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# Investigating snowplow-related injury severity along mountainous roadway in Wyoming

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**Abstract**: Snow removal and deicing using snowplow trucks assist transportation agencies to enhance roadway safety and mobility. However, due to slower travel speeds during these operations, motorists often end up in crashes for poor visibility and disturbance of the snow. Despite the risk associated with snowplows, no previous study was found that exclusively investigate the factors associated with injury severity in snowplow-involved crashes. Therefore, this paper presents an extensive exploratory analysis and fills this knowledge gap by identifying the significant contributing factors affecting the occupant injury severity from the aspects of crashes with snowplow involvement. The study utilized eleven years (2010-2020) of historical snowplow-related crash data from Wyoming. Both the binary logit model and mixed binary logit model were developed to investigate the impacts of the various occupant, vehicle, crash, roadway, and environmental characteristics on the corresponding occupant injury severity. As one of the important findings from this research concludes that other vehicle drivers are more responsible than snowplow drivers contributing to more severe injuries in crashes involving snowplows. Recommendations suggested based on the modeling results are expected to help transportation

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agencies and policymakers take necessary actions in reducing snowplow-involved crashes by targeting appropriate strategies and proper resource allocation.

**Keywords:** winter highway maintenance, snowplows, injury severity, mixed logit model, unobserved heterogeneity, Wyoming, environment

## 1. Introduction

With reduced adhesion and traction of the road surface, snow and ice pose an imminent risk to road users. This results in reduced speed and capacity on the road and presents an unfavorable condition for vehicle maneuverability which may lead to failure to react to incidents by the drivers before the vehicle skid or crash into another object (Qiu & Nixon, 2008; Eisenberg & Warner, 2005). In the United States, snowy, slushy, or icy pavement accounts for 24% of weather-related vehicle crashes each year; however, only 15% occur during snowfall (Eisenberg and Warner, 2005). More than 1,300 lives are lost, and over 116,800 are injured every year in vehicle crashes involving slushy, icy, or snow-covered pavement (FHWA, 2022). The economic impact of road closures due to winter storms is significant, estimating $1.4 billion lost per day in terms of unearned wages if all roads were closed in twelve snowbelt states studied (MnDOT, 1999).

Effective winter road maintenance, such as plowing and salting, is one of the remedies for mitigating the safety impact of adverse winter weather. Safe plowing operation is critical in keeping good road surface conditions for safe traveling during and after a snowstorm (Fu & Perchanok, 2006; Hanbali & Kuemmel, 1992; Norrman et al., 2000). Snowplowing helps improve road safety by keeping the road surface traction at an acceptable level. A study by Fu et al. (2006) found that maintenance operations, including but not limited to anti-icing, and pre-wet salting with plowing and sanding, have reduced crash frequency at a statistically significant level.

The risk of a crash involving snowplow trucks is often ignored when it comes to winter maintenance operations. Not only can a snowplow-related crash cause a lot of property damage and serious injuries or fatalities, but it can also have a significant impact on the rate at which roads are cleared of snow, even if only one snowplow is lost. Zockaie et al. (2018) analyzed Michigan UD-10 Crash Report Forms from 2012 to 2017 and found that snowplows were involved in 1,354 crashes. Due to the slower speeds employed during snow plowing and deicing operations, the possibility of rear-ending collisions between other vehicles and snowplows remains a major safety concern (Zockaie et al., 2018). For example, it was reported that within five days of a snowstorm in February 2021 in Wyoming, there were 10 snowplow rear strikes (The Trucker, 2021). The plowing blades in reduced visibility often render potential blind spots to the snowplow drivers; thereby, chances of a rear-ending with the vehicle traveling in near proximity increases (IOWADOT, 2017).

To address these concerns, state DOTs have experimented with various methods of improving safety during regular winter road maintenance. One approach is to disseminate safety education and conduct outreach programs regularly to improve driving behavior on ice or snow-covered roads, particularly near snowplows. Drivers, for example, are advised to avoid sudden acceleration and deceleration, allowing additional time and space to stop (IOWADOT, 2017; MDOT, 2017). They are also advised to refrain from following snowplows very closely and being aware of the larger size of these kinds of maintenance trucks and the mounted blades, which can occupy extra lane space. Several studies have been conducted to improve winter maintenance operations focusing on crash reduction and advanced technology (MnDOT, 1999; Zockaie et al., 2018; Yen et al., 2000; Evrensel et al., 2008; Heqimi, 2016; Dao et al., 2019; Tang et al., 2015; Camden et al., 2020). However, there is still a significant number of crashes involving snowplows regardless of these efforts to improve safety during winter maintenance, particularly snow removal procedures. Research conducted at Virginia Tech showed that the top contributing factors in these crashes were as follows: 38.4% inattention/misjudgment by snowplow drivers, 23.2% loss of control, 22.8% inattention/misjudgment by other drivers, 7.1% unknown/other, 3.7% poor visibility, 2.6% blind spot, 2.2% operating near the intersection (Camden et al., 2020).

Despite the risk associated with snowplows, there have been a limited number of studies that explored snowplow-related crashes. Moreover, no previous study was found that extensively investigate the factors associated with injury severity in snowplow-involved crashes. Therefore, this study aims to fill this knowledge gap by identifying the significant contributing factors affecting occupant injury severity from the aspects of crashes with snowplow involvement. The factors used in the analysis include occupant, vehicle, crash, roadway, and environmental characteristics. Analyzing the injury severity of snowplow-involved crashes can provide valuable insights to highway safety engineers and transportation planners about the impact of different vehicle-snowplow collisions on occupant injury severity, and enable them to take necessary actions and implement appropriate countermeasures. To the best of the authors' knowledge, this study is the first to examine the contributing factors to occupant-level injury severity by investigating crashes with snowplow involvement along mountainous roadways in Wyoming.

The literature is rich from a myriad of research studies where a wide range of statistical models was used for crash severity analysis in general. Ordered choice models are one of the preferred statistical models due to the ordered nature of the injury severity outcome. However, one shortcoming of these models is that they are predicated on the assumption that all parameters calculated in the models are consistent across observations, ignoring their varied effects on crash injury outcomes. To overcome this constraint, a mixed binary logit model was introduced to examine the severity of snowplow crash-related injuries by permitting the effect of factors to varying randomly across observations along mountainous roads in Wyoming.

The next section of the paper summarizes the major findings from the literature on injury severity of snowplow-related crashes. It is followed by the description of the methodology applied to this research, and sections on descriptive statistics of the investigated variables, as well as the development of statistical models for the occupants. The major conclusions of the paper are presented in the last section. To the best of the authors' knowledge, this study is the first to examine the contributing factors to occupant injury severity by investigating snowplow involved crashes.

## 2. Research methodology

This study employed an ordered logit model to analyze occupant injury severity in snowplow-related crashes due to the ordinal discrete nature of injury severity outcomes, starting with no injury and ending with a fatal injury. Both the binary logit model and mixed binary logit model were developed to investigate the influence of occupant, vehicular, crash, roadway, and environmental characteristics on occupant injury severity in crashes involving snowplows. Three different models were established by considering occupant injury severity as the response variable. Due to the low crash observations in each injury severity level, it was not possible to model five statistically different injury-proportion categories in this study. Hence, the five injury severity outcomes were converted into three categories as follows:

(1) KA (Binary response = 1 if the occupant injury severity is fatal or incapacitating, = 0 otherwise)
(2) BC (Binary response = 1 if the occupant injury severity is non-incapacitating or possible injury, = 0 otherwise)
(3) O (Binary response = 1 if the occupant injury severity is no injury or PDO, = 0 otherwise)

In the binary logistic regression framework, the probability, $P_i$ of encountering occupant injury outcome $i$ is defined as follows:

$$log\left[\frac{P_i}{1-P_i}\right] = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \cdots + \beta_m x_{im} \quad (1)$$

Where, $m$ is the number of explanatory variables, $\beta_0$ is the intercept parameter, $x_i$ is the vector of explanatory variables, and their respective coefficients are denoted by the $\beta$'s. The logit equation can be modified as follows:

$$P_i = \frac{\exp\,(\beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} \ldots + \beta_m x_{im}}{1 + \exp\,(\beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} \ldots + \beta_m x_{im}} \quad (2)$$

Odds ratios are estimated to interpret the effect of the significant factors on injury severity. The odds of a variable ($X_1$) can be calculated as follows:

$$OR = \frac{\left[\frac{P(Y=1|X_1=1)}{P(Y=0|X_1=1)}\right]}{\left[\frac{P(Y=1|X_1=0)}{P(Y=0|X_1=0)}\right]} \quad (3)$$

In the models, these ratios demonstrated the probability of the specific injury category in crashes with the presence or absence of certain conditions. An odds ratio less than and greater than 1 indicates that an increase of one unit on the examined variable would respectively decrease and increase the odds of occupant injuries involved in snowplow-related crashes, whereas an odds ratio equal to 1 means no effect on injury severity.

The binary logit model considers the effect of any individual explanatory variable the same for each observation (Washington et al., 2011), which might not be always true. To overcome this limitation, a mixed binary logit model was also applied in this study. In a mixed logit model framework, the parameters may vary across observations; that is the random parameter's coefficients vary from the injury severity level of one occupant involved in snowplow-related crashes to that of another occupant involved in snowplow-related crashes. Both the binary logit model and mixed binary logit model have similar modeling structure except that at least one parameter is random for the mixed binary logit model. In other words, the coefficients β's are non-fixed and supposed to follow specified distributions (Farid and Ksaibati, 2021). In this study, they were assumed to follow normal distributions. Noted that it is not obvious that all explanatory variables in the model will be identified as random. In the mixed binary logit framework, the probability of injury severity of occupants involved in snowplow-related crashes is expressed by the following equation (Washington et al., 2011):

$$P_i^m = \int \frac{\exp(\beta X_i)}{1+\exp(\beta X_i)} f(\beta|\varphi) d\beta \quad (4)$$

Where, $X_i$ represents the vector of explanatory variables, $\beta$ represents their respective coefficients, $f(\beta|\varphi)$ represents the normal distribution's density function of the random parameters, and $\varphi$ represents the vector of random parameter means and standard deviation. If $f(\beta|\varphi) = 1$, the mixed binary logit model will be converted to the ordinary binary logit model. The result of the integration of the above equation cannot be derived by direct computation. Instead, the distribution of the parameters is simulated and multiple random samples are determined from the simulated distributions (Farid and Ksaibati, 2020). A wide variety of sampling techniques and strategies are utilized in this regard. However, Halton draws is considered the most widely used method and efficient technique because of its less complexity in computation and higher accuracy with fewer samples (Halton, 1960; Bhat, 2003; Train, 2003).

## 3. Data preparation

The data used in the study were collected from two sources: (i) the Critical Analysis Reporting Environment (CARE) System and (ii) WYDOT's Roadway Database. CARE is a crash database software maintained by WYDOT where Wyoming crash data are accumulated every year. The roadway geometric characteristics and cross-sectional elements can be found in WYDOT's Roadway Database. For this study, police-reported crash records from 2010 to 2020 were extracted. The crash records were retrieved into three separate file formats (i.e., crash file, vehicle file, and involved file). The first step was to select the involved file containing person-related crashes along Wyoming roadways to gather information about the drivers, passengers, and other occupants. It was then merged with the vehicle crash file based on the unique crash case number to obtain more details about vehicles and other crash characteristics, including environmental conditions. At this stage, snowplow-related crashes were filtered out and used for further analysis. One advantage of the CARE database is that it provides the exact location of each crash in terms of mileposts. The next step was to combine the person-vehicle crash file with the roadway data file based on the milepost. Therefore, the comprehensive final crash data contained detailed information associated with each snowplow-related crash (e.g., the date and time, location (longitude-latitude and name), the manner of collision, occupant characteristics, environmental conditions, vehicle information, crash severity, and many other roadway characteristics).

Due to the potential temporal instability in crash data, it would be suggested to not use a data with a large span such as the one (i.e., from 2010-2020) used in this study. Since the snowplow-related crashes are considered rare events, 11 years of crash data were taken to avoid a low sample size in the modeling procedure. A quantitative crash and injury summary with vehicle and occupant records focusing on snowplow-related crashes is shown in Table 1. Based on the records, a total of 442 snowplow-related crashes with the involvement of 837 vehicles and 1,084 injuries were found during the 11-year analysis period. Table 1 also presents the number of people involved in each injury category in snowplow-related crashes broken down by occupant types.

Table 2 shows the descriptive statistics of the investigated variables. The factors affecting the occupant injury severity in snowplow-related crashes were broadly classified into occupant characteristics, vehicle characteristics, crash characteristics, and roadway and environmental characteristics. All the variables were converted into categorical predictors and set up as binary (0 or 1). The occupant characteristics included occupant type, age, gender, restraint use, airbag deployment, seating position, license type, license status, license restriction, driver impairment, and driver improper action. This study applies the age boundary from the previous study to define young, middle, and old occupants (Zhu & Srinivasan, 2011a). The seating position of passengers was labeled as front row and second/third row. Impaired driving was recognized based on the driver being in an emotional state (e.g., depressed, angry), ill, fatigued, fainted or asleep, physically disabled, or using drugs or alcohol, whereas the normal driving condition was considered non-impaired driving. Human error is considered to be a critical contributor to crashes. Following too close, drove too fast for the condition, reckless driving, failed to keep a proper lane, improper passing, wrong-way driving, and similar driving errors were classified as improper actions. A recent study by Hossain et al. (2022) indicated an improvement in the prediction accuracy of injury severity analysis for the inclusion of all drivers' demographic information into the model. Therefore, for this study, both impaired driving and improper action were investigated for all drivers including snowplow drivers (SPD) and other vehicle drivers (OD) to observe the effect of the driver at fault on injury severity. The analyzed vehicle characteristics included vehicle towed, HAZMAT placard, vehicle maneuver, vehicle configuration, and estimated speed of the vehicles. Vehicles' estimated speeds were categorized into different ranges based on engineering judgment to investigate their effects on injury severity.

The investigated crash characteristics included facility type, junction relation, alcohol involvement, hit and run, and collision type. The facility was labeled as rural and urban. The presence of interchanges, exits, and entrance ramps was combined as a junction variable. Various collision types were categorized as angle, sideswipe, head-on, and rear-end collisions. Horizontal curves and vertical grades were investigated in this study. Grade types were categorized into the level, upgrade, and downgrade. Other than the dry surface, the roadway covered in ice, snow, slush, rain, etc. was grouped into the not-dry condition. Similarly, different inclement weather conditions were condensed as not-clear. In the binary coded response, zero (0) was considered as the reference category for each variable, which means the modeling results were estimated for the opposite (1) coded factors.

While investigating occupant-level crash data, it is reasonable to assume that the injury severity levels sustained by the occupants involved in the same vehicle or the same multivehicle crash are correlated (Zhu and Srinivasan, 2011a; Eluru et al., 2010). Neglecting such intra-crash and intra-vehicle correlation in crash data may result in biases in parameter estimates. However, there were no variations found in the injury severity of occupants in the same vehicle or the same crash. This implies the occupants involved in any snowplow-related crash most likely experienced a similar kind of injury.

**Table 1: Crash and injury information**

| Crash records (2010-2020) | | | |
|---|---|---|---|
| **Crash type** | **Crash count** | **Vehicle count** | **Occupant count** |
| Snowplows related | 442 | 837 | 1,084 |
| **Occupant injury severity records (2010-2020)** | | | |
| **Occupant type** | **KA** | **BC** | **O** |
| Driver | 5 | 64 | 760 |
| Passenger | 1 | 11 | 197 |
| Other/Unknown | 4 | 11 | 31 |

**Table 2: Descriptive statistics**

| Variable | Description | Frequency | Percent |
|---|---|---|---|
| **Response** | | | |
| KA | 1 if occupant injury severity is fatal or incapacitating, 0 otherwise | 10 | 0.92% |
| BC | 1 if occupant injury severity is non-incapacitating or possible injury, 0 otherwise | 86 | 7.93% |
| O | 1 if the occupant is not injured, 0 otherwise | 988 | 91.14% |
| **Occupant characteristics** | | | |
| Driver | 1 if the occupant is a driver, 0 otherwise | 829 | 76.48% |
| Passenger | 1 if the occupant is a passenger, 0 otherwise | 209 | 19.28% |
| Old | 1 if the age is greater than 55, 0 otherwise | 371 | 34.23% |
| Young | 1 if the age is less than 25, 0 otherwise | 166 | 15.31% |
| Middle | 1 if the age is between 25 and 55, 0 otherwise | 547 | 50.46% |
| Male | 1 if the occupant is male, 0 otherwise | 768 | 70.85% |
| Female | 1 if the occupant is female, 0 otherwise | 191 | 17.62% |
| Restraint usage | 1 if the restraint is properly used, 0 otherwise | 834 | 76.94% |
| Airbag deployment | 1 if the airbag is deployed, 0 otherwise | 49 | 4.52% |
| Front row | 1 if the occupant sits in the front row, 0 otherwise | 917 | 84.59% |
| License type | 1 if the license type is CDL, 0 otherwise | 365 | 33.67% |
| License status | 1 if the license status is clear, 0 otherwise | 804 | 74.17% |
| License restriction | 1 if the license has any restriction, 0 otherwise | 301 | 27.77% |
| SPD impairment | 1 if the impaired driver belongs to snowplows, 0 otherwise | 12 | 1.11% |
| OD impairment | 1 if the impaired driver belongs to other vehicles, 0 otherwise | 19 | 1.75% |
| SPD improper action | 1 if the snowplow driver commits improper action | 167 | 15.41% |
| OD improper action | 1 if the other vehicle driver commits improper action | 227 | 20.94% |
| **Vehicle characteristics** | | | |
| Vehicle towed | 1 if the vehicle is towed, 0 otherwise | 269 | 24.82% |
| HAZMAT placard | 1 if the vehicle has a HAZMAT placard, 0 otherwise | 446 | 41.14% |
| Vehicle maneuver | 1 if the vehicle is maneuvering straight, 0 otherwise | 476 | 43.91% |
| Estimated speed (< 30 mph) | 1 if the vehicle's estimated speed is less than 30 mph, 0 otherwise | 611 | 56.37% |
| Estimated speed (30-40 mph) | 1 if the vehicle's estimated speed is between 30 and 40 mph, 0 otherwise | 156 | 14.39% |
| Estimated speed (40-50 mph) | 1 if the vehicle's estimated speed is between 40 and 50 mph, 0 otherwise | 83 | 7.66% |
| Estimated speed (50-60 mph) | 1 if the vehicle's estimated speed is between 50 and 60 mph, 0 otherwise | 74 | 6.83% |
| Estimated speed (60-70 mph) | 1 if the vehicle's estimated speed is between 60 and 70 mph, 0 otherwise | 47 | 4.34% |
| Estimated speed (70-80 mph) | 1 if the vehicle's estimated speed is between 70 and 80 mph, 0 otherwise | 16 | 1.48% |
| Estimated speed (> 45 mph) | 1 if the vehicle's estimated speed is greater than 45 mph, 0 otherwise | 179 | 16.51% |
| Estimated speed (> 60 mph) | 1 if the vehicle’s estimated speed is greater than 60 mph, 0 otherwise | 63 | 5.81% |

| | | | |
|---|---|---|---|
| **Crash characteristics** | | | |
| Facility type | 1 if the facility type is rural, 0 otherwise | 642 | 59.23% |
| Junction related | 1 if the crash is junction-related, 0 otherwise | 638 | 58.86% |
| Alcohol involved | 1 if the crash has alcohol involvement, 0 otherwise | 25 | 2.31% |
| Hit and run | 1 if the crash has hit and run involvement, 0 otherwise | 54 | 4.98% |
| Angle | 1 if the collision type is angle, 0 otherwise | 294 | 27.12% |
| Sideswipe | 1 if the collision type is sideswipe, 0 otherwise | 271 | 25.00% |
| Rear-end | 1 if the collision type is rear-end, 0 otherwise | 432 | 39.85% |
| Head-on | 1 if the collision type is head-on, 0 otherwise | 32 | 2.95% |
| **Road and environmental characteristics** | | | |
| Horizontal curve | 1 if the crash occurs at the curved segment, 0 otherwise | 156 | 14.39% |
| Downhill | 1 if the crash occurs at the downhill segment, 0 otherwise | 177 | 16.33% |
| Uphill | 1 if the crash occurs at the uphill segment, 0 otherwise | 197 | 18.17% |
| Level | 1 if the crash occurs at the level segment, 0 otherwise | 704 | 64.94% |
| Road condition (not dry) | 1 if the road condition is not dry, 0 otherwise | 1,004 | 92.62% |
| Weather condition (not clear) | 1 if the weather condition is not clear, 0 otherwise | 755 | 69.65% |

## 4. Modeling results and discussions

All the binary logit and mixed binary logit models were developed using the "Rchoice" package in R® statistical software. Initially, all the parameters were included in the model and then backward elimination was applied to remove parameters that were not significant at the 90% confidence level. By going through fine-tuning of mixed binary logit model specification, 40 Halton samples were drawn from simulated normal distributions. The parameters having standard deviations different from zero at the 90% confidence level were identified as random parameters. To examine the possible presence of multicollinearity, the variance inflation factor (VIF) was determined for each predictor. A VIF value in excess of 10 is frequently considered an indication that multicollinearity exists (Kutner et al., 2005). However, the VIF value of all factors in the models fell below the threshold value, indicating no multicollinearity issue. The response variable for each model was different levels of injury severity of occupants involved in snowplow-related crashes. The modeling results of each model are shown in Tables 3, 4, and 5. The presented results also include Akaike's information criterion (AIC), Bayesian information criterion (BIC), and log-likelihood as the goodness of fit (GOF) measures. In all cases, mixed binary logit models exhibited a better fit than the binary logit models based on the GOF measures. Hence, all explanatory variables of mixed binary logit models were interpreted assuming all else was unchanged. The odds ratios obtained from the mixed binary logit models are presented in Table 6.

### 4.1. Random parameters

Three mixed binary logit models were developed considering different levels of occupant injury severity as response variables: KA (Table 3), BC (Table 4), and O (Table 5). In Table 3, the KA model shows that two parameters i.e., junction-related and downhill were identified as random parameters because the standard deviation of the distribution of these factors was found to be statistically significant. All other variables had statistically insignificant standard deviations and thus were specified as nonrandom parameters. The mean and standard deviation of the explanatory variable junction related were obtained as -2.9 and 3.9, respectively. These numbers suggest that the presence of junction increased the likelihood of fatal or incapacitating injuries for 22.9% of occupants and decreased the likelihood of fatal or incapacitating injuries for the remaining 77.1% of occupants. The mean (standard deviation) for the downhill factor was obtained as 2.4 (3.4). This implies that the presence of downhill segments increased the chance of fatal or incapacitating injuries for 76.3% of occupants and decreased the chance of fatal or incapacitating injuries for 23.7% of occupants.

In both the BC model (Table 4) and O model (Table 5), two parameters i.e., vehicle towed and HAZMAT placard was found to produce statistically significant random parameters. With regard to the explanatory variable vehicle towed, the mean (standard deviation) was obtained as 1.7 (3.1) in the BC model and -1.6 (3.8) in the O model. This implies that vehicle towing, when involved in snowplow-related crashes, increased the likelihood of non-incapacitating or possible injuries for 70.9% of cases while increasing the likelihood of no injuries or PDO for 33.7% of cases. The distribution of the HAZMAT placard factor in the B.C. model showed that the likelihood of non-incapacitating or possible injuries increased for 80.8% of cases when the crash was involved with any HAZMAT vehicle. The mean (standard deviation) of the HAZMAT placard factor in the O model was obtained as -0.9 (2.3). These values explain the fact that the involvement of the HAZMAT vehicle increased the probability of no injuries for 34.1% of observations and decreased the likelihood of no injuries for 65.9% of cases.

## 4.2. Occupant characteristics

The modeling results indicate that the estimated odds of non-incapacitating/possible injury increased by 20.0, 3.2, and 5.8 times on average when the occupant was a driver, young, and female, respectively. On the other hand, passengers, middle-aged, and males were found to experience no injury by estimated odds of 10.8, 1.7, and 3.7 times, respectively on average. Wyoming is ranked as one of the lowest seatbelt compliance rates state in the nation although it has a mandatory seat belt use law for all occupants, regardless of the sitting position (Wyoming Seatbelt Coalition, 2022). This could be the probable reason behind the injuries of the driver and young-aged. O'Donnell and Connor (1996) claimed greater physiological strength and injury-sustaining capability of males as compared to females which could be a possible explanation behind serious injuries for female occupants. The estimated odds of occupant fatal/incapacitating injury were found to reduce by 0.1 times on average when the restraints were properly used. The safety provided by seatbelts was found to be effective in reducing severe injuries, as frequently reported in previous studies (Zhu & Srinivasan, 2011a; Haq et al., 2020; Haq et al., 2021a). The deployment of the airbag is expected to reduce the injury severity. However, it was found to increase the estimated odds of fatal/incapacitating and non-incapacitating/possible injury by 195.0 and 8.1 times, respectively on average, while decreasing the estimated odds of no injury by 0.1 times on average. This is attributed to the fact that airbags typically deploy with higher crash impacts. This could be the possible explanation behind higher injury severity. The result is also consistent with the previous study indicating higher severe injuries for airbag deployment (Obeng, 2008; Haq et al., 2021b). The driver's physical and mental condition is always a critical factor that influences how well he can avoid or react to a serious collision to maximize safety. In this study, impaired driving was categorized into impairment by snowplow drivers and other drivers involved in snowplow-related crashes. Impaired snowplow driving was found to be involved in more fatal/incapacitating occupant injury by estimated odds of 91.8 times on average. Impairment by other drivers in snowplow-related crashes increased the estimated odds of non-incapacitating/possible injuries on occupants by 56.5 times and decreased the estimated odds of no injuries on occupants by 0.01 times on average. This result complies with other studies in the literature (Chen et al., 2016; Haq et al., 2020; 2021a).

The study explored the effects of driver's license type, status, and restriction on injury severity and they were found significant in some cases. The drivers with a commercial driving license (CDL) were found to be involved in more non-incapacitating/possible injuries by an estimated odds of 4.2 times on average. The possible reason could be the overexposure of this group in the dataset. The estimated odds of non-incapacitating/possible injury decreased by 0.4 and 0.5 times on average when the drivers had clear license status and restriction, respectively. They were also found to experience no injury by estimated odds of 1.7 and 2.1 times. It seems possible that drivers having clear license status and restrictions may drive more carefully as compared to the opposite group. While investigating driving errors, both snowplow and other driver improper actions were found significant to increase the estimated odds of non-incapacitating/possible injuries on occupants by 3.1 and 6.5 times and decrease the estimated odds of no injuries by 0.2 and 0.1 times on average, respectively. This finding also implies that other drivers are more responsible than snowplow drivers contributing to more serious injuries to the occupants in snowplow-related crashes.

## 4.3. Vehicle characteristics

If the crash involved any vehicle with a HAZMAT placard, the estimated odds of fatal/incapacitating and non-incapacitating/possible injury increased by 20.6 and 3.6 times on average, respectively while the estimated odds of no injury decreased by 0.4 times on average. This is because of the flammable substances and HAZMAT spill, which could eventually create injurious impacts on the people involved in the crash and the environment. The disastrous effects of HAZMAT transporting the vehicle on injury severity are quite frequently reported in the previous literature (Uddin and Huynh, 2018; Haq et al., 2021a; 2021b). The occurrence of vehicle towing after the crash was found to increase the estimated odds of occupant non-incapacitating/possible injury by 5.4 times, whereas decreasing the estimated odds of no injury by 0.2 times on average. It is reasonable to find higher injury severity as the vehicles colliding with greater impacts typically requires towing service to clear the crash site. Vehicles maneuvering straight were found to decrease the estimated odds of occupant non-incapacitating/possible injury by 0.5 times while increasing the estimated odds of no injury by 2.2 times on average. This implies that other than maneuvering straight, vehicles maneuvering left, right, or U-turn increased the risk of higher injuries to the occupants involved in snowplow-related crashes. This is attributed to the fact that snowplows have to maintain a very low speed on turning. Other motorists drive into a snow cloud, not realizing they are following too close to the plow and hitting the backend of the snowplow truck. Moreover, vehicles passing a snowplow on the right side often end up colliding with a wing plow that sticks out from the side of the truck in the case of a two-lane road. Vehicle speed is always a critical factor in injury severity as higher speeds typically result in greater impacts with severe injuries. Therefore, this study categorized the estimated speed of the vehicle in various ranges as indicated in Table 1, and found only three classes (i.e., < 30 mph, > 60 mph, and 60-70 mph) as significant contributions to occupant injury severity. The estimated odds of fatal/incapacitating injury increased by 54.7 times on average when the estimated speed of any vehicle exceeds 60 mph in snowplow-related crashes. Vehicles traveling less than 30 mph and 60-70 mph were found to decrease no injury to occupants involved in snowplow-related crashes by estimated odds of 0.3 and 0.2 times on average. In other words, this implies that the two speed categories (i.e., < 30mph and 60-70 mph) increased severe injuries. This is due to the fact that snowplows typically travel slower at speeds of 30 mph on average, depending on conditions. While operating snowplows in adverse weather, motorists traveling at higher speeds often end up with rear-end crashes for poor visibility due to the disturbance of the snow.

## 4.4. Crash characteristics

When it comes to crash characteristics, the presence of junctions decreased the estimated odds of fatal/incapacitating injury by 0.1 times on average. It seems reasonable that junction area typically consists of merging or diverging sections which makes the drivers travel at slower speeds resulting in lower injury severity in those locations while non-junction segments seem to be more vulnerable due to the higher speeds. A similar result was reported in the previous study (Zhu & Srinivasan, 2011b). Alcohol involvement was found to increase occupant fatal/incapacitating injury by an estimated odds of 24.4 times. Such injurious impact of alcohol on severe injury was quite frequently reported by previous studies (Lemp et al., 2011; Haq et al., 2020; 2021a; 2021b). Crashes occurring on rural roadways and angle collision types were found to increase non-incapacitating/possible injury on occupants by estimated odds of 2.8 and 2.5 times on average, respectively. This is due to the fact that the majority of Wyoming roadways are distinguished as rural. Therefore, the high exposure to such facilities could be the possible reason behind serious injuries. The results are found in compliance with the previous study (Haq et al., 2021b). When a snowplow-related crash involves a hit-and-run, the estimated odds were found to decrease by 0.3 times on average for non-incapacitating/possible injury and increase by 56.2 times on average for no injury. It is possible that hit-and-run typically causes property damage only, with no injuries. A similar result was indicated in a previous study (Haq et al., 2021b).

## 4.5. Road and environmental characteristics

Among the roadway geometrics, the presence of a horizontal curve and downhill segment was found to increase the estimated odds of occupant fatal/incapacitating injury by 16.0 and 11.1 times on average, respectively. Such impacts of challenging roadway geometrics on severe injuries are quite frequently reported in the literature (Chen & Chen, 2011; Islam et al., 2014; Pahukula et al., 2015; Naik et al., 2016; Haq et al., 2020; 2021a; 2021b). The estimated odds of non-incapacitating/possible injury increased by 1.6 times on average when the crash occurred on the level segment. On the other hand, crashes that occurred on uphill segments were found to increase no injury by an estimated odds of 8.9 times on average. It is reasonable due to the lower speeds maintained by the vehicles while traveling on uphill segments. When it comes to environmental characteristics, adverse weather was found to increase occupant fatal/incapacitating and non-incapacitating/possible injury by estimated odds of 13.8 and 2.9 times on average, respectively while decreasing no injury by estimated odds of 0.4 times on average. While operating snowplows in inclement weather, crashes often occur for poor visibility due to the disturbance of the snow. Such impacts of adverse weather on severe injuries were frequently mentioned in previous studies (Haq et al., 2020; 2021a; 2021b).

**Table 3: Binary and mixed binary logit model results for injury severity of KA**

| Variable | Binary logit model | | Mixed binary logit model | |
|---|---|---|---|---|
| | Coefficient estimate | P-value | Coefficient estimate | P-value |
| Constant | -7.831 | < 0.001 | -9.947 | < 0.001 |
| **Occupant characteristics** | | | | |
| Restraint usage | -2.103 | 0.022 | -3.071 | 0.042 |
| Airbag deployment | 3.926 | < 0.001 | 5.273 | 0.004 |
| SPD impairment | 2.999 | 0.034 | 4.520 | 0.027 |
| **Vehicle characteristics** | | | | |
| HAZMAT placard | 2.596 | 0.041 | 3.027 | 0.061 |
| Estimated speed (> 60 mph) | 2.084 | 0.039 | 4.002 | 0.036 |
| **Crash characteristics** | | | | |
| Junction related | -1.790 | 0.050 | -2.858 | 0.061 |
| Parameter distribution's standard deviation | NA | NA | 3.845 | 0.091 |
| Alcohol involved | 2.887 | 0.051 | 3.196 | 0.090 |
| **Road and environmental characteristics** | | | | |
| Horizontal curve | 1.690 | 0.047 | 2.775 | 0.053 |
| Downhill | 1.847 | 0.021 | 2.406 | 0.016 |
| Parameter distribution's standard deviation | NA | NA | 3.364 | 0.090 |
| Adverse weather | 1.355 | 0.091 | 2.622 | 0.059 |
| **Model fit statistics** | | | | |
| Observation, N | 1,084 | | 1,084 | |
| Log-likelihood | -30.585 | | -33.488 | |
| AIC | 88.976 | | 87.170 | |
| BIC | 152.019 | | 143.848 | |

**Table 4: Binary and mixed binary logit model results for injury severity of BC**

| Variable | Binary logit model | | Mixed binary logit model | |
|---|---|---|---|---|
| | Coefficient estimate | P-value | Coefficient estimate | P-value |
| Constant | -2.667 | < 0.001 | -2.840 | 0.001 |
| **Occupant characteristics** | | | | |
| Driver | 1.916 | < 0.001 | 2.996 | 0.001 |
| Young | 0.892 | 0.010 | 1.172 | 0.019 |
| Female | 1.023 | 0.001 | 1.760 | 0.002 |
| Front row | -0.510 | 0.004 | -0.999 | 0.091 |
| Airbag deployment | 1.094 | 0.015 | 2.095 | 0.019 |
| OD impairment | 2.097 | 0.011 | 4.035 | 0.007 |
| License type (CDL) | 0.855 | 0.041 | 1.434 | 0.038 |
| License status (clear) | -0.521 | 0.002 | -0.831 | 0.095 |
| License restriction | -0.577 | 0.072 | -0.694 | 0.087 |
| SPD improper action | 0.797 | 0.068 | 1.134 | 0.066 |
| OD improper action | 0.940 | 0.014 | 1.866 | 0.022 |
| **Vehicle characteristics** | | | | |
| Vehicle towed | 1.510 | < 0.001 | 1.677 | < 0.001 |
| Parameter distribution's standard deviation | NA | NA | 3.043 | 0.018 |
| HAZMAT placard | 1.539 | 0.005 | 1.847 | 0.041 |
| Parameter distribution's standard deviation | NA | NA | 2.118 | 0.048 |
| Vehicle maneuver (straight) | -0.614 | 0.030 | -0.758 | 0.096 |
| **Crash characteristics** | | | | |
| Hit and run | -1.832 | 0.083 | -3.106 | 0.087 |
| Facility type (rural) | 0.557 | 0.067 | 1.015 | 0.038 |
| Angle | 0.569 | 0.047 | 0.912 | 0.042 |
| **Road and environmental characteristics** | | | | |
| Horizontal curve | -0.944 | 0.028 | -1.435 | 0.061 |
| Level | 0.215 | 0.081 | 0.491 | 0.079 |
| Adverse weather | 0.698 | 0.022 | 1.097 | 0.048 |
| **Model fit statistics** | | | | |
| Observation, N | 1,084 | | 1,084 | |
| Log-likelihood | -232.317 | | -236.060 | |
| AIC | 516.120 | | 512.633 | |
| BIC | 632.355 | | 625.865 | |

**Table 5: Binary and mixed binary logit model results for injury severity of O**

| Variable | Binary logit model | | Mixed binary logit model | |
|---|---|---|---|---|
| | Coefficient estimate | P-value | Coefficient estimate | P-value |
| Constant | 2.388 | < 0.001 | 2.691 | < 0.001 |
| **Occupant characteristics** | | | | |
| Passenger | 1.592 | < 0.001 | 2.383 | 0.003 |
| Middle | 0.368 | 0.007 | 0.529 | 0.029 |
| Male | 0.689 | 0.022 | 1.301 | 0.028 |
| Airbag deployment | -1.625 | < 0.001 | -3.018 | < 0.001 |
| OD impairment | -2.364 | 0.002 | -4.840 | 0.003 |
| License status (clear) | 0.514 | 0.029 | 0.541 | 0.001 |
| License restriction | 0.497 | 0.034 | 0.756 | 0.091 |
| SPD improper action | -0.682 | 0.064 | -1.440 | 0.033 |
| OD improper action | -0.736 | 0.060 | -1.849 | 0.056 |
| **Vehicle characteristics** | | | | |
| Vehicle towed | -1.574 | < 0.001 | -1.596 | < 0.001 |
| Parameter distribution's standard deviation | NA | NA | 3.799 | 0.023 |
| HAZMAT placard | -0.575 | < 0.001 | -0.925 | 0.010 |
| Parameter distribution's standard deviation | NA | NA | 2.259 | 0.017 |
| Vehicle maneuver (straight) | 0.535 | 0.046 | 0.771 | 0.095 |
| Estimated speed (< 30 mph) | -0.518 | 0.068 | -1.093 | 0.048 |
| Estimated speed (between 60 and 70 mph) | -0.859 | 0.050 | -1.594 | 0.097 |
| **Crash characteristics** | | | | |
| Hit and run | 1.799 | 0.086 | 4.028 | 0.098 |
| **Road and environmental characteristics** | | | | |
| Uphill | 1.070 | 0.008 | 2.188 | 0.009 |
| Adverse weather | -0.683 | 0.018 | -1.018 | 0.036 |
| **Model fit statistics** | | | | |
| Observation, N | 1,084 | | 1,084 | |
| Log-likelihood | -254.192 | | -258.666 | |
| AIC | 553.332 | | 548.383 | |
| BIC | 648.152 | | 643.124 | |

**Table 6: Average odds ratio results of the mixed binary logit models**

| Variable | Average odds ratio | | |
|---|---|---|---|
| **Occupant characteristics** | KA | BC | O |
| Driver | - | 20.01 | - |
| Passenger | - | - | 10.84 |
| Young | - | 3.23 | - |
| Middle | - | - | 1.70 |
| Male | - | - | 3.67 |
| Female | - | 5.81 | - |
| Restraint usage | 0.05 | - | - |
| Airbag deployment | 195.00 | 8.13 | 0.05 |
| Front row | - | 0.37 | - |
| License type (CDL) | - | 4.20 | - |
| License status (clear) | - | 0.44 | 1.72 |
| License restriction | - | 0.50 | 2.13 |
| SPD impairment | 91.84 | - | - |
| OD impairment | - | 56.54 | 0.01 |
| SPD improper action | - | 3.11 | 0.24 |
| OD improper action | - | 6.46 | 0.16 |
| **Vehicle characteristics** | | | |
| Vehicle towed | - | 5.35 | 0.20 |
| HAZMAT placard | 20.64 | 6.34 | 0.40 |
| Vehicle maneuver (straight) | - | 0.47 | 2.16 |
| Estimated speed (< 30 mph) | - | - | 0.34 |
| Estimated speed (60-70 mph) | - | - | 0.20 |
| Estimated speed (> 60 mph) | 54.71 | - | - |
| **Crash characteristics** | | | |
| Facility type (rural) | - | 2.76 | - |
| Junction related | 0.06 | - | - |
| Alcohol involved | 24.44 | - | - |
| Hit and run | - | 0.05 | 56.15 |
| Angle | - | 2.49 | - |
| **Road and environmental characteristics** | | | |
| Horizontal curve | 16.04 | 0.24 | - |
| Downhill | 11.09 | - | - |
| Uphill | - | - | 8.92 |
| Level | - | 1.63 | - |
| Adverse weather | 13.76 | 2.99 | 0.36 |

## 5. Conclusions and recommendations

Keeping up roadways in snowbelt states amid the winter is exceptionally challenging, especially in rural states like Wyoming. Snow, combined with strong wind, bone-chilling temperatures, fog, and vehicles covered up by snow, can make driving conditions not only difficult but also nearly impossible. Depending on the intensity, snowfall can deteriorate visibility, pavement friction performance, vehicle stability, and maneuverability. Snow removal and deicing using snowplow trucks assist transportation agencies to enhance roadway safety and mobility. However, due to slower travel speeds during these operations, motorists often end up in crashes for poor visibility and disturbance of the snow. Despite the risk associated with snowplows, no previous study was found that extensively investigate the factors associated with injury severity in snowplow-involved crashes. Therefore, this paper presents an extensive exploratory analysis and fills this knowledge gap by identifying the significant contributing factors affecting the occupant injury severity from the aspects of crashes with snowplow involvement.

The term "crash" refers to an event that occurs at random. Statistical models facilitate a deeper comprehension of their variability by analyzing the factors associated with these random occurrences. This study used ordered logit models to investigate occupant injury severity in snowplow-related crashes due to the ordinal discrete nature of injury severity outcomes. The ordered logit model, also known as a binary mixed-logit model, has widespread use in crash severity analysis as it enables model parameters to vary across observations to account for data heterogeneity (Haleem and Gan, 2013; Liu and Fan, 2020). Eleven years (2010-2020) of historical snowplow-related crash data from Wyoming were used to identify the impacts of the various occupant, vehicle, crash, roadway, and environmental characteristics on the corresponding occupant injury severity.

The results obtained from three separate models demonstrate various significant factors contributing to occupant injury severity in snowplow-related crashes. Based on the modeling results, a number of safety implications can be outlined. First, while investigating driving errors, other vehicle drivers were found more responsible than snowplow drivers to contribute to more severe injuries when colliding with snowplow trucks. This finding recommends introducing more targeted special training programs on how to drive next to a snowplow on a challenging roadway with reduced visibility. In 2007, Winter Safety Campaign was launched by Clear Roads, promoting national multimedia (audio-visual) on winter driving safety. Using the slogan "Ice and Snow…Take It Slow", Clear Roads established a standard logo and a range of sample campaign materials. Many state and local agencies customized the campaign materials to forward these messages within their own states (Clear Roads, 2022). Therefore, existing safety programs should foster and reinforce this type of targeted training. Also, this type of training should become a part of the entry-level driver training or at the very least the onboarding training in snowbelt states. In the training of new young drivers, particular emphasis on the proper use of safety equipment and the dangers of driving close to snowplows, and how to navigate safely and properly should be considered when producing warnings and other means to communicate dangers. Second, while examining vehicle characteristics, vehicles' estimated speeds exceeding 60 mph were found to contribute to more severe injuries. Winter maintenance operations using snowplows are typically performed at reduced speeds directly in the roadway travel lanes, resulting in significant speed differences as compared to other traffic. Wyoming Highway Patrol (WHP) should take stricter measures on enforcing slow driving during snowfall or snowplow operations. Lastly, more severe snowplow-related crashes occurred in challenging roadway geometry (i.e., horizontal curve and downhill segment) and during adverse weather conditions. More warning signs should be installed at locations with severe downgrades. WYDOT could also enhance delineation and friction for horizontal curves. Moreover, WYDOT should upgrade advanced warning systems by displaying messages on dynamic message signs (DMS) to remind drivers about the importance of being cautious during the above-mentioned conditions. Findings from this study are expected to help WYDOT and policymakers take necessary actions in reducing snowplow-involved crashes in Wyoming by targeting appropriate strategies and proper resource allocation.

Several data limitations and gaps were encountered in this research. The CARE crash database has many missing or unknown values in the investigated variables, which were discarded in this study. This could bias the modeling results. Continuing research will examine the impact of the driver at fault and speed variation of snowplow-related crashes via separate models. Investigating the conspicuity of snowplow trucks is another emerging research of interest that will be conducted in the future to examine the safety benefits of making snowplow trucks more visible to motorists using warning lights and reflective tape. Finally, with the implementation of a connected vehicle pilot (CV) deployment program in Wyoming, this study can provide opportunities to conduct future research by incorporating real-time weather and traffic data on the individual snowplow-involved crash level.

## Declaration statements

The authors report no potential conflict of interest.

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## References


Bhat, C.R. (2003). Simulation estimation of mixed discrete choice models using randomized and scrambled Halton sequences. *Transportation Research Part B: Methodological,* 37 (9), 837-855. https://doi.org/10.1016/S0191-2615(02)00090-5

Camden, M.C., Hickman, J.S., Tidwell, S., Soccolich, S.A., Hammond, R., & Hanowski, R.J. (2020). Defensive Driving for Snowplow Operators (No. CR 18-01). Minnesota. Department of Transportation. Clear Roads Pooled Fund.

Chen, C., Zhang, G., Huang, H., Wang, J., & Tarefder, R.A. (2016). Examining driver injury severity outcomes in rural non-interstate roadway crashes using a hierarchical ordered logit model. *Accident Analysis & Prevention*, 96, 79–87. https://doi.org/10.1016/j.aap.2016.06.015

Chen, F., & Chen, S. (2011). Injury severities of truck drivers in single- and multi-vehicle accidents on rural highways. *Accid. Anal. Prev.,* 43(5), 1677–1688. https://doi.org/10.1016/j.aap.2011.03.026

Clear Roads. (2022). *Research for Winter Highway Maintenance*. Retrieved from https://clearroads.org/

Dao, B., Hasanzadeh, S., Walker, C.L., Steinkruger, D., Esmaeili, B., & Anderson, M.R. (2019). Current practices of winter maintenance operations and perceptions of winter weather conditions. *Journal of Cold Regions Engineering*, (3), 04019008. https://doi.org/10.1061/(ASCE)CR.1943-5495.0000191

Eisenberg, D., & Warner, K.E. (2005). Effects of snowfalls on motor vehicle collisions, injuries, and fatalities. *American Journal of Public Health*, 95(1), 120-124. https://doi.org/10.2105/AJPH.2004.048926

Eluru, N., Paleti, R., Pendyala, R. M., & Bhat, C. R. (2010). Modeling multiple vehicle occupant injury severity: A copula-based multivariate approach. *Transportation Research Record*, *2165*, 1-11. https://doi.org/10.3141/2165-01

Evrensel, C.A., Jiang, Y., Kim, K., Dur, O., Hu A., and Ma, K. (2008). Winter Maintenance Improvements: Phase I. Report No: RDT08-001. Nevada Department of Transportation (NDOT).

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

Farid, A., & Ksaibati, K. (2020). Modeling two-lane highway passing-related crashes using mixed ordinal probit regression. *Journal of Transportation Engineering, Part A: Systems*, *146*(9), 04020092. https://doi.org/10.1061/jtepbs.0000428.

Federal Highway Administration (FHWA). *Snow and Ice*. http://www.ops.fhwa.dot.gov/weather/weather_events/snow_ice.htm

Fu, L., & Perchanok, M.S. (2006). *Effects of winter weather and maintenance treatments on highway safety* (No. 06-0728).

Haleem, K., & Gan, A. (2013). Effect of driver's age and side of impact on crash severity along urban freeways: A mixed logit approach. *Journal of Safety Research*, *46*, 67-76. https://doi.org/10.1016/j.jsr.2013.04.002

Halton, J.H., (1960). On the efficiency of evaluating certain quasirandom sequences of points in evaluating multi-dimensional integrals. *Numerische Mathematik, 2*(1), 84-90. https://doi.org/10.1007/BF01386213

Hanbali, R.M., & Kuemmel, D.A. (1992). Traffic accident analysis of ice control operation. *Transportation Research Board*.

Haq, M. T., Ampadu, V. M. K., & Ksaibati, K. (2023). An investigation of brake failure related crashes and injury severity on mountainous roadways in Wyoming. *Journal of Safety Research*, *84*, 7-17. https://doi.org/10.1016/j.jsr.2022.10.003

Haq, M. T., Zlatkovic, M., & Ksaibati, K. (2020). Investigating occupant injury severity of truck-involved crashes based on vehicle types on a mountainous freeway: A hierarchical Bayesian random intercept approach. *Accident Analysis & Prevention*, *144*, 105654. https://doi.org/10.1016/j.aap.2020.105654

Haq, M. T., Zlatkovic, M., & Ksaibati, K. (2021a). Assessment of commercial truck driver injury severity as a result of driving actions. *Transportation Research Record*, *2675*(9), 1707-1719. https://doi.org/10.1177/03611981211009880

Haq, M. T., Zlatkovic, M., & Ksaibati, K. (2021b). Assessment of commercial truck driver injury severity based on truck configuration along a mountainous roadway using hierarchical Bayesian random intercept approach. *Accident Analysis & Prevention*, *162*, 106392. https://doi.org/10.1016/j.aap.2021.106392

Heqimi, G. (2016). *Using spatial interpolation to determine impacts of snowfall on traffic crashes*. Michigan State University.

Hossain, M. J., Ivan, J. N., Zhao, S., Wang, K., Sharmin, S., Ravishanker, N., & Jackson, E. (2023). Considering demographics of other involved drivers in predicting the highest driver injury severity in multi-vehicle crashes on rural two-lane roads in California. *Journal of Transportation Safety & Security*, *15*(1), 43-58. https://doi.org/10.1080/19439962.2022.2033899

Iowa Department of Transportation (IOWADOT). (2017). *Safe Travel around Snowplows*. https://iowadot.gov/maintenance/pdf/SafeTravelAroundSnowplows.pdf.

Islam, S., Jones, S. L., & Dye, D. (2014). Comprehensive analysis of single-and multi-vehicle large truck at-fault crashes on rural and urban roadways in Alabama. *Accident Analysis & Prevention*, *67*, 148-158. https://doi.org/10.1016/j.aap.2014.02.014.

Kutner, M. H., Nachtsheim, C.J., Neter, J., & Li, W. (2005). *Applied Linear Statistical Model*. 5th ed., New York, NY: McGraw-Hill/Irwin.

Lemp, J. D., Kockelman, K. M., & Unnikrishnan, A. (2011). Analysis of large truck crash severity using heteroskedastic ordered probit models. *Accident Analysis & Prevention*, *43*(1), 370-380. https://doi.org/10.1016/j.aap.2010.09.006

Liu, P., & Fan, W. (2020). Exploring injury severity in head-on crashes using latent class clustering analysis and mixed logit model: A case study of North Carolina. *Accident Analysis & Prevention*, *135*, 105388. https://doi.org/10.1016/j.aap.2019.105388

Michigan Department of Transportation (MDOT). (2017). *Michigan NETS Winter Driving Safety Tips*. https://www.michigan.gov/documents/Nov05_144130_7.pdf.

Minnesota Department of Transportation (MnDOT). (1999). Evaluation of the Minnesota Department of Transportation's Intelligent Vehicle Initiative Snowplow Demonstration Project on Trunk Highway 19 Winter 1998-1999. Booz·Allen & Hamilton Inc.

Naik, B., Tung, L. W., Zhao, S., & Khattak, A. J. (2016). Weather impacts on single-vehicle truck crash injury severity. *Journal of Safety Research*, *58*, 57-65. https://doi.org/10.1016/j.jsr.2016.06.005

Norrman, J., Eriksson, M., & Lindqvist, S. (2000). Relationships between road slipperiness, traffic accident risk and winter road maintenance activity. *Climate Research*, *15*(3), 185-193. https://doi.org/10.3354/cr015185

O'Donnell, C.J., & Connor, D.H. (1996). Predicting the severity using models of ordered multiple choice. *Accident Analysis and Prevention*, *28*(6), 739–753. https://doi.org/10.1016/S0001-4575(96)00050-4

Obeng, K. (2008). Injury severity, vehicle safety features, and intersection crashes. *Traffic Injury Prevention*, *9*(3), 268–276. https://doi.org/10.1080/15389580802040311.

Pahukula, J., Hernandez, S., & Unnikrishnan, A. (2015). A time of day analysis of crashes involving large trucks in urban areas. *Accident Analysis & Prevention*, *75*, 155-163. https://doi.org/10.1016/j.aap.2014.11.021

Qiu, L., & Nixon, W. A. (2008). Effects of adverse weather on traffic crashes: systematic review and meta-analysis. *Transportation Research Record*, *2055*(1), 139-146. https://doi.org/10.3141/2055-16

Tang, W.J., Zhang, G.H., & Liao, M.J. (2015). A framework of winter road maintenance optimization. In *2015 11th International Conference on Natural Computation (ICNC)* (pp. 1057-1061), IEEE. https://doi.org/10.1109/ICNC.2015.7378138

The Trucker. (2021). *Multiple snowplows hit on Wyoming interstates, highways over five-day period*. Retrieved from https://www.thetrucker.com/trucking-news/the-nation/multiplesnowplows-hit-on-wyoming-interstates-highways-over-five-day-period

Train, K.E. (2003). *Discrete Choice Methods with Simulation*. First Ed., Cambridge University Press, Cambridge. https://doi.org/10.1017/CBO9780511753930

Uddin, M., & Huynh, N. (2018). Factors influencing injury severity of crashes involving HAZMAT trucks. *International Journal of Transportation Science and Technology*, *7*(1), 1-9. https://doi.org/10.1016/j.ijtst.2017.06.004.

Washington, S.P., Karlaftis, M.G., & Mannering, F. (2011). *Statistical and Econometric Methods for Transportation Data Analysis*, second ed. Chapman & Hall/CRC, Boca Raton.41.

Wyoming Seatbelt Coalition. (2022). *Buckle Up for Life, Wyoming*. Retrieved from https://buckleup4lifewy.org/

Yen, K., Tan, H-S., Steinfeld, A., …. & Ravani, B. (2000). *Development of an advanced snowplow driver assistance system (ASP-II). Final Report of Contract RTA65A0054*. California Department of Transportation.

Zhu, X., & Srinivasan, S. (2011a). Modeling occupant-level injury severity: An application to large-truck crashes. *Accident Analysis and Prevention*, 43(4), 1427–1437. https://doi.org/10.1016/j.aap.2011.02.021

Zhu, X., & Srinivasan, S. (2011). A comprehensive analysis of factors influencing the injury severity of large-truck crashes. *Accident Analysis & Prevention*, *43*(1), 49-57. https://doi.org/10.1016/j.aap.2010.07.007

Zockaie, A., Saedi, R., Gates, T. J., Savolainen, P. T., Schneider, B., Ghamami, M., ... & Zhou, C. (2018). *Evaluation of a Collision Avoidance and Mitigation System (CAMS) on Winter Maintenance Trucks* (No. OR 17-103). Michigan. Dept. of Transportation. Research Administration.