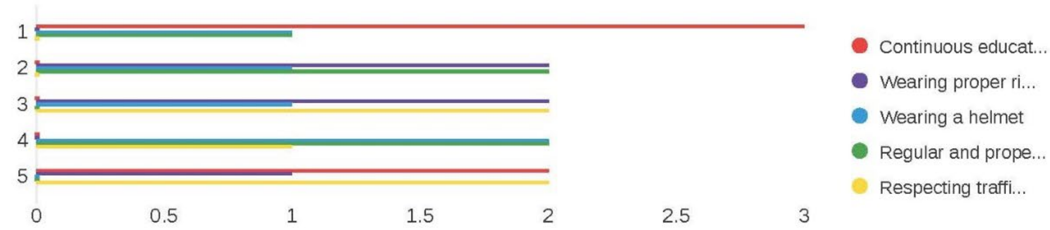
Q12 - 12. Based on your experience / opinion, on the scale of 1 (most important) to 6 (least important), rank the STRATEGIES that could reduce the number and severity of motorcycle crashes (drag the answers to create a list):



Field	Min	Max	Mean	Standard Deviation	Variance	Responses
Education and training	1	1	1	0	0	5
Enforcement	2	6	4	2	3	5
Helmet use requirement	2	6	4	2	3	5
Road maintenance	2	5	3	1	1	5
Upgrades to traffic control / signage / pavement markings	3	5	4	1	1	5
Installation of motorcycle safety devices on the road (e.g. motorcycle crash barriers)	4	6	5	1	1	5

Field	1	2	3	4	5	6	Total
Education and training	5	0	0	0	0	0	5
Enforcement	0	1	2	0	0	2	5
Helmet use requirement	0	2	0	1	0	2	5
Road maintenance	0	2	2	0	1	0	5
Upgrades to traffic control / signage / pavement markings	0	0	1	1	3	0	5
Installation of motorcycle safety devices on the road (e.g. motorcycle crash barriers)	0	0	0	3	1	1	5

Q13 - 13. Based on your experience / opinion, on the scale of 1 (most important) to 5 (least important), rank the preventive measures that MOTORCYCLE RIDERS should take to reduce the probability of crashes and severity of injuries (drag the answers to create a list):



Field	Min	Max	Mean	Standard Deviation	Variance	Responses
Continuous education and training	1	5	3	2	4	5
Wearing proper riding gear	2	5	3	1	1	5
Wearing a helmet	1	4	3	1	1	5
Regular and proper motorcycle maintenance	1	4	3	1	1	5
Respecting traffic control and rules of the road	3	5	4	1	1	5

Field	1	2	3	4	5	Total
Continuous education and training	3	0	0	0	2	5
Wearing proper riding gear	0	2	2	0	1	5
Wearing a helmet	1	1	1	2	0	5
Regular and proper motorcycle maintenance	1	2	0	2	0	5
Respecting traffic control and rules of the road	0	0	2	1	2	5

Q14 - 14. Please provide any additional comments and recommendation which, in your opinion, could help improve motorcycle safety:

14. Please provide any additional comments and recommendation which, in your opinion, could help improve motorcycle safety:
Keep your head and eyes up.
More awareness training as part of licensing an auto driver
I think the motorcycle rider needs to operate defensively and assume other vehicles do not see them.