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Examining the Risk Factors of Rear-End Crashes at Signalized Intersections

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Abstract

Rear-end crashes are among the most common crash types at signalized intersections. To examine the risk factors for the occurrence of this crash type, this study involved the analysis of nine years of intersection crash records in the state of Wyoming. With that, the contributing factors related to crash, driver, environmental, and roadway characteristics, including pavement surface friction, were investigated. A binomial logistic regression modeling approach was applied to achieve the study's objective. The results showed that three factors related to crash and driver's attributes (commercial vehicle involvement, speeding, and driver's age) and four factors related to environmental and roadway characteristics (lighting, weather conditions, area type, whether urban or rural and pavement friction) are associated with the risk of rear-end crash occurrence at signalized intersections. This study provides insights into the mitigation measures to implement concerning rear-end crashes at signalized intersections.

Keywords

Rear-End Crashes, Signalized Intersections, Pavement Friction, Intersection Safety, Binomial Logistic Regression

1. Introduction

Intersections are commonly recognized as crash-prone locations on roadway networks. As such, intersection crashes tend to have higher injury severity compared to other roadway segments. Intersection crashes are accountable for more than 20% of road traffic fatalities and more than 40% of total crash injuries in the United States. Complex traffic movements from different road users establish the intersections as hazardous locations for all road users [1] [2] [3] [4].

Rear-end crashes are one of the most frequent crash types on US roads accounting for almost 30% of total crashes [3]. They are also one of the common crash types that occur at intersections [5]. In addition, they comprise 7% of the fatal crashes [6]. Signalized intersections can even experience more rear-end crashes due to the increased diversity of actions under signal indication changes. Distracted driving and following vehicles too closely (tailgating) raise the risk of observing rear-end crashes. Maintaining a sufficient buffer distance between vehicles is necessary to provide sufficient reaction time for abrupt maneuvers and stopping [7]-[12].

Typically, various crash, driver, environmental, and roadway characteristics all influence the risk and severity of crashes [13] [14]. Among roadway attributes, pavement surface friction may be a commonly omitted variable in crash safety analyses. Pavement friction is expected to affect the occurrence of rear-end crashes at signalized intersections since it is directly related to the stopping sight distance.

Pavement friction is a critical resisting force eliminating the relative motion between the tires and the pavement surface [15]. The pavement friction decreases with time due to traffic movements that polish the aggregate texture in the pavement surface layer. Therefore, the state DOTs and transportation agencies monitor the friction levels constantly. The FHWA recommends the use of continuous pavement friction measurement (CPFM) to continuously measure pavement friction throughout the road networks including tangents, curves, and intersections [16]. Elkhazindar *et al.* [17] surveyed pavement friction management practices among State Departments of Transportation (DOTs). The survey revealed that only eleven DOTs collect friction data on specific road characteristics (curves, ramps, and intersections), by request to investigate safety concerns. Increasing wet pavement crashes are commonly the main safety concern encouraging friction data collection at specific road locations.

Wet pavement crashes are usually related to skid resistance, as friction force is significantly reduced by wet pavement conditions. Dry pavements can experience a similar issue if available friction is substantially less than the design criteria for the roadway [18] [19]. Wyoming has one of the highest snowfall rates in the US, with over 30% of crashes in the state occurring on non-dry road surfaces, including wet, icy, snowy, or slushy road surfaces [20] [21] [22]. Pavement surface treatments play a critical role in maintaining adequate friction levels and intersection safety. Chip seals, micro-milling, hot-mix asphalt (HMA) overlays, open-graded friction course (OGFC), and High Friction Surface Treatments (HFST) are among the surface treatments that may be used as spot applications to increase the friction levels where higher friction is required, such as at intersections [18] [23] [24] [25].

The proper identification of contributing factors to this specific crash type requires investigating the main potential risk factors. This study aimed to examine the effects of risk factors affecting the occurrence of rear-end crashes at signalized intersections. The investigated factors in this study included crash, driver, environmental, and roadway attributes, including pavement friction. A binomial logistic regression model was developed to examine the impact of these factors on the risk of this crash occurrence. The following content entails a review of the previous relevant studies in the road safety literature, this research's methodology, the data description, empirical analysis results with their discussion, and the conclusion.

2. Literature Review

This section comprises a review of a variety of studies related to rear-end crashes and skid resistance. The knowledge gaps in those studies are pointed out and this research's contribution is discussed.

Wang *et al.* [26] investigated the temporal stability of the precursors that give rise to both rear-end and other traffic crashes utilizing a random parameters approach with heterogeneity in means and variances. Using data from the Beijing-Shanghai expressway, the authors found that multiple factors impact the injury severity risks of both rear-end and other crashes. However, the skid resistance of the pavement surface was not well examined. Similarly, Yu *et al.* [27] utilized data from North Carolina's work zones to investigate the injury severity risk factors of rear-end crashes. Even though the research team incorporated the pavement surface type, whether paved or unpaved, the pavement friction number was omitted from the analysis.

Ahmadi *et al.* [28] explored the contributory factors that lead to rear-end crashes in California using the multinomial logit, random parameters multinomial logit, and support vector machine (SVM) structures. In particular, the aim was to gauge the impacts of the contributory factors on injury severity risk. The SVM model performed the best to a limited extent. Even though the authors considered crash contributing factors from a multitude of facets, such as the driver's characteristics, vehicle characteristics, and roadway design features, the skid resistance of the pavement surface was not incorporated in the models.

Lee *et al.* [29] examined the impact of the pavement's international roughness index (IRI), among other factors, on freeway safety. The authors employed data from Arizona, Michigan, Florida, Colorado, and Maryland. Such states represent a wide spectrum of the roadway and environmental conditions. As per the study's findings, higher IRI's, which constitutes a measure of pavement surface degradation, translated to a larger crash frequency. Other findings were reported concerning the travel speed and traffic volume. Although the authors investigated the IRI's effects on safety and developed regression models that are aimed at predicting the count of crashes, including one that is used for predicting rear-end crash frequency, the study has its shortcomings. That is, the authors employed IRI data instead of pavement surface friction number data. Also, the effects of junctions were not considered in the analysis.

Lee *et al.* [30] implement Bayesian ordinal logistic regression models to investigate the impact of pavement quality on crash injury severity. The research team utilized data from Florida. As per the results, deteriorated pavement surfaces raised the severity of multiple-vehicle crashes on both roads with low posted speed limits and those with high-speed limits. This was not the case for single-vehicle crashes. Yet, the authors incorporated the pavement condition variable instead of the friction number in their models.

Chen *et al.* [31] developed a random parameter seemingly unrelated negative binomial regression model to examine the effects of the roughness of the pavement surface on two-lane and multilane highway safety. The model's framework captures both unobserved heterogeneity effects and correlations among the different crash severity categories. The authors concluded that deteriorated pavement surfaces give rise to a higher crash frequency on multilane highways contrary to the case of two-lane highways. As such, reduced pavement roughness levels translate to fewer counts of injury and property damage-only crashes on multilane highways. Similar to the aforementioned studies, this study did not involve the examination of the impact of the pavement surface's skid resistance on crash severity.

Mayora and Piña [32] examined skid resistance data of rural two-lane highways in Spain to evaluate the impact of skid resistance on road safety and ascertain the influence of enhancing pavement skid resistance on safety. The data were collected using sideway force coefficient routine investigation machinery (SCRIM). It was found that higher skid resistance levels were inversely correlated with crash frequencies in both wet and dry road surface conditions. However, the authors investigated general trends instead of those of specific crashes, such as rear-end crashes.

Fwa [33] developed a methodological approach for establishing minimum acceptable pavement friction levels. The author maintains that, under wet road surface conditions, vehicles traverse roads with various water layer depths at different speeds. These widely varying conditions do not necessarily represent that of the standardized skid resistance testing procedure. This prompts the proposition of a more effective pavement management strategy.

Hussein *et al.* [34] conducted a before-after safety analysis of signalized intersections that were subjected to pavement maintenance in Melbourne, Australia. The research team considered pavement surface roughness, skid resistance, rutting, average annual daily traffic (AADT) volume, posted speed limit, lighting condition, whether daytime or nighttime, and whether the road surface was dry or wet. The results of the study indicated that maintaining the pavement surface reduced both crash frequency and severity. However, the authors did not differentiate between rear-end crashes and others. Other related studies include those of Karlaftis and Golias [35], Roy *et al.* [36], Miller and Johnson [37], Park *et al.* [38], Ouyang *et al.* [39], Abdel-Aty *et al.* [40], McCarthy *et al.* [41], Zhao *et al.* [42], and Papadimitriou *et al.* [43].

In general, there is a growing interest in research related to the relationship between pavement surface friction and safety. However, to the best of the authors' knowledge, the investigation of the effects of the pavement surface's skid resistance on the risk of the occurrence of rear-end crashes is limited. In this research, the risk of observing rear-end crashes as opposed to other crashes at intersections, conditional on their occurrences, is modeled as a function of a crash, environmental, socio-demographic, and roadway factors especially pavement skid resistance.

3. Methodology

This study involved the employment of a binary logistic regression model to identify the contributing factors to the occurrence of rear-end crashes at signalized intersections [44] [45]. The outcome of the model was whether a crash was a rear-end crash or another type of crash. In the framework of the binary logistic regression model, the probability, P_i, of encountering a rear-end crash, i, is defined as follows [45]:

$$P_i = \frac{\exp\left(\beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \cdots + \beta_p X_{pi}\right)}{1 + \exp\left(\beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \cdots + \beta_p X_{pi}\right)} \tag{1}$$

The predictors, X's, are the crash contributing factors, and the coefficients are represented by the β's. The model parameters were interpreted by their odds ratios and the 90th confidence interval was selected as the basis for retaining statistically significant parameters.

The odds ratio is defined as the odds of the signalized intersection crash being a rear-end crash provided the effect of a parameter, relative to those of the crash of being a rear-end crash conditional on the absence of the effect of the parameter assuming all else is controlled. For instance, the odds of a signalized intersection crash being a rear-end crash given that the crash occurred at an urban intersection may be lower than those of the crash being a rear-end crash provided that it occurred at a rural intersection. The odds ratios were computed as the exponentiation of the parameters' coefficients. For more information about the binary logistic regression model, the reader is referred to Hosmer *et al.* [45].

4. Data Preparation

In this study, an analysis of crash data from the Critical Analysis Reporting Environment (CARE) package of the Wyoming Department of Transportation (WYDOT) was conducted. The data comprised records of 5618 crashes at 165 signalized intersections from January 2007 through December 2017 except for the years 2010 and 2011. Crashes defined as intersection-related crashes are those that occurred within 250 feet (76.2 meters) from the center of the intersection as per the American Association of State Highway and Transportation Officials [46]. **Figure 1** presents the manner of collision distribution for the examined dataset.

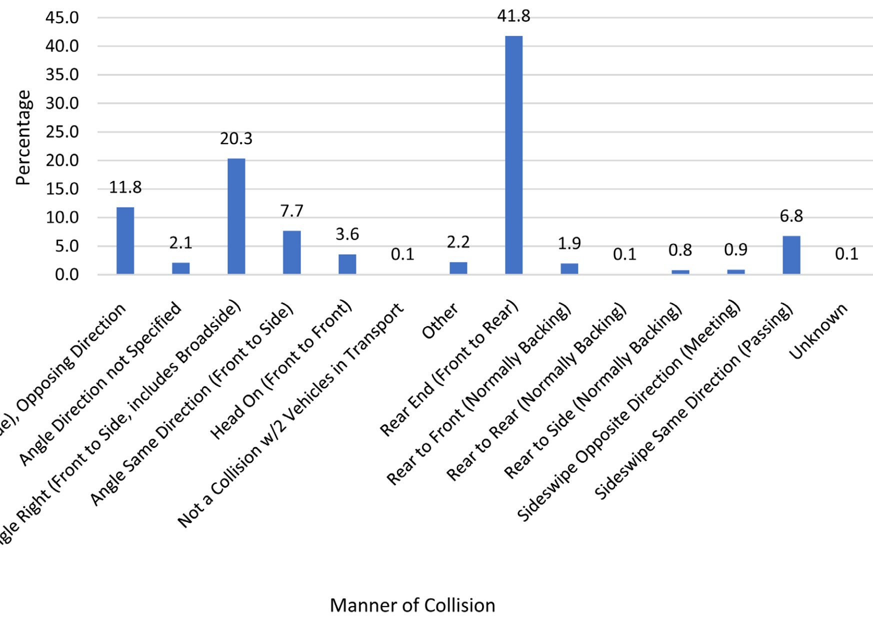

Figure 1. The manner of collision distribution for the crash records.

The figure illustrates how rear-end crashes are the most frequent crash type at signalized intersections in Wyoming. Nationally, rear-end crashes are the most common crash type at intersections, comprising more than 36% of total intersection crashes [20]. This emphasizes the need to thoroughly examine the contributing factors for rear-end crashes at intersections, particularly signalized intersections. Pavement friction data were collected using the locked-wheel tester of the Wyoming Department of Transportation (WYDOT).

The locked-wheel equipment is composed of a trailer with two wheels fitted with full-size tires (15 by 6 inches), one or both of which are used to measure longitudinal friction. 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 device measures 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). Therefore, with a 40-mph test speed, the test time presents testing the pavement surface for 59 ft. The friction measurements can only be recorded periodically over short intervals of time because of the full-lock requirement [47].

The field 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 is not measured at the intersection, the closest two measurements (before and after the intersection) are averaged to estimate the friction at the intersection. In addition, the friction numbers were estimated at no-measurement years by averaging the measurements of the previous and the subsequent years when no maintenance work was applied at this road segment (decreasing friction numbers). This approach assumes that the friction levels are deteriorating at a consistent rate over the three years.

The friction measurements were matched with the crash records of their respective years. Each row of the dataset represented a unique crash record with the friction number at the intersection, measured within the crash year. Table 1 presents summary statistics of the data.

In this study, the response variable was defined as whether the crash type was a rear-end or a non-rear-end crash or not. Rear-end and non-rear-end crashes represented 41.8% and 58.2% of the total crash records, respectively. Crashes included in the dataset were only those that involved multiple vehicles at signalized intersections.

The examined roadway characteristics in this study were pavement friction, intersection type, intersection location, and the speed limit of the major route. The pavement friction was incorporated as the only continuous predictor in this analysis with values ranging from 19 to 66 and amounting to an average of 39. Figure 2 presents the friction number distribution for the crash records count.

The intersections were categorized per type as T-intersection (reference category) and intersections with four legs or more. Intersections with four legs or more comprised 87.3% of the examined locations. The intersections were classified as urban or rural according to the U.S. Census Bureau's data [48]. Urban intersections accounted for 98.4% of the studied locations, while rural intersections (reference category) comprised only 1.6%. The speed limit on major routes at the intersections ranged from 20 to 55 mi/h with an average of 34.5 mi/h.

Lighting, road surface condition, and weather were investigated as the environmental characteristics. 71.7% of crashes took place in daylight conditions (reference category), while 28.3% of crashes occurred in non-daylight conditions

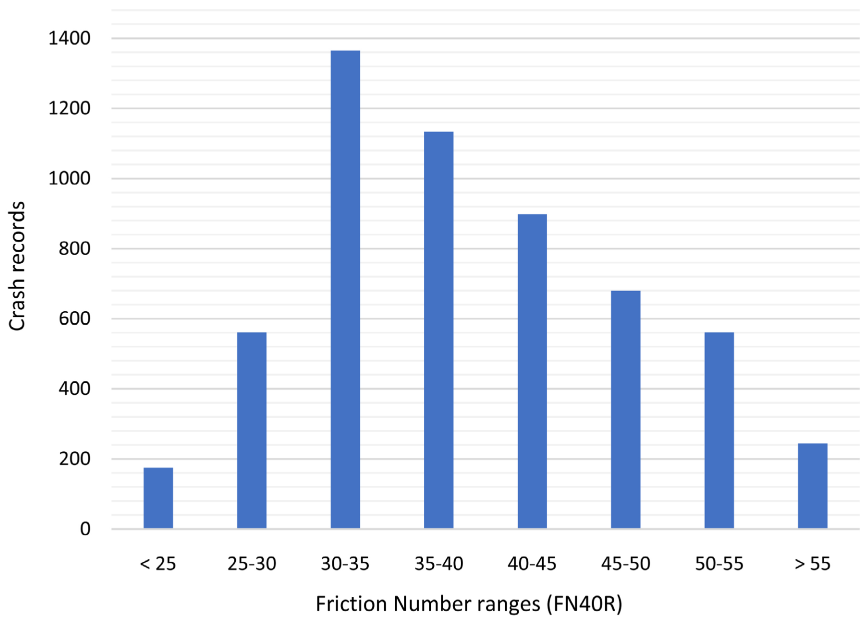

Figure 2. Friction data distribution for the crash records count.

Table 1. Data summary statistics.

Binary Response	Frequency	Percent	
Response			
Rear-end crashes	2348	41.8	
Non-rear-end crashes	3270	58.2	
Roadway Characteristics			
Type: four legs or more (1 if yes or 0 otherwise)	4907	87.3	
Location: urban (1 if yes or 0 otherwise)	5529	98.4	
Environmental Characteristics			
Non-daylight (1 if yes or 0 otherwise)	1154	20.5	
Non-dry road surface (1 if yes or 0 otherwise)	1589	28.3	
Adverse weather (1 if yes or 0 otherwise)	915	16.3	
Crash Characteristics			
Commercial motor vehicle (CMV) involvement (1 if yes or 0 otherwise)	326	5.8	
Blowing snow (1 if yes or 0 otherwise)	74	1.3	
Work zone related (1 if yes or 0 otherwise)	45	0.8	
Weekend crash (1 if yes or 0 otherwise)	2015	35.9	
Driver's Characteristics			
Speeding (1 if yes or 0 otherwise)	745	13.3	
Driving under the influence (DUI) (1 if yes or 0 otherwise)	249	4.4	
Continuous Variables			
	Mean	Minimum	Maximum
Roadway Characteristics			
Pavement friction number	39	19	63
The speed limit of the major route (mi/h)	34.5	20	55
Driver's Characteristics			
Driver 1's age	38.9	9.0	102
Driver 2's age	40.4	9.0	102

(dusk, dawn, dark lighted, and dark unlighted). The road surface condition was classified as dry (reference category) and non-dry road surface. Crashes on non-dry road surfaces represented 24.5% of the total crashes. The non-dry road surface category included conditions, such as wet, icy, snowy, slushy, frosty, and any other adverse conditions. The weather at the crash time was categorized as clear (reference category) and adverse weather. Crashes that occurred during adverse weather conditions comprised 16.3% of the total crashes. The adverse weather category included blizzard, hail, snow, rain, fog, and any other unfavorable weather conditions.

Several crash-specific characteristics were examined in this study. Commercial motor vehicle (CMV) involvement in the crash was examined, with 5.8% of crashes involved CMVs. CMVs included large trucks, medium-sized trucks, motor homes, construction vehicles, and buses [7].

Crashes related to blowing snow accounted for 1.3% while work zone-related crashes only comprised 0.8% of total crashes. The crashes were classified as weekend and weekday (reference category) crashes. Crashes that occurred on weekends represented 35.9% of the total crashes.

The examined driver's attributes included driver's age, speeding, and condition. The driver's age was considered for each of the two involved drivers as a continuous variable, and drivers older than 99 were estimated as 102 years old. Records of crashes with three or more vehicles had the ages of the drivers of the two foremost vehicles that were involved in the crash.

The speeding factor was examined as speeding and no-speeding (reference category) crashes. They comprised 13.3% and 86.7% of the crash records, respectively. Driving under the influence (DUI) was also examined and crash records were classified as crashes with drivers in normal condition (reference category) and crashes involving at least one driver under the influence, which represented 4.4% of the crashes. Independent variables were tested for multicollinearity and the testing results indicated that the predictors were not highly correlated.

5. Empirical Analysis

A binary logistic regression model was developed to examine the risk factors contributing to rear-end crash occurrences at signalized intersections. The model examined the full set of characteristics including roadway characteristics (pavement friction number, number of legs at the intersection, intersection location, and speed limit on the major route of the intersection), environmental conditions (lighting conditions, road surface conditions, and adverse weather), crash characteristics (CMV involvement, snow-blowing related, work zone related, and day of the week), and driver's attributes (age, speeding, and driving under the influence condition). The analysis results are presented in **Table 2**. Note that statistically insignificant parameters at the 90th percentile confidence level were removed from the model.

The empirical analysis results showed that pavement friction had a negative relationship with rear-end crash occurrences at signalized intersections. Also, crashes at urban intersections were less likely to be rear-end crashes. Crashes that occurred in adverse weather conditions or under non-daylight conditions were less likely to be rear-end crashes. In addition, signalized intersection crashes that involved CMVs were less likely to be rear-end crashes. Driver's age was inversely related to rear-end crash occurrences at signalized intersections.

Table 2. Binary logistic regression model results.

Coefficients	Estimate	Standard Error	P-Value
Constant	1.386	0.269	<0.001
Roadway Characteristics			
Pavement friction	−0.021	0.003	<0.001
Location: Urban	−0.377	0.219	0.085
Environmental Characteristics			
Non-daylight conditions	−0.330	0.070	<0.001
Adverse weather conditions	−0.219	0.081	0.007
Crash Characteristics			
CMV involvement	−0.957	0.137	<0.001
Driver's Characteristics			
Driver Age	−0.011	0.001	<0.001
Speeding	0.239	0.086	0.005
Model Fit Summary			
Residual deviance		7437.4	
Null deviance		7636.2	
χ^2		198.8	
Degrees of Freedom		7	
P-Value		<0.001	

Notes: - = Statistically insignificant parameters at the 90th percentile confidence level were removed from the model; CMV = commercial motor vehicle.

Speeding crashes were more likely to be rear-end crashes compared to other types of crashes. **Table 3** presents the odds ratios for the statistically significant risk factors.

The odds ratio indicated that for every 1 unit increase in friction number, the odds that the collision type at the signalized intersection was a rear-end collision decreased by nearly 2%. This result, consistent with Mayora and Piña [32], emphasizes the significance of maintaining adequate friction levels at the intersections to mitigate the risk of rear-end crash occurrences.

Maintaining pavement friction at sufficient levels can significantly reduce the risk of rear-end crashes. WYDOT recommends minimum values for friction as (FN40R = 40) [17]. Maintaining this friction level at signalized intersections will reduce the odds of rear-end crashes from 0.718 to 0.629. While having a minimum friction threshold at (FN40R = 45) will decrease the odds of rear-end crashes to 0.559. A minimum friction threshold of (FN40R = 50) will keep the risk of rear-end crashes at only 0.474, down from 0.718 if no minimum thresholds are followed. **Figure 3** illustrates the association between minimum pavement friction values and the rear-end crash odds at signalized intersections.

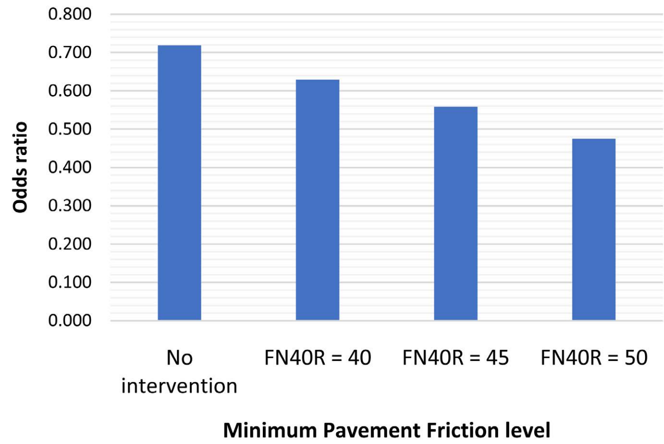

Figure 3. Minimum friction value and the odds of rear-end crash at signalized intersections.

Table 3. Parameters' odds ratios.

Parameter	Odds Ratio	Confidence Limits	
		5%	95%
Constant	3.998	2.568	6.222
Pavement Friction	0.979	0.974	0.984
Location: Urban	0.686	0.478	0.985
Non-Daylight conditions	0.719	0.640	0.806
Adverse weather conditions	0.804	0.703	0.917
CMV involvement	0.384	0.305	0.480
Driver Age	0.989	0.987	0.992
Speeding	1.270	1.103	1.463

Note: CMV = Commercial Motor Vehicle.

Urban signalized intersections had 31.4% lower odds of experiencing rear-end crashes compared to rural signalized intersections. This finding reveals that rural signalized intersections have a higher risk of rea-end crash occurrences compared to urban intersections, which is specifically critical to the state of Wyoming since it has a higher number of rural and semirural intersections. Mohamed *et al.* [49] reported similar findings.

As for the lighting conditions, crashes that occurred under non-daylight conditions, had 28.1% lower odds of being rear-end crashes compared to crashes that occurred under daylight. Possibly, daytime traffic volumes are higher than nighttime volumes. Also, the morning and afternoon peak times may affect driving behavior and contribute to the crashes. This finding aligns with Yan *et al.* [7].

Crashes that occurred in adverse weather conditions had a reduction of 19.6% in the odds of encountering rear-end crashes compared to crashes that occurred in clear or cloudy weather conditions. Plausibly, drivers are cautious while approaching intersections under adverse weather conditions which decreases the risk of having a rear-end crash.

CMV involvement was a factor that was found to significantly reduce the odds of rear-end crashes. Crashes involving CMVs had a reduction of 61.6% in the odds that the collision type was a rear-end collision. Generally, drivers tend to maintain sufficient buffer distances while interacting with large trucks or buses due to the severe consequences of colliding with these vehicles. In addition, large trucks are noticeable and move slowly in the traffic stream, which discourages aggressive drivers from following them. This contradicts the findings of Yan *et al.* [7].

The odds ratios indicated that for every 1-year increase in the driver's age, the risk that the collision type at the signalized intersection was a rear-end collision decreased by almost 1%. This finding aligns with Yan *et al.* [7]. In addition, speeding crashes had an increase of 27% in the odds that the collision type was a rear-end collision compared to non-speed related crashes. These findings may be attributed to cautious driving behaviors of the elderly and leaving sufficient gaps while following vehicles. Also, traffic control at intersections is beneficial to older drivers since it mitigates the effect of their slower reactions. This reduces the risk of having rear-end crashes, a finding that is in line with Mohamed *et al.* [49].

6. Conclusion and Recommendations

This study constituted an attempt to explore the contributing factors of rear-end crashes at signalized intersections. The study involved examining various risk factors including crash, driver, environmental, and roadway characteristics. A binomial logistic regression model was developed to investigate these factors. The analysis results showed that seven different explanatory variables were significant risk factors contributing to rear-end crash occurrences at signalized intersections.

Pavement friction was found to have a negative relationship with rear-end crash risk as a 1-unit increase in friction number decreased the odds of having a rear-end crash by roughly 2%. Maintaining minimum friction values at 40 will reduce the odds of rear-end crashes from 0.718 to 0.629. While preserving minimum friction values at 45 will reduce the risk of these crashes to 0.559. Maintaining the friction thresholds at 50 will keep the odds of rear-end crashes at only 0.474. Another finding is that the risk of observing rear-end crashes at rural intersections is higher. In addition, crashes that occurred in adverse weather or lighting conditions were less likely to be rear-end crashes. Furthermore, crashes involving a CMV had a lower risk of being rear-end crashes while speed-related crashes at signalized intersections are more likely to be rear-end crashes. The driver's age had an inverse relationship with rear-end crash risk as a 1-year increase in the driver's age decreased the risk of rear-end crashes by nearly 1%.

The findings of this study emphasized the key role of pavement friction in intersection safety and how pavement friction can be a main contributing factor to crashes of certain types. It is recommended to maintain pavement friction levels at adequate levels to decrease crash risk at intersections, particularly rear-end crashes. Significant efforts are needed to enhance driver's behavior, particularly for younger drivers, in terms of speeding and car-following (tailgating). Traffic law enforcement and the improvement of drivers' awareness are recommended to improve intersection safety and reduce crash risk and severity. This study's findings may provide a better understanding of the contributing factors to rear-end crashes and assist in planning effective countermeasures.

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Conflicts of Interest

The authors declare that they have no conflict of interest.

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