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Multinomial Logistic Regression Modeling of Motorcycle Crash Severities - Wyoming Case Study

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ABSTRACT

Motorcycle riders and passengers are much more likely to be killed or severely injured in a crash, and on average about 15% of all traffic fatalities include motorcyclists. Between 2008 and 2019, the average motorcycle crash frequency in Wyoming was 286 crashes/year, 17 of those being fatal. This paper assesses injury severity of motorcycle-related crashes in Wyoming using 12 years of motorcycle crash data and applying multinomial logistic regression modeling to determine the odds ratios for injury severity. Four models were developed and analyzed, based on the setting and the number of vehicles involved. The most common factors affecting injury severity 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 urban areas, and in rural areas with multi-vehicle involvement. Certain vehicle maneuvers are also associated with a more severe crash outcome.

1. Introduction

Motorcycle fatalities comprise a large percentage of traffic fatalities in the U.S., in excess of 15% (National Motorcycle Institute, n.d.), and are closely followed by serious injuries. According to the National Highway Traffic Safety Administration (NHTSA), the mean fatality crash rate for motorcycles is more than six times higher than that for passenger cars, and motorcycle account for about 0.6% of all Vehicle Miles Traveled (VMT) (NHTSA, 2021). Between 2015 and 2019, the average number of motorcycle fatalities in the 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.). In 2019, there were 13 motorcycle fatalities in Wyoming, representing 9% of all traffic fatalities in the State. The State of Wyoming does not have a comprehensive helmet requirement law, and the helmet is only required for riders and passengers aged 17 or younger, with the exception of mopeds (IIHS, 2022). Of all motorcycle fatalities in Wyoming, it is estimated that 57% were not using a helmet (NHTSA, 2021).

The goal of this paper is to assess the significance of crash characteristics and the most common contributing factors on motorcycle crash injury severities in Wyoming. The data used in the analysis is 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, driver condition and action (e.g. riding under the influence or speeding), are some of the most common factors attributed to motorcycle crashes. Motorcycle riders and passengers are overrepresented in traffic fatalities. It is generally accepted that motorcycle crashes result in higher severity due to the exposure of the riders and the lack of construction and restrain elements, which exist in other vehicle types. Even though efforts are being made to improve motorcycle safety, a more proactive and collaborative approach is needed to address this issue.

The research presented in this paper assesses the correlation between different characteristics and factors, and their individual and mutual effects on motorcycle crash severities. Furthermore, where some continuous and nominal/ordinal categorical variables were dichotomized in previous research (e.g., drivers' age: young vs. old), this study utilizes continuous and categorical predictors as they are - without arbitrary dichotomization - which provides a better insight into their effects. Four multinomial logistic regression models were developed and analyzed in this research: (1) rural single motorcycle crashes; (2) rural multi-vehicle motorcycle-related crashes; (3) urban single motorcycle crashes; (4) urban multi-vehicle motorcycle-related crashes. The separate assessment was performed as it was initially found that the characteristics and contributing factors differ based on the setting (urban or rural), and the number of vehicles involved in a motorcycle crash (single or multi-vehicle). This study does not address various types of facilities in rural and urban areas, and this will be the topic of future research. The paper is organized in six sections. The next section provides an overview of selected literature related to motorcycle crashes, severities, and contributing factors. It is followed by the description of the data used in the research. Chapter four describes the research methodology and modeling process, followed by the results and discussion section. The conclusions of the paper are provided in section six.

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 and Knoflacher, 2017). Due to the lower use of resources and less required space, motorcycles can contribute to more sustainable transportation systems (Jittrapirom and Knoflacher, 2017; Rose et al, 2012). The motorcycle can utilize up to five times less space than a car (Jittrapirom and Knoflacher, 2017; Bakker, 2018), consumes less energy in production and operation, and emits less CO2 (Pfaffenbichler and Circella, 2009). However, motorcycles are usually treated solely on the basis of their safety characteristics (Wigan, 2002). This is due to the fact that 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% of all traffic fatalities. No systematic motorcycle transportation policy exists, although steps have been taken to develop an active motorcycle safety agenda. Over the years, researchers have been analyzing motorcycle safety with the aim to determine the most common contributing factors, severity levels and potential countermeasures to reduce motorcycle crash frequencies, or their severities. Various approaches have been used in motorcycle safety research. A study using the naturalistic motorcycle driving study analyzed the most common crash and near-crash occurrences, types and contributing circumstances (Williams et al, 2016). It found that the most common incident type was a ground impact at low speeds (in 57% of recorded incidents), which includes maneuvers at low speeds (parking, slow turns, U-turns and similar). It was followed by road departures, and other vehicles turning across the motorcycle path (10% each of total crashes). Motorcycles rear-ending other vehicles were represented by 7% of all motorcycle-related crashes. Other crash types were represented by 3% or less. The Motorcycle Crash Causation Study (MCCS), sponsored by the Federal Highway Administration (FHWA), performed a detailed analysis on 351 on-scene crash investigations and 702 control cases with motorcycle involvement, aimed at identifying the factors leading to crashes and the resulting injuries (Nazametz et al, 2019). The study found that 40 crashes (11.4%) were fatal, 269 crashes (76.6%) involved multiple vehicles, and 22 fatalities (26.8%) were single vehicle cases. Close to 80% of multi-vehicle crashes were intersection-related. The absence of traffic control, horizontal curves, roadside fixed objects, view obstructions were some of the common contributing circumstances found in the study. Another study focused on crash occurrence on horizontal curves of rural two-way undivided highways in Florida (Xin et al, 2017). The authors used a random-parameters negative binomial (RPNB) model to assess the factors that determined the occurrence of motorcycle crashes. The study found that the horizontal curve radius significantly influences motorcycle crash occurrence on these types of roads. Particularly horizontal curves with the radius of less than 460 m were found to increase the likelihood of motorcycle crashes and the probabilities of severe injuries. Similarly, a study conducted in Norway applied a matched case-control study design to analyze the safety effects of horizontal curves, lane and shoulder widths on single-motorcycle crashes (Kvasnes et al, 2021). The study found significant effects of sharp horizontal curves (less than 200 m) on single-motorcycle crash occurrences. A significant number of motorcycle-related multi-vehicle crashes in urban areas occur at intersections. These crashes also result in more fatalities, where about 30% of fatal motorcycle crashes occur at intersections (Scopatz et al, 2018). As motorcycle crashes result in more fatalities and serious injuries, research efforts have been focused on analyzing motorcycle crash severities and contributing factors using various methods. A 2006 study using crash data from Indiana applied nested logit and multinomial logit models to assess motorcyclists' injury severities in single and multi-vehicle crashes (Savolainen and Mannering, 2007). The results showed that increasing age is correlated with more severe injuries, and that collision type, roadway characteristics, alcohol, helmet use and unsafe speed were all significant factors related to injury severity. A recent study on single motorcycle crashes explored the effects of motorcyclists' age in combination with other factors using the mixed logit model and crash data from Florida (Islam, 2021). The results indicated inter-correlation between different factors and age (e.g. speeding, helmet use, alcohol consumption, motorcycle type, etc.). As an example, the study found that not wearing a helmet increases the likelihood of fatal injury for the age group of 50 and above, while it decreases for the middle age group (30–49). However, not wearing a helmet increases the likelihood of severe injury for the middle age group, but decreases it for the older age group. This study also showed the importance of analyzing multiple factors in combination when it comes to the injury severity outcomes of motorcycle crashes. Another study used 20 years of crash data from Pennsylvania and an integrated spatiotemporal analytical approach to assess 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 and latent class multinomial logit models examined the factors affecting single-vehicle motorcycle crash severity outcomes (Shaheed and Gkritza, 2014). This research found a significant relationship between severe motorcycle crash injuries and factors such as speeding, run-off road, collision with fixed object, overturn or rollover, riding on high-speed and rural roads, rider's age more than 25, not using a helmet, and riding under the influence. A study using motorcycle crash data from Texas applied multinomial logit models to identify differences in factors affecting motorcycle crash injury severity (Geedipally et al, 2011). The analysis was performed on crashes in urban and rural areas. The results showed that alcohol, gender, lighting, and horizontal and vertical curves have significant impact on motorcyclists' injury severity in urban areas. In rural areas, the significant factors affecting injury severity were found to be similar as in urban areas, with the addition of motorcyclists' age (older than 55), single-vehicle crashes, angular crashes, and divided highways. A previous research study on motorcycle safety in Wyoming applied binary and mixed binary logistic models with random parameters to assess the injury severity of single and multi-vehicle motorcycle-related crashes (Farid and Ksaibati, 2021). The study found that the most severe single motorcycle crashes involve collisions with animals and traffic barriers, followed by horizontal curves and older drivers. Riding under the influence and on roads with higher posted speed limits resulted in higher severity for both single and multi-vehicle crashes.

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. Multinomial logit models were applied in several studies, as it was shown that the crash variables are inter-correlated and, when combined, have different effects on severity outcomes than when observed as isolated. This paper adds to the current body of knowledge on motorcycle-related crash injury severity by exploring different types of crashes based on the setting and the number of vehicles involved, and the combination of factors affecting each type. The study is using the multinomial logistic regression to determine the individual and mutual effects of different characteristics and factors on motorcycle crash severities.

3. Data Preparation and Description

The study presented in this paper uses 12 years of Wyoming crash data (2008-2019) obtained through WYDOT's CARE crash database, as well as the Average Annual Daily Traffic (AADT) data obtained from WYDOT's traffic data portal (WYDOT, 2022). The crash data include separate databases on crash, vehicle and person levels. As this study only focuses on the crash-level, the databases were combined to extract the needed parameters (e.g. helmet use exists in the person database, so it was matched using the crash ID number). The AADT data were matched to the crash data using the route number, direction and milepost, for each year separately. However, it is worth noting that the AADT data were not available for each crash (58% of recorded motorcycle crashes have corresponding AADT data). 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 crash factors used in this research include the crash case number, year, month, day, number of vehicles (single and multi-vehicle), setting (urban and rural), route, AADT, manner of collision, vehicle maneuver, driver action, junction relation, lighting, weather, driver age and gender, alcohol, wild animal and speeding involvement, helmet use, and crash severity (KABCO scale). The breakdown of 12-year motorcycle crashes with respect to the number of vehicles and setting is provided in Table 1.

The number of total motorcycle-related crashes had a decreasing trend from 2008 to 2019, with the exception of 2015. The percentage of fatal (K) and incapacitating (A) crashes combined varied between 25% and 37% of total motorcycle-related crashes during the 12 year period, as shown in Figure 1, with the average of 31.2%.

The monthly motorcycle-related crash frequencies follow a normal distribution trend, meaning that the majority of crashes occur during the summer months (May-Sep), with the peak in August (28% of total yearly crashes).

Table 1. 12-Years Motorcycle-Related Crash Frequencies in Wyoming

Type	Total	Fatal (K)	Incapacitating (A)	Non-incapacitating (B)	Possible (C)	No injury (O)	Unknown
Single	2,058	115	583	920	273	85	82
Multi	1,371	87	292	436	235	101	220
Rural	1,601	143	563	614	166	106	9
Urban	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
Urban Single	833	24	150	421	146	17	75
Urban Multi	995	35	162	321	196	63	218

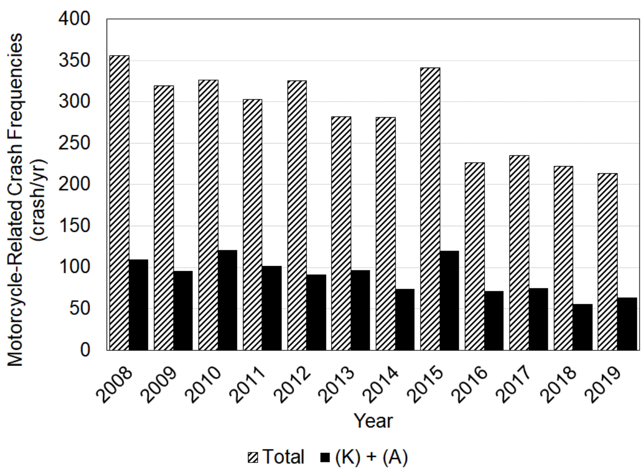

Figure 1. Total and (K) + (A) Motorcycle-Related Crashes in WY 2008 – 2019

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

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

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 performs a multinomial logistic regression analysis using the 12 years of crash data.

4. Research Methodology

Multinomial logistic regression (MLN) is a promising approach in analyzing crash severities, since it does not require an assumption of the trends in the dataset and can be applied to categorical variables, which are common in safety data (Abdulhafedh, 2017). Furthermore, injury severity levels are often divided into two categories (e.g. fatal + incapacitating injury, and others), making it suitable to apply binary logit or probit models (Abdulhafedh, 2017; Kononen et al, 2011). MLN models can consider three or more discrete outcomes, which is the case with the crash database used in this study with a total of five severity outcomes (fatal, incapacitating injury, non-incapacitating injury, possible injury, and no injury). The crashes of unknown severity were not considered for inclusion in the models.
The general formulation of the MLN model is as follows (Greene, 2012):

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

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 unknown), and $\boldsymbol{\alpha}_\mathbf{j}$ is the vector of regression coefficients.

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

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

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

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

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

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

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

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

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

5. Results and Discussion

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

5.1. Rural Single MLN Model

Table 2 shows the MLN 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, 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 the odds of crash severities.

Table 2. Rural Single MLN Model and Odds Ratios

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

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

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

5.2. Rural Multi-Vehicle MLN Model

The results for the rural multi-vehicle MLN model are given in Table 3. 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, 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 which 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 3. Rural Multi-Vehicle MLN Model and Odds Ratios

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

Note. LR value = 170.19, p-value < 0.001. McFadden's R^2 = 0.23301. * = significant at the 0.05 level, ** = significant at the 0.01 level, *** = significant at the 0.001 level.
Reference levels: *Crash Severity*: No Injury; *Junction Relation*: Non-Junction; *Veh. Maneuver*: Straight; *Alcohol Involved*: No; *Speed Involved*: No; *Helmet*: Helmet Used

5.3. Urban Single MLN Model

The resulting coefficients and odds ratios of the MLN model for urban single motorcycle crashes are presented in Table 4. 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 4. Urban Single MLN Model and Odds Ratios

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

Note. LR value = 366.52, p-value < 0.001. McFadden's R^2 = 0.10103. * = significant at the 0.05 level, ** = significant at the 0.01 level, *** = significant at the 0.001 level.
Reference levels: *Crash Severity*: No Injury; *Junction Relation*: Non-Junction; *Weather*: Clear; *Driver Action*: No Improper Driving; *Alcohol Involved*: No; *Animal Involved*: No; *Speed Involved*: No; *Helmet*: Helmet Used

5.4. Urban Multi-Vehicle MLN Model

Table 5 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 5. Urban Multi-Vehicle MLN Model and Odds Ratios

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

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

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

6. Conclusions

Motorcycle riders and passengers are much more likely to be killed or severely injured in a crash, and on average about 15% of all traffic fatalities include motorcyclists. There are multiple factors that affect the crash occurrence and severity outcome of motorcycle-related crashes. This paper performs a crash-level analysis on 12 years of motorcycle-related crash data from Wyoming to determine the effects of various factors on the crash severity level.

The analysis was performed though multinomial logistic regression modeling 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; (4) urban multi-vehicle motorcycle-related crashes. For each model, the significant exposure measures were first determined, and then their odd ratios were computed to determine the association between the exposure and outcome, using no injury as the outcome reference level. In all four models, it was found that speeding and alcohol involvement increase the odds of any injury crash multifold. Additionally, for single motorcycle crashes, vehicle maneuver and driver action exposure measures were found to have significant effects on injury level. Helmet use can reduce the odds of fatal and serious injuries in single motorcycle crashes. For multi-vehicle crashes, it was found that junction relation and vehicle maneuver exposure measures have significant effects on odds ratios of injury crashes compared to no injury. Additionally, road and weather conditions impact injury severity level in single rural motorcycle crashes, while weather also impacts severity level in single urban motorcycle crashes. Manner of collision factors have additional effects on the severity of urban multi-vehicle motorcycle related crashes. Helmet use is found to reduce the odds of fatality and non-incapacitating injuries in urban multi-vehicle crashes.

The results of the study presented in this paper can provide guidance on selecting proper engineering, education and enforcement measures which have the potential to reduce the occurrence and severity of motorcycle-related crashes. However, in order to provide effective countermeasures, more analysis is needed to determine the detailed specifics of motorcycle-related crashes. Therefore, this study is the first step in a comprehensive assessment of motorcycle-related crashes in Wyoming.

The next steps will include analysis on vehicle and person levels, to better understand the relationships and dynamics of contributing factors, including additional exposure measures which do not exist on the crash-level.

The results of the current study can lead to several practical recommendations on low-cost countermeasures that would have the possibility to reduce the frequency and severity of motorcycle-related crashes. The installation of traffic signs, such as curve warning, animal warning, warning for gravel on the roadway, grooved payment and rough road, wind warning and no-passing zones at appropriate locations in rural areas could directly address some of the contributing factors in rural motorcycle crashes. The installation of motorcycle-friendly crash barriers at sharp curves would reduce the severity of run-off-road motorcycle crashes potentially occurring at this locations. Pavement sealant used to fill cracks in the pavement, especially if applied longitudinally in horizontal curves, when combined with the motorcycle turning dynamics, can cause a loss of traction and a dangerous situation for the motorcyclist, leading to a potential crash. It is recommended to avoid this type of sealant application, especially in the vicinity of sharp horizontal curves. As the presence of junctions is one of the major contributing factors in multi-vehicle rural motorcycle crashes, more attention should be given to the sufficient intersection sight distances and approach speed control. The same recommendation can apply to intersections in urban areas. The helmet use law in Wyoming, as well as other states, should be stricter, as the results show an increase in the odds for severe motorcycle crashes when helmets are not used. More speed and driving under the influence education and enforcement should be implemented in all settings. As this research progresses, more location-specific measures will be recommended for implementation.

The limitations of the presented study are mainly related to the missing or biased data included in the crash-level datasets (e.g. many reports did not record the severity level, helmet use, or other factors, and there are no AADT values for many routes). There might be possible errors in some factors which were imported from other databases, although this would be minimal as the crash ID was used for this purpose. Furthermore, except for certain sections of interstates in Wyoming, no motorcycle volume data exist in the databases, so the correct motorcycle percentages can only be estimated or assumed. In follow-up research, some of these limitations will be overcome by using more information provided in the vehicle and person-level crash databases.

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