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A Random Parameters Approach to Investigate Injury Severity of Two-Vehicle Crashes at Intersections

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Abstract: Roadway intersections are crash-prone locations and, hence, ensuring the safety of road users at intersections has been a major concern for transportation professionals. It is critical to identify the risk factors that contribute to severe crashes at intersections to implement the appropriate countermeasures. Greater emphasis is needed on two-vehicle crashes since they represent the majority of intersection crashes. In this study, a random parameter ordinal probit model was developed to estimate the contributing factors of injury severity of two-vehicle crashes at intersections. Nine years of intersection crash data in Wyoming were analyzed in this model. The study involved the investigation of the influence of a set of intersection, drivers, environmental, and crash characteristics on crash injury severity. The results demonstrated urban and signalized intersections were related to lower severity levels. In addition, higher pavement friction is more likely to be associated with less severe crashes. Crashes that involved drivers who are females or impaired and crashes on weekends were associated with higher severity levels. Intersection crashes that occurred on non-dry road surfaces, in adverse weather conditions, or that involved large vehicles, or out-of-state drivers were less likely to be severe.

Keywords: crash injury severity; pavement friction; intersection safety; driver attributes; unobserved heterogeneity effects; random parameters

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1. Introduction

Intersections are commonly recognized as crash hotspots on roadway networks. Intersection crashes are likely to be severe since they are responsible for more than 20% of all traffic-related fatalities and more than 40% of crash injuries in the US as per the Federal Highway Administration (FHWA). Intersections are considered hazardous locations due to complex conflicting traffic movements from different road users in addition to disregarding traffic controls [1–7].

Two-vehicle crashes are the most common crash type at intersections. From 2016 to 2020, two-vehicle crashes represented more than 82% of the total crash count at intersections in the US. They were also responsible for more than 57% and 75% of fatalities and injuries at intersections, respectively. Increasing traffic volumes, emerging technologies in traffic management, and developing vehicle automation are adding to the complexity of intersection safety management. Traffic control and safety at intersections can be even more challenging with multimodal operations [8–14].

Various roadway, environmental, crash, and driver characteristics contribute to the frequency and severity of intersection-related crashes. Among these roadway characteristics is pavement surface friction, which is a major influencer of crash counts and injury severity. Pavement friction is the resisting force eliminating the relative motion between the vehicle tires and the pavement surface [15,16]. The friction levels deteriorate with time due to the aggregate polishing under traffic movements. Therefore, the friction levels

should be consistently monitored. The FHWA recommends using continuous pavement friction measurement (CPFM) to continuously measure pavement friction on road segments along with specific locations such as curves, ramps, and intersections [17,18]. Elkhazindar et al. [19] aimed to survey pavement friction management policies among State DOTs. The results presented that only eleven DOTs collect friction data on specific road characteristics by request, to examine safety concerns. Increasing rates of wet pavement crashes are commonly the major safety concern initiating friction data collection at such locations.

Wet pavement crashes are commonly linked to skid resistance since friction force is significantly reduced by wet pavement conditions. Dry pavements can face the same issue if available friction is considerably less than the design criteria for the roadway [16,20,21]. Wet pavement crashes are a common issue in the state of Wyoming, since it has one of the highest snowfall rates in the United States, with more than 30% of crashes in the state occurring on non-dry road surfaces [13,22]. Pavement surface treatments play a major role in providing sufficient friction levels and ensuring intersection safety. Chip seals, micro-milling, open-graded friction course (OGFC), and high friction surface treatments (HFST) are some of the surface treatments that can be used as spot applications to increase pavement friction levels at locations with higher friction demand, such as intersections [20,23,24]. Crash analysis studies have shown a strong correlation between insufficient friction supply, the likelihood of crash occurrence, and the incurring of severe injuries [25–28].

The complexity of the interaction between predictors and omitted variable bias has been challenging for road safety researchers. Therefore, there has been increasing interest in random parameters, also known as mixed modeling approaches. Random parameter models can account for the unobserved heterogeneity effects of the contributing factors on the response. Accounting for the unobserved heterogeneity effects and omitted variable bias results in more accurate estimates of the predictors' effects [22,29–33]; the quantification of the effects of crash contributing factors on injury severity is critical to alleviating intersection safety concerns [32,33].

Srinivasan [34] proposed an ordered random parameter mixed logit to investigate the crash injury severity. The modeling results detected systematic variations within the crash severity thresholds depending on individual, traffic, crash-related, and vehicle characteristics. Christoforou et al. [31] developed a random parameter ordered probit model to examine the injury severity of vehicle occupants. The study results showed how this modeling approach addressed the differential influence of the modeled independent variables and how using an ordinary ordered probit model could create biased results due to neglecting unobserved heterogeneity effects.

The objective of this study was to examine the role of roadway and driver characteristics in two-vehicle crash severity at intersections. The study investigated the influence of pavement surface friction which is a commonly omitted risk factor. This work included developing a random parameter ordinal probit model to explore the influence of crash, driver, environmental, and roadway characteristics on the injury severity of two-vehicle crashes at intersections.

2. Literature Review

Traffic crash severity can be attributed to a wide set of roadways, road user, environmental, and crash characteristics. Traffic safety researchers have attempted to examine the impact of road user's attributes on intersection crash probability and injury severity. This section reviews multiple studies related to injury severity of two-vehicle crashes at intersection, along with the influence of driver characteristics and pavement friction on crash severity. The limitations of the reviewed studies are identified, and this study contribution is discussed. The studies [35–39] had a common limitation as they did not consider pavement friction in the analyses.

Chen et al. [35] developed a logistic regression model to analyze the risk factors impacting intersection crash severities for drivers and vulnerable road users. The study identified seven significant factors associated with intersection crash severity. They were

the driver's age, driver's gender, speed limit, traffic control, time of day, crash type, and restraints usage. The authors found that older male drivers (older than 65) are more likely to be involved in a fatal intersection crash. Furthermore, crashes involved pedestrians and non-use of restraints have a higher fatality likelihood.

Lombardi et al. [36] developed a multivariate logistic regression model to evaluate the association between the driver's age and gender and fatal intersection crashes. The research team explored 48,733 fatal intersection crashes from 2011 to 2014 in the US. The results of this study demonstrated that teenagers and elderly drivers (55+ years) are more likely to be involved in fatal intersection crashes unlike drivers aged 20 to 54. The risk of fatal crashes was doubled for all drivers above 85 years old. The impact of crash-related factors differed considerably between drivers younger and older than 65 years old. These factors included lighting, time of day, weather, day of the week, roadway type, number of lanes, traffic control, speed limit, and driving speed.

Kidando et al. [2] examined real-time traffic and signal data to study the occupant injury severity of signalized intersection crashes. The findings demonstrated that senior drivers (65+) are less likely to be involved in severe crashes at signalized intersections. On the contrary, female drivers are more likely to be involved in severe crashes, compared to male drivers. The authors did not consider any of the road surface characteristics in the analysis.

Gong et al. [37] utilized a random parameter multinomial logit model to identify the most influential risk factors in two-vehicle crashes. The study identified several risk factors impacting the driver's injury severity at intersection and non-intersection crashes. As per the results, female drivers and elderly drivers (older than 65) were more likely to be involved in severe crashes. However, the results also showed that two-vehicle crashes at intersections were less likely to incur severe injuries relative to non-intersection crashes. This could be related to the decreased speed of vehicles approaching the intersections. Other previous studies had contradictory results while identifying the age group of drivers at risk.

Sharafeldin [40] developed an ordinal probit model to study the contributing factors to intersection crash severity. The study considered a set of roadway attributes and environmental conditions as the explanatory variables. The results showed that sufficient pavement friction levels would mitigate the crash severity. In addition, crashes in urban areas and crashes on non-dry road surfaces are less likely to be severe. Although the study incorporated pavement friction, the authors only considered roadway and environmental factors and did not incorporate any of the driver's or crash characteristics, including the number of crashing vehicles.

Zhang [38] developed an ordered probit model to study the driver injury severity at intersections. The study examined the US DOT-Fatality Analysis Reporting System (FARS) crash records for the year 2011. The study considered various driver, vehicle, and crash characteristics including the number of vehicles involved in the crash. The results showed that older drivers, females, drivers under the influence, and drivers in smaller vehicles are more likely to sustain severe injuries.

Yuan [39] developed mixed logit models to analyze the injury severity of two-vehicle crashes at unsignalized intersections. The authors examined crash, environmental, driver, and vehicle attributes as potential risk factors. The study considered the vehicle characteristics separately depending upon whether it is the striking or struck vehicle. The authors reported that crashes that occurred in rural area, on weekends, or that involved teen drivers are more likely to be severe. In addition, crashes under adverse weather conditions were less likely to cause severe injuries.

Sharafeldin [41] examined the contributing factors to crash injury severity at intersections. The authors developed a Bayesian ordinal probit model to analyze the crash records of the state of Wyoming. The study identified several significant factors affecting crash severity, including pavement friction. Although the authors incorporated pavement

friction in the model, the study investigated a limited dataset and did not consider driver characteristics, or the number of vehicles involved in the crash.

The drivers' characteristics play a major role in intersection crash injury severity as previously noted. Even though two-vehicle crashes are by far the most common crashes at intersections, the role of driver's attributes in the severity of these crashes is not fully examined. In addition, pavement friction is a commonly omitted variable in crash safety analyses. Pavement friction has a direct relation to the driver's attributes since the safety role of friction is related to the driver's reaction and driving behavior. To the best of the authors' knowledge, no study has yet to examine the impact of pavement friction on the injury severity of two-vehicle intersection crashes. This study explored the relationship between several road attributes, driver characteristics, environmental conditions, and their influence on the injury severity of two-vehicle crashes at intersections.

3. Data Preparation

This study analyzed crash data that were collected from the Critical Analysis Reporting Environment (CARE) package of the Wyoming Department of Transportation (WYDOT). The dataset was prepared such that each data point represented a crash record. The data comprised records of 7300 two-vehicle crashes at 337 intersections from January 2007 through December 2017 except for the years 2010 and 2011. In this study, the intersection crashes considered were those that were located within 250 feet (76.2 m) from the center of the intersection as per the American Association of State Highway and Transportation Officials [42]. All crashes in this dataset involved only two vehicles with no pedestrians, cyclists, or motorcyclists (vulnerable road users) involved.

The pavement friction data were collected by WYDOT personnel using the locked-wheel tester.

The locked-wheel tester is a trailer with two wheels fitted with full-size tires (15 by 6 inches), one or both of which are used for longitudinal friction measurements. The testing tires are either standard smooth or standard ribbed tires. The smooth tire is sensitive to macrotexture while the ribbed tire is more sensitive to microtexture [15]. A locked-wheel tester measures pavement friction by fully locking up the test wheel(s) and recording the average sliding force for a period of 3 s and reporting a 1-s average after reaching the fully locked state (100% slip). The friction measurements can only be recorded periodically over short intervals of time because of the full-lock requirement. The Friction Number (FN) is reported as (FN40R), which is measured by a locked wheel testing device, using a standard ribbed tire at a speed of 40 mile per hour.

The collected friction data were calibrated by WYDOT at the regional calibration center. When not available directly, the friction number available at the intersection was estimated based on the friction measurements along the major route of the intersection. When the friction was not measured at the intersection, the closest two measurements (before and after the intersection) were averaged to estimate the friction at the intersection. In addition, the friction numbers were estimated on years when no data were collected, by averaging the measurements of the previous and the subsequent years when no maintenance work was applied at this road segment (decreasing friction numbers) as per Equation (1).

$$FN\ (Year) = \frac{FN\ (Year-1) + FN(Year+1)}{2} \quad (1)$$

This approach assumes that the friction is deteriorating at a consistent rate over the three years. The friction measurements were linked to the crashes that occurred in the same whole year. The study only considered crashes occurred in years with available measured or estimated friction measurements at the intersections. Therefore, there is no missing friction data in the examined crash records. Each row of the dataset represented a unique crash record with the friction number at the intersection, measured or estimated within the crash year. Table 1 presents summary statistics of this study's data parameters. The count and percent columns are referring to the "1" category for each stated variable.

Table 1. Data Summary Statistics.

Continuous Variable			
	Mean	**Minimum**	**Maximum**
Pavement friction	39.43	18.65	71
Binary variables			
Response		Count	Percent
No injury (property damage only, PDO, or O)		5741	78.6
Possible injury or suspected minor injury (BC)		1460	20.0
Fatal injury or suspected serious injury (KA)		99	1.4
Roadway and environmental characteristics			
Type: four legs or more (1 if yes or 0 otherwise)		6301	86.3
Location: urban (1 if yes or 0 otherwise)		6930	94.9
Traffic control: signalized (1 if yes or 0 otherwise)		6970	95.5
Grade: uphill (1 if yes or 0 otherwise)		146	2.0
Grade: downhill (1 if yes or 0 otherwise)		465	6.4
Lighting: non-daylight (1 if yes or 0 otherwise)		1466	20.1
Road condition: non-dry surface (1 if yes or 0 otherwise)		1997	27.4
Adverse weather (1 if yes or 0 otherwise)		1131	15.5
Crash characteristics			
Weekend crash (1 if yes or 0 otherwise)		2623	35.9
Hit and run crash (1 if yes or 0 otherwise)		480	6.6
At least one large vehicle involved		502	6.9
Driver's characteristics			
At least one teen (<20) driver involved		1841	25.2
At least one senior (>54) driver involved		2999	41.1
At least one female driver involved		4845	66.4
At least one out-of-state driver involved		1161	15.9
At least one impaired driver involved		489	6.7

This study examined the injury severities sustained at the crash level. The crash injury severity levels in this study were categorized as 0 (property damage only [PDO] or no injury), 1 (possible or evident injury), and 2 (disabling or fatal injury). The number of injuries per crash was not accounted for in this study. PDO crashes comprised 78.6% of the crash records. Possible and evident injury crashes represented 20% while disabling and fatal injury crashes represented 1.4% of the data.

Several roadway and environmental characteristics were examined in this study. The pavement friction was considered the only continuous variable in the model with values ranging between 18 and 71 with an average of 39. The intersections were categorized according to the number of intersection legs. Intersections with four or more legs comprised 86.3% of total intersections. The intersections were classified as urban or rural according to the U.S. Census Bureau's definition [43]. Urban intersections represented almost 95% of the crash locations. The traffic control at the intersection was examined as signalized intersections comprised 95.5% of the intersections. As for the intersection grade, uphill and downhill grade intersections represented 2 and 6.4% of the intersections respectively, while the rest of the intersections (91.6%) were leveled. As for the lighting condition at crash time, crashes that occurred under non-daylight conditions comprised 20.1% of total crash records. Crashes that occurred on the non-dry road surface (wet, ice, snow, slush,

etc.) represented 27.4% of total crashes. Crashes that occurred during adverse weather conditions comprised 15.5% of crash records. Adverse weather included snowing, rain, fog, blizzard, hail, and any other inclement weather conditions. It is worth mentioning that all variables were checked for multicollinearity and the results showed that no variables were highly correlated.

In addition, crash-specific characteristics were examined in this study. The crashes were categorized as whether they occurred on a weekday or the weekend, hit and run or not, and whether they involved large vehicles. Large trucks, medium-sized trucks, motor homes, construction vehicles, and buses were considered large vehicles. Low portion (7%) of crashes involved at least one large vehicle.

Driver's age, gender, home state, and condition were examined. Driver's age was categorized into three categories, teen (<20), mid-aged (20–54), and senior (>54) [36]. About a quarter of crash records had at least one teen driver involved. While more than 40% of crashes had at least one senior driver involved. Two-thirds of crashes involved at least one female driver. A considerable proportion of crash records involved at least one out-of-state driver. Out-of-state drivers are those with home residency in other states than Wyoming, where this study was conducted. A small proportion of crashes involved at least one impaired driver. Impaired drivers included drivers under the influence of alcohol, drugs, or medications and drivers who were asleep, fainted, or ill.

Age groups' selection varies in the literature, especially for the extreme groups' limits. For this study, the driver's age was categorized as teen (younger than 20), mid-aged (20 to 54, reference category), and senior (older than 54). Lombardi et al. [36] followed a similar approach for categorizing drivers' ages.

4. Methods

Due to the ordinal nature of the injury severity scale, ordered response models were extensively employed to investigate the risk factors of crash injury severity. Ordered logit and probit models were widely utilized to model the influence of various factors on injury severity [30,31,34,44–46].

One of the main shortcomings of non-random parameter analysis is commonly associated with neglecting the systematic variations (unobserved heterogeneity effects). This limitation can lead to biased and incorrect conclusions [31]. Random parameters can be included to account for such effects across the dataset. Various studies involved the employment of mixed ordered logit and probit models to investigate the influencing factors in crash injury severity [30,31,34,37,44,45].

For this study, a random parameter probit model was developed to analyze the factors impacting intersection crash injury severity. According to Eluru et al. [47], the ordered probit structure defines the latent propensity (y_i^*) for each crash, i, as follows:

$$y_i^* = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \ldots + \beta_P X_{Pi} + \epsilon_i \quad (2)$$

The risk factors are represented by the Xs while their regression coefficients are represented by the β's, which are obtained using the maximum likelihood estimation (MLE) method. The random error term is identified by ε_i and it is assumed to be normally distributed.

The response formulation is expressed as the following [47] where ψ is a threshold that is estimated via MLE.

$$y_i = \begin{cases} \text{O}, & y_i^* < 0 \\ \text{BC}, & 0 < y_i^* < \psi \\ \text{KA}, & y_i^* > \psi \end{cases} \quad (3)$$

The following equation, according to Eluru et al. [47], is used for computing the outcome probabilities, $P(.)$, where $F(.)$ is the function of the cumulative standard normal distribution:

$$P(y_i = 0) = F\left(-\left(\beta_0 + \sum_{p=1}^{P} \beta_p X_{pi}\right)\right) \quad (4)$$

$$P(y_i = 1) = F\left(\psi_1 - \left(\beta_0 + \sum_{p=1}^{P} \beta_p X_{pi}\right)\right) - F\left(-\left(\beta_0 + \sum_{p=1}^{P} \beta_p X_{pi}\right)\right) \quad (5)$$

$$P(y_i = 2) = 1 - F\left(\psi_1 - \left(\beta_0 + \sum_{p=1}^{P} \beta_p X_{pi}\right)\right) \quad (6)$$

The random parameters ordinal probit structure has at least one parameter designated to be random. The coefficient of this random parameter is permitted to vary across the dataset. The model is reconfigured as the following to accommodate the random parameters, where j represents the injury severity level [32].

$$P^m(y_i = j) = \int (P(j) \times f(\boldsymbol{\beta}|\boldsymbol{\varphi}))d\boldsymbol{\beta} \quad (7)$$

The coefficient's vector, $\boldsymbol{\beta}$, is specified as $\boldsymbol{\beta} + \boldsymbol{\omega}_i$ where $\boldsymbol{\omega}_i$ is a normally distributed variable. $\boldsymbol{\varphi}$ is the vector of the distributions' means and variances. The density function of the random parameters is represented by the term, $f(\boldsymbol{\beta} \mid \boldsymbol{\varphi})$. The outcome probabilities, P_i^m's, cannot be computed directly due to the high dimensional integral. To overcome this issue, the density function is simulated, multiple samples are drawn from $\boldsymbol{\beta}$ and the probabilities P_i^m's are calculated for each sample. The estimated probability is the average of the computed probabilities. The Halton draws method, which specifies a sequence of non-random draws, is utilized for this study. The Halton draws method is identified to develop accurate estimates of the random parameters' probability distributions compared to methods with fully random draws. One thousand Halton draws were sampled for this study since this number of draws was shown to result in reliable estimates of the random parameters [45,48,49]. Marginal effects are computed to identify the influences of the contributing factors on crash injury severity. A marginal effect is an average difference in probability of injury severity j, $\Delta P(y = j)$, as a result of the variable's influence (i.e., its value changes from 0 to 1), given that all other variables are controlled [50].

5. Results and Discussion

An ordered probit model was developed to perform a preliminary analysis of the prepared intersection crash data. The preliminary ordered probit model examined the full set of explanatory variables which included the driver's age, the driver's gender, pavement friction, intersection type (urban/rural), traffic control, lighting, surface condition, and weather. The 95th percentile confidence level was used in the analysis. The log-likelihood ratio test was also conducted to test for the model's significance. The results of the developed preliminary model are presented in Table 2.

The preliminary results showed that some of the explanatory variables were insignificant (Table 2). These variables were tested as random parameters using the 'Rchoice' package [51]. A random parameter ordered probit model was then developed including three random parameters. The results of the model are presented in Table 3.

Table 2. Ordinary ordered probit model results.

Coefficients	**Estimate**	**Standard Error**	***p*-Value**
Constant	−0.353	0.082	<0.001
Type: urban	−0.299	0.082	<0.001
Traffic control: signalized	−0.270	0.087	0.002
Weekend crash	0.080	0.034	0.018
Road condition: non-dry surface	−0.164	0.038	<0.001
At least one female driver involved	0.129	0.035	<0.001
At least one impaired driver involved	0.467	0.059	<0.001
At least one large vehicle involved	−0.196	0.069	0.005
ψ	1.451	0.040	<0.001
Log-likelihood		−4076	
Log-likelihood of constant-only model		−4155	
Log-likelihood Ratio χ^2		158	
Degrees of freedom		7	
p-Value		<0.001	

Statistically insignificant parameter at 95th percentile confidence level removed from the model.

Table 3. Random parameter ordered probit model results.

Coefficients:	**Estimate**	**Standard Error**	***p*-Value**
Constant	0.166	0.250	0.507
Type: urban	−0.455	0.134	<0.001
Traffic control: signalized	−0.373	0.132	0.005
Weekend crash	0.116	0.047	0.014
Road condition: non-dry surface	−0.189	0.069	0.006
At least one female driver involved	0.174	0.051	0.001
At least one impaired driver involved	0.615	0.102	<0.001
At least one large vehicle involved	−0.289	0.103	0.005
Random parameters			
Mean friction	−0.013	0.006	0.026
Standard deviation of pavement friction	0.020	0.006	<0.001
Mean adverse weather	−0.459	0.180	0.011
Standard deviation of adverse weather	1.090	0.244	<0.001
Mean: at least one out-of-state driver involved	−0.165	0.121	0.175
Standard deviation: at least one out-of-state driver involved	0.706	0.244	0.004
ψ	1.977	0.231	<0.001
Log-likelihood		−4064	
Log-likelihood of constant-Only model		−4155	
Log-likelihood Ratio χ^2		206	
Degrees of freedom		13	
p-Value		<0.001	

The empirical analysis results showed that higher pavement friction numbers were more likely to be associated with lower severity crashes. The friction was found to be a random parameter. With a mean of −0.013 and a standard deviation of 0.02, 74.8% of the crashes had a negative coefficient for friction, as they had a lower injury severity with increased pavement friction. A total of 25.2% of the crashes had a positive coefficient for friction, as they had a higher injury severity with increased pavement friction. The adverse weather conditions variable was found to be a random parameter in this study. The results showed that 66.3% of the crashes under adverse weather conditions were less severe compared to 33.7% of the crashes with increased injury severity. Drivers who are out of state are less likely to involve in severe crashes at intersections as 59.2% of intersection crashes involved these drivers were less severe.

The variable marginal effects are presented in Table 4. In Table 4, the $\Delta P(.)$'s denotes the changes in crash injury severity risks. Each variable's effect on the response was inferred assuming all else was controlled and the friction number is 39 (average value).

Table 4. Variable marginal effects.

Variable	Marginal Effects %		
	***P* (y = O)**	***P* (y = BC)**	***P* (y = KA)**
Type: urban	15.25	−14.53	−0.72
Traffic control: Signalized	12.80	−12.16	−0.65
Weekend crash	−4.42	4.07	0.35
Road condition: non-dry surface	6.82	−6.42	−0.40
At least one female driver involved	−6.69	6.12	0.56
At least one impaired driver involved	−24.11	20.79	3.32
At least one large vehicle involved	10.17	−9.62	−0.55
Mean: pavement friction	10.13	−9.32	−0.81
Mean: adverse weather	15.36	−14.63	−0.73
Mean: at least one out-of-state driver	5.97	−5.61	−0.36

Notes: The friction variable's marginal effects were computed assuming that its value changed from 25 to 45 and that all other variable values were 0, ΔP (y = O) = change in the likelihood of incurring no injury, ΔP (y = BC) = change in the likelihood of incurring possible or suspected minor injury, and ΔP (y = KA) = change in the likelihood of incurring fatal or suspected serious injury.

As shown in Table 4, crashes at urban intersections were found to be less severe than crashes at rural intersections. It was estimated that, on average, an urban intersection crash would have a 14.53% and a 0.72% lower chance of resulting in BC 1 and KA injuries, respectively, relative to rural intersection crashes. The higher injury severity in rural finding can be related to the higher speed limits, driver vulnerability to distraction, and fatigue due to long travel distances and poor access to medical assistance compared to urban areas. These findings align with those of [39,40]. This finding emphasizes that crashes on rural intersections have higher injury severity levels, which is particularly important to Wyoming since it has a large number of rural and semirural intersections.

Signalized intersection crashes were found to be less likely to be severe (marginal effect = −12.16% and −0.65% for BC and KA injuries, respectively). Plausibly, signalized intersections witness less severe crashes compared to stop-controlled intersections. This can be related to driver's failure to stop at unsignalized intersection due to non-compliance with traffic control or distraction under the absence of signals that warn the drivers approaching the intersection.

The day of the week at the crash was found to be a significant risk factor. It was estimated that, on average, crashes that occurred on weekends would have 4.07% and 0.35% higher chances of resulting in BC and KA injuries, respectively, relative to crashes that occurred on weekdays. This is due to the fact that crashes on weekends usually involve

more speeding, reckless driving or driving under the influence. Yuan et al. [39] reported similar findings. Non-dry road surface conditions were less likely to be related to severe injury crashes (marginal effect = −6.42% and −0.4% for BC and KA injuries, respectively). This finding could be related to the cautious driving behavior and prevalent lower speeds observed under these conditions.

The driver's gender was correlated with the crash severity, as female drivers, compared to male drivers, tended to be more involved in severe injury crashes. Crashes involved at least one female driver had 6.12% and 0.56% higher chances for resulting BC and KA injuries, respectively. Similar findings reported by [2,37]. Driver's condition was found to play a major role in influencing injury severity likelihoods conditional on the occurrences of crashes. Crashes involved at least one impaired driver would raise the probability of sustaining BC and KA injuries by 20.79% and 3.32%, respectively. Driving under the influence of alcohol, drugs, medications or in an impaired condition is well documented to cause severe crashes. These conditions can cause slower or over reactions, poor estimating of distance and speed which significantly limit the ability of safe driving.

Large vehicle involvement was found to reduce the chances of obtaining severe injuries in two-vehicle intersection crashes. Crashes involved at least one large vehicle would have 9.62% and 0.55% lower chances of resulting in BC and KA injuries, respectively. Larger and heavier vehicles with higher centers of gravity provide more protection for the occupants in case of crashing, compared to smaller (passenger) vehicles. This finding aligns with those reported by Zhang et al. [38].

As for pavement surface friction, it was estimated that increasing the pavement friction from 25 to 45 would reduce the risk of incurring injuries for 74.8% of the crashes. The average marginal effect for this variable was computed as −9.32% and −0.81% for BC and KA injuries, respectively, while assuming all other variable values were 0. The finding is related to the fact that pavement friction directly affects the driver's ability to safely maneuver and stop the vehicle, as discussed in the introduction. Insufficient friction levels increase the crash probability and severity at all roadway segments, especially at locations where friction demand is higher, such as ramps, curves, and intersections. Najafi et al. [26] and Sharafeldin et al. [40,41] reported similar findings. This result emphasizes the significance of maintaining adequate friction levels at the intersections to mitigate the crash injury severity.

The results showed that 66.3% of the crashes involved adverse weather conditions were less severe with marginal effect computed as −14.63% and −0.73% for BC and KA injuries, respectively. These results could be because drivers tend to travel more cautiously and approaching the intersections at lower speeds during such conditions [39,41]. The model's results also indicated that 59.2% of crashes involved at least one out-of-state driver were less severe, with the marginal effect of −5.61% and −0.36% for BC and KA injuries, respectively. This can be related to cautious driving behavior of out-of-state drivers due to their unfamiliarity with the road environment. Drivers who are unfamiliar with the routes tend to travel at lower speeds, while familiar drivers can be involved in dangerous driving behaviors due to their over-confidence with the road network. In addition, in-state vehicles are more likely to neglect traffic control at intersections and run red lights [52,53].

6. Conclusions and Recommendations

This study was focused on exploring the influencing factors of the injury severity of two-vehicle crashes at intersections. The study examined a comprehensive set of contributing variables including driver's characteristics, environmental conditions, intersection and crash characteristics, and their effect on injury severity. A random parameter ordinal probit model was developed to explore the severity of risk factors.

The results showed that three parameters were random with heterogeneous influences on the injury severity. Pavement friction was found to be a random parameter with higher pavement friction numbers more likely to be associated with lower severity crashes. The chances of observing no-injury crashes were higher in the presence of adverse weather

conditions. Out-of-state drivers were more likely to be involved in less severe crashes. The model results identify several significant factors with fixed effect on crash severity. Female drivers, compared to male drivers, were found to be more prone to severe injuries. Adverse road surface conditions were associated with less severe crashes. Crashes occurred at signalized and urban intersections were found to be less severe. Drivers in large vehicles were found to sustain less severe injuries. Crashes involved impaired drivers and crashes on weekends were found to have higher severity levels.

Several recommendations can be made based on this study's findings. Regular maintenance of an acceptable level of friction is recommended to mitigate crash injury severity at intersections. In addition, the findings related to the driver's characteristics can be further investigated to plan tailored countermeasures for these drivers' groups with a higher risk of being involved in severe crashes. These strategies relate to the driver's educational and enforcement campaigns. Rural and unsignalized intersections require more attention for the planning and implementation of countermeasures as they witness higher injury crashes. Regular friction monitoring and higher friction levels are recommended at rural and unsignalized intersections to alleviate the probability of severe crashes. Regular monitoring for drivers with a history of impaired driving is recommended to reduce the probability of these high-severity crashes. Special monitoring and law enforcement are required for high-risk intersections (rural–unsignalized) with significant crash history.

7. Study Limitations and Future Research

The study had a limitation as the crash records did not identify the at-fault driver, striking or struck vehicle. This additional information would help to identify the characteristics of the at-fault drivers in severe intersection crashes. In addition, this would define the influence of vehicle attributes on two-vehicle crash severity, depending on its role (striking/struck).

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