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Analysis of Injury Severity of Work Zone Truck-Involved Crashes in South Carolina for Interstates and Non-Interstates

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Abstract: This study investigates factors contributing to the injury severity of truck-involved work zones crashes in South Carolina (SC). The outcome of interest is injury or property damage only crashes, and the explanatory factors examined include the occupant, vehicle, collision, roadway, temporal, and environmental characteristics. Two mixed (random parameter) logit models are developed, one for non-interstates with speed limits less than 60 miles per hour (mph) and one for interstates with speed limits greater than or equal to 60 mph, using South Carolina statewide truck-involved work zone crash data from 2014 to 2020. Results of log-likelihood ratio tests indicate that separate speed models are warranted. The factors that were found to contribute to injury at the 90% confidence level in both models (interstate and non-interstate) are (1) dark lighting conditions, (2) female (at-fault) drivers, and (3) driving too fast for roadway conditions. Significant factors that apply only to non-interstates are SC or US primary roadways, activity area of the work zone, at-fault drivers under 35, sideswipe collision, presence of workers in the work zone, and collision with fixed objects. Significant factors that apply only to interstates are three or more vehicles, rear-end collision, location before the first work zone sign, and weekdays.

Keywords: crash injury severity; truck-involved crashes; work zone crashes; mixed logit model

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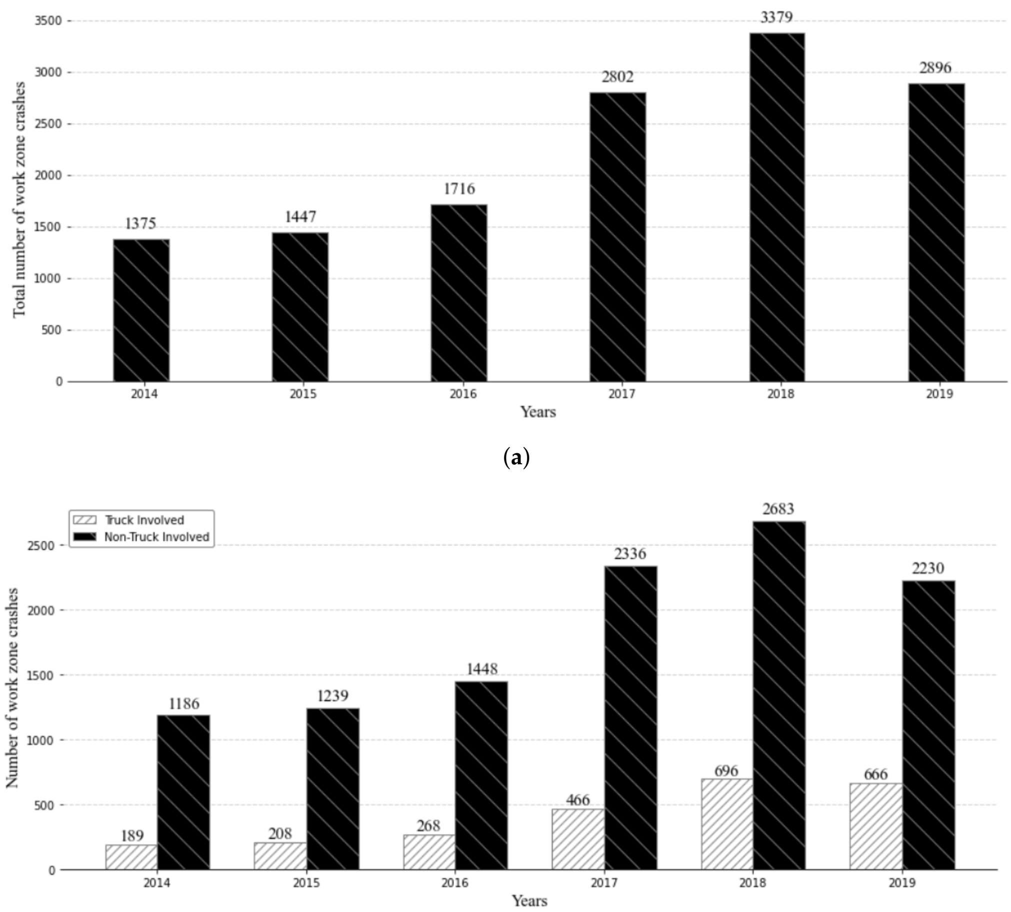
1. Introduction

Safety of workers during highway construction or maintenance is a major concern and well-recognized problem by the State Departments of Transportation (DOTs) because work zones alter the normal traffic flow, requiring motorists to change their speeds, process information from roadside signs, make merging maneuvers, and travel next to cones or barricades. These activities can lead to vehicular crashes and injury to motorists and workers in the work zones. Trucks, in particular, face additional challenges when navigating work zones compared to the passenger vehicles. The difficulties are due to longer stopping distance, larger blind spots, reduced maneuverability in narrower lanes, and reduced brightness or increased glare during nighttime operations in work zones. Truck-involved crashes in work zones pose a greater risk for injuries and fatalities, and they are more serious in nature than crashes that occur in non-work zones [1]. Additionally, truck-involved crashes pose a greater economic impact as trucks carry high-value goods and require a longer incident clearance time. Despite initiatives implemented at federal and state levels to improve work zone safety (e.g., Rule on Work Zone Safety and Mobility, National Work Zone Awareness Week), truck-involved crashes in work zones have continued to increase in recent years.

In the US, the number of fatal crashes in work zones has increased from 533 in 2011 to 774 in 2020 (a 45.2% increase). The number of truck-involved fatalities in work zones has increased from 169 in the year 2011 to 240 in the year 2020 (a 42% increase) [2]. Moreover, a higher proportion of fatal crashes in work zones are attributed to trucks. In 2020, trucks accounted for more than one-quarter of fatal crashes in work zones nationwide (204 out of total 774 crashes) [2]. A similar trend is observed in the state of South Carolina. The number of work zone collisions increased from 1375 in 2014 to 2896 in 2019 (a 110.6% increase) with the highest occurring in 2018, as shown in Figure 1a [3]. Moreover, work-zone-related collisions resulted in an annual average of 13 people killed and 25 seriously injured from 2014 to 2019. The number of truck-involved collisions in work zones is significant, as shown in Figure 1b [3]. It increased from 189 in 2014 to 666 in 2019 (a 252.4% increase), with the peak occurring in 2018. The increasing trend from 2014 to 2019 is a concern, given that the number of work zones is expected to increase significantly due to the increase in funding for construction projects [4]. It should be noted that due to the COVID-19 pandemic, the total number of crashes and truck-involved crashes in work zones in South Carolina decreased in 2020. Nevertheless, an understanding of the underlying contributing factors is necessary for developing countermeasures to eliminate or mitigate truck-involved crashes at work ones.



(**a**)

(**b**)

Figure 1. Number of crashes in work zones in South Carolina from 2014 to 2019: (**a**) total, and (**b**) truck-involved.

Previous studies [5–10] have indicated that speed is a contributing factor to injury severity of truck-involved crashes in work zones. However, these studies used speed as a categorical variable in their models. The interaction between variables is complex, and can vary significantly across different speed categories. For example, while the aggregate model may suggest that higher speeds may contribute to injury severity in truck-involved crashes in work zones, its effect may vary under different speed values. That is, crashes in work zones with speed limits above a threshold increase the likelihood of injury (e.g., [7,8]), while crashes in work zones with speed limits below a threshold have no effect on the likelihood of injury [11]. As such, disaggregating truck-involved crashes in work zones by speed can provide additional insights on the effect of speed on truck-involved work zone crashes.

Recognizing that not all road projects cause the same level of work zone impacts, the Federal Highway Administration established a category of projects called"significant projects" [12], which are those that are likely to have much greater effects on traffic conditions in and around their work zones than others will. Interstate projects are typically classified as significant projects [12]. For this reason, it is speculated that the crashes in work zones on interstates and their contributing factors may be different than those that occur on secondary or primary roads (non-interstates). Therefore, the objective of this study is to investigate factors that contribute to injury of truck-involved crashes in work zones in South Carolina for interstates (speed limit $\geq$ 60 mph) and non-interstates (speed limit $<$ 60 mph); there are some expressways in South Carolina that have a posted speed limit of 60 mph. A mixed logit (random parameter logit) model is developed for each, using South Carolina statewide work zone crash data from 2014 to 2020. Mixed logit models have been used more frequently in recent years due to their ability to account for unobserved heterogeneity [13–22]. In addition, mixed models require less detailed crash-specific data compared to fixed-parameter logit models [23]. To the best of the authors' knowledge, this study is the first to examine the difference in factors that contribute to truck-involved crash injuries in work zones between interstates and non-interstates. By examining both types of roads (interstates vs. non-interstates) or both types of projects (significant vs. nonsignificant), this study aims to identify the key differences in factors that lead to crash injuries so that targeted interventions and policies can be developed for the respective roadway type. To this end, this study contributes to the current body of work that seeks to improve work zone control design practices to prevent injuries and save lives.

The remainder of this paper is organized as follows. A brief review of related studies is provided in the next section, followed by a description of the dataset. Next, the methodology employed in this paper is presented. Then, model estimation results are presented and discussed. The paper concludes with a discussion of key findings, limitations, and future work.

2. Literature Review

Identifying the factors that impact the severity of crashes involving trucks has been a problem of interest to a number of researchers. Truck-involved crashes have been examined in a very wide range of scenarios ranging from single-truck collisions to rural versus urban settings to crashes in work zones. A common theme, which is in line with intuition, across all the work in this space is the importance of speed. Khattak et al. [5] focused specifically on single-truck collisions (rollovers) in the state of North Carolina. Through an ordered probit model, they found that dangerous driving behavior such as reckless driving, speeding, and alcohol/drug use are key risk factors in such crashes. Further, they observed that roadways with more curves, crashes involving trucks transporting hazardous materials, and post-crash fires lead to more severe injuries. Khorashadi et al. [6] compared the factors between rural and urban crashes when trucks are involved. From a methodological perspective, they divided their data into rural and urban samples, and used a multinomial logit model to identify the most relevant factors impacting injury severity. They found that tractor–trailer combinations increased the likelihood of severe injury, and this effect was especially pronounced in urban settings. A similar dynamic was observed for crashes where drug or alcohol use was reported. With regard to the uniqueness of factors impacting crashes in the two settings, they found that crashes in rural (urban) settings had 13 (17) unique factors that were not observed in urban (rural) settings. Further, they observed that excessive speeding contributed to more severe injuries in rural areas. Uddin and Huynh [7] built on this work by specifically considering how light conditions interact with rural and urban settings, while also accounting for heterogeneity through the use of a mixed logit model. They found that age, gender, truck type, AADT, speed, and weather conditions were found to have distinctly different impacts across the combinations of light condition and roadway type (rural/urban). Interestingly, they found that higher speed limits result in more severe injuries in dark conditions in rural settings, but less severe injuries in urban settings. In a similar vein, Uddin and Huynh [8] used a mixed logit model to examine the factors that impact injury severity under different weather conditions. They divided their data into three samples based on the weather condition (dry, rain, snow) at the time of a crash. They found that gender, time of day, the type of truck, the type of crash (rear-end and sideswipe), and speed limit were among the main factors impacting injury severity in different ways across the three weather conditions. They found that high speed limits increased the likelihood of more severe crashes in rainy conditions but did not observe such a relationship in snowy conditions.Chen et al. [9] and Liu and Fan [10] provided further nuance by considering how these factors vary specifically in a river-crossing tunnel and for rear-end crashes, respectively. Chen et al. [9] investigated a number of factors (driver, environment, vehicle, and tunnel-related). Regarding the impact of speed, they found that severe injuries are more likely when posted speed limits are greater than 80 mph. Liu and Fan [10] used a mixed logit model and found that it is "better" to model speed limit over 50 mph as a random parameter. They found that driving under the influence of alcohol or drugs, rural roadways, dark light conditions, grade roadway configurations, and speed limits over 50 mph are more likely to result in severe injuries. Using a nonparametric tree approach, Chang and Chien [24] rank-ordered factors that impact injury severity and found that speed is a fairly important factor in predicting injury severity. We contribute to this stream of research on crashes involving trucks in two ways. First, we specifically focus on truck-involved crashes in work zones, which represent an especially precarious type of roadway, as highlighted in Section 1. Second, we build on the aforementioned findings regarding speed by examining how factors affecting injury severity vary across two speed limits (below and above 60 mph), which represent interstate and non-interstate roads.

While the aforementioned papers focused on truck-involved crashes in general, some studies focused specifically on truck-involved crashes in work zones, given the precarity of the movement of such large vehicles in tight spaces involving workers. Khattak and Targa [1] compared truck- and non-truck-involved crashes in work zones. Unsurprisingly, they found that the presence of trucks resulted in more severe injury, especially in work zones. This impact of the presence of trucks on injury severity is accentuated by two-way (unprotected) roadways, detours in the opposite direction, and high posted speed limits. Weng et al. [25] built a crash risk model to examine which vehicle patterns are more likely to result in crashes in work zones. They found that car–truck following patterns are the most likely to result in crashes, with speed being positively associated with the likelihood of a crash. They also found that rear-end crash risk is higher under the following situations: (1) work intensity is high, (2) in the lane adjacent to the work zone, (3) high flow of traffic, and (4) high fraction of heavy vehicles. Osman et al. [26] used a variety of models (multinomial logit, nested logit, ordered logit, and generalized ordered logit) to examine the factors impacting injury severity in truck-involved crashes in work zones. With respect to work zone characteristics impacting injury severity, they found that work on shoulders or medians resulted in more severe injuries, while lane closures and crashes in the transition area were typically less likely to result in severe injuries. They also found that higher posted speed limits were associated with more severe injuries. Building on the work of Khorashadi et al. [6] and Uddin and Huynh [7], Yu et al. [27] examined how injury-severity-related factors vary across urban and rural settings specifically in the context of work zones. They compared the use of a mixed logit model and a partial proportional odds logit model to account for unobserved heterogeneity, and found that the latter performs better. Further, they observed that speeding is especially relevant in urban settings and suggested the countermeasure of higher speeding fines in urban work zones. Zhang and Hassan [28] used a random-parameter-ordered probit model to investigate factors that contributed to work zone rear-end crashes on Egypt's highways. Their results indicated that speeding and foggy weather should be modeled as random parameters, and were found to positively impact the likelihood of crashes taking place. Further, they observed that the risk of rear-end crashes was greater during nighttime and on weekends. Gupta et al. [11] used a random forest model to characterize the most important factors that impact fatality in truck-involved work zone crashes. Unlike most of the other work in this space, they did not find speed to be among the most important factors. Instead, they observed that pedestrian involvement and poor lighting conditions were the primary factors impacting injury severity. They also found that distracted drivers and the lack of airbags resulted in more severe injuries. A summary of the work related to truck-involved crashes in work zones is shown in Table 1. We contribute to this stream of work on truck-involved crashes in work zones by specifically accounting for whether the crash occurred on an interstate or non-interstate road. We achieve this by splitting our data based on the posted speed limit, which is especially relevant given that a majority of prior work has found that higher speed limits result in more severe injuries. By examining which factors are more impactful on interstate and non-interstate roads, we shed light on how work zones must be designed for these two types of roads. From a methodological perspective, we draw on the extant literature [7,8,27] by using a mixed logit model to account for heterogeneity across observations.

Table 1. Prior studies examining injury severity for truck-involved crashes in work zones.

Authors	Focus	Methodology	Injury Severity Levels	Primary Findings
Khattak and Targa [1]	Compare injury severity of truck-involved and non-truck involved crashes	Ordered probit	Fatality, severe injury, moderate injury, minor injury, no injury	Crashes involving trucks led to more severe injuries than non-truck involved crashes especially in work zones
Osman et al. [26]	Investigate causal factors contributing to injury severity in truck involved crashes	Multinomial logit, nested logit, ordered logit, generalized ordered logit (GORL)	Serious injury, injury, no injury	GORL works best. Primary factors include high speed limits, daytime, no control of access, rural principal arterials
Yu et al. [27]	Compare factors for rural and urban highways	Mixed logit (MXL), partial proportional odds logit (PPO)	Fatality/incapacitating/non-incapacitating, possible injury, PDO	PPO outperforms MXL. Lack of restraint & DUI are most influential. Unique factors across rural and urban highways
Zhang and Hassan [28]	Rear-end crashes	Random parameter ordered probit	Severe injury, injury, no injury	Speeding, foggy weather, weekends, nighttime, heavy vehicles are more likely to lead to severe injury
Gupta et al. [11]	General truck-involved work zone crashes	Ordered logistic decision trees, random forests	Fatal, injury, PDO	Pedestrian involvement, lighting conditions, safety equipment, driver condition and age, and work zone location are the primary contributors to fatal crashes

3. Materials and Methods

3.1. Data Description

In this study, mixed models were developed using South Carolina statewide work zone crash data from 2014 to 2020. In total, there were 15,727 crashes, with 93 being fatal, 176 having major injury, 674 having minor injury, 2451 having possible injury, and 12,333 having no injury. To prepare the dataset for modeling, it was filtered to include only those crashes that involved at least one truck, whether at fault or not. In the truck-involved work zone crash dataset, there were 3064 crashes with 29 (0.95%) being fatal, 36 (1.75%) with major injury, 121 (3.95%) with minor injury, 381 (12.43%) with possible injury, and 2496 (81.46%) with no injury. Due to the small number of observations per injury severity level, the five levels were combined into two: injury and property damage only (PDO), where injury includes fatal, major injury, minor injury, and possible injury. The final dataset contained 565 injury and 2488 PDO observations. It should be noted that the final dataset had 11 fewer observations [3064 − (565 + 2488)] than the initial dataset because these crash records did not have posted speed limits.

To evaluate the effect of the posted speed limit on the roadway where the work zone is located, the final dataset was first divided into three different speed limit categories: less than 40 mph, between 40 and 60 mph, and 60 mph or greater. The number of observations for the less than 40 mph category was 312. For this reason, only two speed limit categories were used” less than 60 mph and greater than or equal to 60 mph. The former category had 305 injury crashes and 1443 PDO crashes, whereas the latter category had 260 injury crashes and 1045 PDO crashes. The reason for choosing 60 mph as the demarcation speed is that interstates typically have a posted limit of 60 mph or higher, and guidelines for setting up work zones on interstates are more stringent. Table 2 presents the injury severity level frequency and percentage distribution by speed limit categories.

Descriptive statistics of explanatory variables examined in this study are shown in Table 3. They include characteristics related to vehicles, crashes, roadways, work zones, day and time, environment, and drivers.

Table 2. Injury severity level frequency and percentage distribution by posted speed limit levels.

Speed Category	Total Observation	Injury (%)	PDO (%)
Less than 60 mph	1748	305 (17.45)	1443 (82.55)
Greater than or equal to 60 mph	1305	260 (19.92)	1045 (80.08)

Table 3. Descriptive statistics of variables by two posted speed levels.

Variables	Speed < 60 mph		Speed ≥ 60 mph	
	Mean	Std. Dev.	Mean	Std. Dev.
Driver Characteristics				
Gender (1 if female driver is at fault in a crash, 0 otherwise)	0.15	0.35	0.11	0.32
Younger drivers (1 if age of at-fault driver are group below 35 years, 0 otherwise)	0.26	0.44	0.25	0.43
Middle-aged drivers (1 if age of at-fault driver is between 35 and 50 years, 0 otherwise)	0.24	0.47	0.24	0.43
Older drivers (1 if age of at-fault driver is above 50 years, 0 otherwise)	0.35	0.47	0.29	0.46
Driving too fast (1 if the contributing factor of crash is driving too fast, 0 otherwise)	0.28	0.45	0.39	0.49
Distracted (1 if the contributing factor of crash is distracted, 0 otherwise)	0.04	0.2	0.01	0.08

Table 3. *Cont.*

Variables	Speed <60 mph		Speed ≥60 mph	
	Mean	Std. Dev.	Mean	Std. Dev.
Failed (1 if the contributing factor of crash is failed to yield right of way, 0 otherwise)	0.08	0.27	0.02	0.15
Improper usage (1 if the contributing factor of crash is improper lane usage, 0 otherwise)	0.31	0.46	0.38	0.49
Under influence (1 if the contributing factor of crash is under the influence, 0 otherwise)	0.02	0.13	0.02	0.14
Crash Characteristics				
1 vehicle (1 if the number of vehicles involved in a crash is 1 or more, 0 otherwise)	0.06	0.24	0.06	0.23
2 vehicles (1 if the number of vehicles involved in a crash is 2, 0 otherwise)	0.84	0.37	0.77	0.42
3+ vehicles (1 if the number of vehicles involved in a crash is 3 or more, 0 otherwise)	0.10	0.30	0.17	0.37
Rear end (1 if manner of collision is rear end, 0 otherwise)	0.30	0.46	0.37	0.48
Sideswipe (1 if manner of collision is sideswipe, 0 otherwise)	0.36	0.48	0.38	0.48
Angle (1 if manner of collision is angle, 0 otherwise)	0.16	0.36	0.08	0.28
Fixed object (1 if 1st harmful event is fixed object, 0 otherwise)	0.07	0.26	0.09	0.28
Not fixed object (1 if 1st harmful event is not fixed object, 0 otherwise)	0.91	0.28	0.89	0.31
No collision (1 if 1st harmful event is no collision, 0 otherwise)	0.01	0.12	0.02	0.015
Roadway Characteristics				
SC, US Primary (1 if crash occurred in SC or US Primary, 0 otherwise)	0.25	0.43	0.01	0.12
Interstate (1 if crash occurred in interstate , 0 otherwise)	0.59	0.49	0.98	0.14
County/secondary/ramp (1 if crash occurred in county, secondary, or ramp, 0 otherwise)	0.16	0.37	0.01	0.07
Curve (1 if crash occurred in a curve, 0 otherwise)	0.04	0.19	0.03	0.17
Straight on grade (1 if crash occurred in a straight on grade, 0 otherwise)	0.11	0.32	0.12	0.33
Straight level (1 if crash occurred in a straight level, 0 otherwise)	0.83	0.37	0.84	0.37
Roadway (1 if first harmful event occurred on roadway, 0 otherwise)	0.90	0.29	0.89	0.32
Two-way undivided (1 if traffic-way is two-way undivided, 0 otherwise)	0.27	0.44	0.01	0.07
Environmental Characteristics				
Dark (1 if crash occurred in a dark lighting condition, 0 otherwise)	0.28	0.45	0.26	0.44
Dawn or dusk (1 if crash occurred in a dawn or dusk lighting condition, 0 otherwise)	0.03	0.17	0.04	0.19
Daylight (1 if crash occurred in a daylight lighting condition, 0 otherwise)	0.69	0.46	0.69	0.46
Clear (1 if crash occurred in a clear weather condition, 0 otherwise)	0.87	0.34	0.85	0.36
Dry (1 if crash occurred in a dry surface condition, 0 otherwise)	0.89	0.30	0.89	0.32

Table 3. *Cont.*

Variables	Speed <60 mph		Speed ≥60 mph	
	Mean	Std. Dev.	Mean	Std. Dev.
Work Zone Characteristics				
Shoulder/median (1 if work zone type is shoulder or median, 0 otherwise)	0.42	0.49	0.56	0.5
Lane closure (1 if work zone type is lane closure, 0 otherwise)	0.36	0.48	0.25	0.44
Lane shift/crossover (1 if work zone type is lane shift or crossover, 0 otherwise)	0.07	0.26	0.1	0.3
Activity area (1 if work zone location is activity area, 0 otherwise)	0.71	0.46	0.63	0.48
Before first sign (1 if work zone location is before first sign, 0 otherwise)	0.02	0.15	0.06	0.5
Advanced warning (1 if work zone location is advanced warning area, 0 otherwise)	0.09	0.28	0.12	0.32
Termination/transition (1 if crash location is termination or transition area, 0 otherwise)	0.18	0.39	0.20	0.40
Workers present (1 if workers present, 0 otherwise)	0.62	0.49	0.45	0.5
Temporal Characteristics				
Weekday (1 if crash happens on weekday, 0 otherwise)	0.89	0.30	0.87	0.33

3.2. Methodology

Based on the previous studies, mixed logit models have been considered as an efficient method to overcome unobserved heterogeneity due to accounting for observation-specific variation for explanatory variables [17,23,29–32]. In Sections 4.1–4.3, the details of developing the mixed logit model, marginal effect of factors, and likelihood ratio test for separated datasets are presented, respectively.

3.2.1. Mixed Logit Model

The utility function for the mixed logit model is derived by establishing the linear relation between injury severity level i for observation crash n, which is demonstrated in Equation (1) [7,32,33].

$$Y_i n = \beta_i X_i n + \epsilon_i n \tag{1}$$

where $Y_i n$ is defined as a variable explaining each injury severity level i ($i \in$ I representing injury and no injury severity level) for driver n . β_i is considered as a vector of estimated parameters, $X_i n$ is a vector of explanatory variables affecting work zone driver-injury severity level i and $\epsilon_i n$ is the error term or extreme value to capture unobserved heterogeneity distributed independent and identically over time, individual and alternatives. If the error term is generalized extreme value distributed, then the choice probability can be determined using the standard multinomial logit shown in Equation (2).

$$P_n(i) = \frac{exp\left[\beta_i X_i n\right]}{\sum_{i \in I} exp\left[\beta_i X_i n\right]} \tag{2}$$

$P_n(i)$ is regarded as the probability of injury severity level i caused by driver n. Mixed logit models allow the vector of estimated parameters to vary across different crashes. Each element of β_i may be either fixed or randomly distributed with fixed means, allowing for heterogeneity within the observed crash dataset. Extending the above multinomial logit model, Equation (3) can be rewritten as

$$P_n(i|\phi) = \frac{exp[\beta_i X_i n]}{\sum_{i \in I} exp[\beta_i X_i n]} f(\beta_i|\phi) d\beta_i \tag{3}$$

where $P_n(i|\phi)$ is the weighted average of the multinomial logit probabilities called mixed logit. The weight used to estimate the probability is calculated by $f(\beta_i|\phi)$, which is the density function of β_i, and ϕ is the parameter vector. The density function uses a distribution of parameter ϕ, where both a mean and variance are estimated. For the current work, normal distribution is used. It should be noted that elements of β_i are fixed and randomly distributed with specific statistical distributions. If the estimated variance is statistically significant then the modeled injury severity levels vary with respect to X across observations and account for crash-specific variation due to unobservables [34]. To overcome the computation complexity of estimating the parameters, β_i maximum likelihood estimation is implemented using simulation-based procedure and Halton draws ([35]). The pseudo R-squared (ρ^2) value is used to assess the overall model fit; it is computed using Equation (4).

$$\rho^2 = 1 - \frac{LL(\beta)}{LL(0)} \tag{4}$$

In the above equation, $LL(0)$ is defined as the log-likelihood at zero and $LL(\beta)$ calculates log-likelihood at convergence.

3.2.2. Marginal Effect

Marginal effect is used to determine how the probability of injury severity levels would be changed considering one unit change in the explanatory variables illustrated in Equation (5).

$$M^{P_i n}_{X_i n_k} = P_i n\left[given X_i n_k = 1\right] - P_i n\left[given X_i n_k = 0\right] \tag{5}$$

In the above equation, $P_i n$ states the the probability of injury severity level i for driver n, and $X_i n_k$ is the k-th independent variable affecting injury severity level i for driver n.

3.2.3. Likelihood Ratio Test

To determine whether the data should be modeled using two different speed categories, the log-likelihood ratio (LR) test between the full model using the entire dataset and speed models using separate datasets shown in Equation (6) was performed [34].

$$LR_{full} = -2\left[LL\left(\beta^{full}\right) - LL\left(\beta^{speed<60}\right) - LL\left(\beta^{speed>=60}\right)\right] \tag{6}$$

The model's log-likelihood at convergence for the full model on the entire dataset is defined as $LL(\beta^{full})$, while $LL(\beta^{speed<60})$ and $LL(\beta^{speed>=60})$ are the model's log-likelihood at the convergence on the separated datasets for speed limit less than 60 mph and speed limit greater than or equal to 60 mph, respectively. It should be noted that to calculate the log-likelihood values for two separate speed limits, the variables identified from the full model should be tested on the two categorized speed limit datasets. The LR statistic has χ^2 distribution with the degree of freedom computed by the difference among the summation of the number of estimated variables in two models and the number of estimated variables in the full model.

Parameter transferability is another test [34] often used to ascertain whether two different speed limits should be modeled separately; it is calculated using Equation (7).

$$LR_{a_b} = -2\left[LL\left(\beta^{a_b}\right) - LL\left(\beta^{a}\right)\right] \tag{7}$$

The log-likelihood at convergence for speed model a on the data from model b is defined as $LL(\beta^{a_b})$, and the log-likelihood at convergence for speed model a is defined as $LL(\beta^{a})$. The degree of freedom of this test is equal to the number of estimated variables in β^{ab}.

To estimate contributing factors affecting injury severity levels and to test the need to estimate separate models, the NLOGIT software (version 6) was used. The process used to produce model estimates is shown in Figure 2. As shown, this study used three datasets provided by the South Carolina DOT (1) unit crash dataset, which contains information of all vehicles involved in crashes, (2) location dataset, which provides environmental and temporal characteristics of the crashes, and (3) occupant dataset, which includes details about the occupants of all vehicles involved in the crashes. It is important to note that each dataset has a different number of observations. To create the final dataset for modeling in Nlogit software, the three datasets were merged using a common index, and this was accomplished using Python programming. The dataset was then filtered to include only truck-involved crashes and relevant variables. Subsequently, the variables were categorized based on previous research and SCDOT practices. The last data preparation step involved creating binary variables for modeling. The forward and backward stepwise selection method was used to arrive at the final model specification. A variable was retained in the model if it was significant at the 90% confidence interval. Models were compared against one another using the log-likelihood at convergence and the McFadden pseudo R-squared.

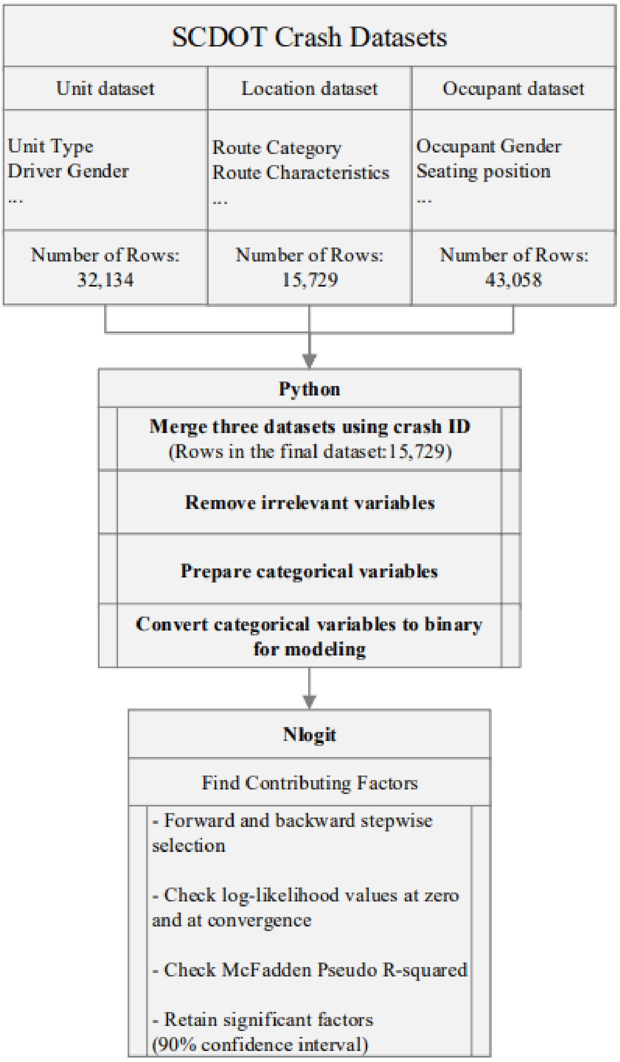


Figure 2. Model estimation process.

4. Results

The log-likelihood ratio test using Equation (6) yielded a value of 20.92 with 10 degrees of freedom (ρ-value < 0.022); the log-likelihood value for the full model is −1329.43, the log-likelihood value for the posted speed limit less than 60 mph is −744.83, and the log-likelihood value for the posted speed limit greater than or equal to 60 mph is −574.14. To find the log-likelihood values for the different speed categories, the full model is needed, and its estimation results are shown in Table 4. The result of the log-likelihood test suggests that the two different speed limit groups should be modeled separately with over 95% confidence.

Table 4. Parameter estimates and marginal effects for full model.

Variable	Coefficient	t-Statistic	ρ-Value	Marginal Effects	
				Injury	PDO
Defined for injury					
Rear end (standard deviation of parameter distribution)	0.86 (1.037)	4.02 (1.68)	0.000 (0.09)	0.064	−0.064
Constant	−0.49	−2.31	0.020		
Two vehicles	−1.24	−8.67	0.000	−0.109	0.109
Interstate	−0.42	−3.36	0.000	−0.039	0.039
Dark	0.42	3.52	0.000	0.017	−0.017
Female	0.53	3.54	0.000	0.011	−0.011
Weekday	−0.40	−2.62	0.009	−0.441	0.441
Lane shift/crossover	−0.49	−2.25	0.025	−0.004	0.004
Under influence	−1.04	−2.76	0.006	0.004	−0.004
Model statistics					
Number of observations	3064				
Log-likelihood at zero, LL(0)	−2123.8				
Log-likelihood at convergence, LL(β)	−1329.4				
$\rho^2 = 1 - \text{LL}(\beta)/\text{LL}(0)$	0.37				

It follows from the parameter transferability tests that two separate mixed logit models are to be estimated, one for posted speed limit less than 60 mph (representing non-interstates) and one for posted speed limit greater than or equal to 60 mph. Table 5 shows the results of this test. Each model predicts two levels of injury severity: injury and PDO. A simulation-based maximum likelihood method was utilized to estimate parameters β_i for the mixed logit models. To estimate random parameters, the normal distribution was considered and 500 Halton draws were used. The normal distribution was adopted because it was found to be statistically significant in a number of previous studies [7,8,13,14]. During the model development process, variables were retained in the specification if they had t-statistics corresponding to the 90% confidence level or higher on a two-tailed t-test. The random parameters were retained if their standard deviations had t-statistics corresponding to the 90% confidence level or higher. Model estimation results are shown in Tables 6 and 7 along with marginal effects of all the variables included in the final specifications. It should be noted that other demarcation speeds such as <50 mph and ≥50 mph were not evaluated. Thus, the following results and their implications apply only for selected demarcation speed, <60 mph and ≥60 mph.

Table 5. Results of parameter transferability tests for two speed limit categories.

Speed Limit Category	Speed Limit Category	
	<60 mph	≥60 mph
<60 mph	-	32.69 (10) ($p < 0.001$)
≥60 mph	28.28 (12) ($p = 0.005$)	-

Table 6. Parameter estimates and marginal effects for speed less than 60 mph model.

Variable	Coefficient	t-Statistic	ρ-Value	Marginal Effects	
				Injury	PDO
Defined for injury					
Two vehicles (standard deviation of parameter distribution)	−2.37 (2.72)	−3.13 (3.12)	0.002 (0.002)	−0.0044	0.0044
Constant	−2.40	−5.78	0.000		
SC, US primary	1.10	3.85	0.000	0.2880	−0.2880
Dark	0.67	2.78	0.005	0.0176	−0.0176
Female	0.71	2.25	0.024	0.0096	−0.0096
Age less than 35	0.51	2.32	0.020	0.0133	−0.0133
Activity area	0.49	−2.12	0.034	0.0304	−0.0304
Driving too fast	1.09	−4.48	0.000	0.0404	−0.0404
Sideswipe	−0.86	2.81	0.005	−0.0171	0.0171
Workers present	0.45	−2.01	0.004	0.0249	−0.0249
Fixed object	−1.28	3.53	0.000	−0.0097	0.0097
Model statistics					
Number of observations	1748				
Log-likelihood at zero, LL(0)	−1211.62				
Log-likelihood at convergence, LL(β)	−730.77				
$\rho^2 = 1 - \text{LL}(\beta)/\text{LL}(0)$	0.397				

Table 6 shows the parameter estimates for the model corresponding to work zone crashes where the posted speed limit of the roadway is less than 60 miles per hour. A positive coefficient implies that the variable is positively associated with the likelihood of that specific injury severity level. In other words, an increase in an independent variable with a positive coefficient results in a higher probability of occurrence of the specific injury severity level. In this model, one indicator variable, *two vehicles,* has a statistically significant standard deviation (random parameter). This result suggests that the effect of the *two vehicles* variable on injury severity varied significantly across crashes. This coefficient is normally distributed with a mean of −2.37 and a standard deviation of 2.72, indicating that this variable has a positive impact on 19.18% of observations (increases the likelihood of an injury crash) and a negative impact on 80.82% of observations (decreases the likelihood of an injury crash). This finding suggests that for a majority of truck-involved crashes in work zones where the roadway posted speed limit is below 60 mph (representing non-interstates), the involvement of two vehicles (as opposed to any other number) reduces the likelihood of an injury crash.

Table 7. Parameter estimates and marginal effects for truck-involved crashes in work zones with posted speed limit greater equal 60 miles per hour.

Variable	Coefficient	t-Statistic	ρ-Value	Marginal Effects	
				Injury	PDO
Defined for injury					
Constant	−2.42	−7.40	0.000		
Shoulder median (standard deviation of parameter distribution)	−1.1 (2.62)	2.13 (3.74)	0.033 (0.000)	0.0325	−0.0325
Multi vehicles	1.82	7.20	0.000	0.0484	−0.0484
Driving too fast	0.61	2.52	0.012	0.0330	−0.0330
Rear end	0.96	3.86	0.000	0.0526	−0.0526
Weekday	−0.71	−2.68	0.007	−0.0607	0.0607
Before first sign	0.64	−1.80	0.072	0.0051	−0.0051
Dark	0.95	−4.16	0.000	0.0308	−0.0308
Female	0.65	−2.35	0.019	0.0094	−0.0094
Model statistics					
Number of observations	1305				
Log-likelihood at zero, LL(0)	−904.56				
Log-likelihood at convergence, LL(β)	−567.27				
$\rho^2 = 1 - \text{LL}(\beta)/\ \text{LL}(0)$	0.37				

Table 7 shows the parameter estimates for the model corresponding to work zone crashes where the posted speed limit of the roadway is 60 mph or greater. In this model, one indicator variable, *shoulder/median*, has a statistically significant standard deviation (random parameter). This result suggests that the effect of the *shoulder/median* variable on injury severity varied significantly across crashes. This coefficient is normally distributed with a mean of 1.1 and a standard deviation of 2.62, indicating that this variable has a positive impact on 66.27% of observations (increases the likelihood of an injury crash) and a negative impact on 33.73% of observations (decreases the likelihood of an injury crash). This finding suggests that for a majority of truck-involved crashes in work zones where the roadway posted speed limit is 60 mph or greater (representing interstates), crash occurrence on a shoulder or median increases the likelihood of injury. A possible explanation for this is the use of concrete barriers on interstates in South Carolina and the smaller clear zones in some areas. According to the Federal Highway Administration, "By creating Clear Zones, roadway agencies can increase the likelihood that a roadway departure results in a safe recovery rather than a crash, and mitigate the severity of crashes that do occur".

Building separate injury severity models based on posted speed limits allows for a deeper understanding of how contributing factors vary across different speed limit ranges. The two models presented in Section 4 show that there are considerable differences in terms of the combination of factors affecting injury severity, and the magnitude of the impact of these factors. These results highlight the fact that the posted speed limit of the roadway where the work zone is located interacts greatly with other factors impacting injury severity. Table 8 provides a summary of the variables that are statistically significant for the two speed limit ranges. The random parameters are not included in this table because they have varying impacts across observations.

Table 8. Model comparisons.

Variable	Speed <60 mph		Speed ≥60 mph	
	Injury	PDO	Injury	PDO
SC, US primary	⇑	⇓		
Dark	⇑	⇓	⇑	⇓
Female	⇑	⇓	⇑	⇓
Younger drivers	⇑	⇓		
Activity area	⇑	⇓		
Driving too fast	⇑	⇓	⇑	⇓
Sideswipe	⇓	⇑		
Workers present	⇑	⇓		
Fixed object	⇓	⇑		
3+ vehicles			⇑	⇓
Rear end			⇑	⇓
Before 1st sign			⇑	⇓
Weekday			⇓	⇑

4.1. Driver Characteristics

Female drivers that are at fault are found to be more likely to suffer an injury in truck-involved crashes in work zones. This relationship is consistent across both speed limit ranges. For work zones with posted speed limits under 60 mph, the probability of suffering an injury is higher by 0.0096 for female drivers. In work zones with posted speed limits above 60 miles per hour, this probability is higher by 0.0094 for female drivers. This finding is consistent with those found by other studies [8,35,36]. In terms of the impact of the at-fault driver's age on injury severity, this is observed only when the posted speed limit is below 60 mph. In work zones with lower roadway posted speed limits, the probability of suffering an injury is higher by 0.013 for drivers below the age of 35 (compared to drivers whose age is 35 or greater).

4.2. Work Zone Characteristics

The presence of workers has a positive impact on the likelihood of injury for truck-involved crashes when the roadway posted speed limit is below 60 mph. The presence of workers increases the probability of suffering an injury by 0.0249. For work zones with low roadway speed limits (<60 mph), crashes occurring in the activity area have a higher probability (by 0.0304) of resulting in injury compared to any other part of a work zone. In contrast, for work zones with high roadway speed limits (≥60 mph), crashes occurring before the first sign have a higher probability of injury. This probability is higher by 0.0051 compared to the probability of injury for crashes occurring in any other section of a work zone.

4.3. Collision Characteristics

Collisions caused by a vehicle that is driving too fast for conditions are more likely to result in injury. This finding is aligned with that of Kai Wang [36]. This is the case for any posted speed limit. In work zones where the roadway speed limit is low (<60 mph), driving too fast for conditions increases the probability of injury by 0.04. Similarly, in work zones with high speed limits (≥60 mph), this results in a probability increase of 0.03. These findings suggest that it is imperative to focus on persuading drivers to refrain from driving too fast for conditions. In fact, the South Carolina Department of Public Safety announced, on 18 July 2022, the return of their speed crackdown—Operation Southern Slow Down—aimed at reducing traffic collisions across the southeast. During the week-long campaign in mid-July, drivers across the state of South Carolina saw the message "Slow down, speed kills" on interstates' dynamic message signs. In work zones with high speed limits (≥60 mph), crashes involving three or more vehicles are more likely to result in injury than those involving fewer vehicles. The magnitude of the increase in probability is 0.0484.

From the perspective of the manner of collision, in work zones with low speed limits (<60 mph), sideswipes are less likely to result in injury than other types of collision; they are 1.71% less likely to result in injury. On the other hand, in work zones with high speed limits (≥60 mph), rear-end collisions increase (compared to any other collision type) the probability of injury by 0.0526. This finding corresponds to the expectation that the higher the collision speed of rear-end crashes, the higher the probability of severe injury sustained by the drivers and occupants involved. This finding implies that drivers did not abide by the work zone warning signs and slow down sufficiently when traversing the work zone. Uddin and Huynh [8] found that rear-end crashes are less likely to cause major injuries under normal weather conditions. The difference in finding is due to the fact that their study focused on truck driver injury severity. It could also be due to the number of injury severity levels considered. Their study had three levels (no injury, minor injury, and major injury) while ours has just two (PDO and injury).

In work zones with low speed limits (<60 mph), collisions with fixed objects are less likely to result in injury than other collision types (collisions with nonfixed objects or crashes not involving a collision). A similar finding was reported by Uddin and Huynh [8] and Naik et al. [37] for truck-involved crashes that are not specific to work zones.

4.4. Roadway and Environmental Characteristics

From a lighting perspective, dark conditions are more likely to result in injury irrespective of the roadway posted speed limit. In work zones with low speed limits (<60 mph), the probability of injury is higher by 0.0176 under dark conditions. In work zones with high speed limits (≥60 mph), the probability of injury is higher by 0.0308 under dark conditions. Similar conclusions were drawn by other studies [8,13,28,36]. These findings suggest that the difficulty of driving in dark conditions is exacerbated in work zones with high posted speed limits. Thus, the use of lighting and advanced work zone warning systems should be utilized in dark conditions to reduce the likelihood of injury in dark conditions. Injuries are more likely to occur on routes that are classified as SC or US primary routes, but this is true only in work zones with low posted speed limits (<60 mph).

4.5. Temporal Characteristics

In work zones with low speed limits (<60 mph), crashes occurring on weekdays are less likely to result in injury in comparison to weekends. Specifically, when the roadway posted speed limits are below 60 mph, crashes resulting in an injury are 6% less likely on weekdays. This finding corroborates the results obtained by Zhang and Hassan [28]. The reason why there may be a lower probability of crashes on weekdays could be attributed to the fact that there is typically no work zone activity on the weekends. No such relationship is observed for work zones with high speed limits (≥60 mph).

5. Discussion

Recall that the research question of this study is whether there is a difference in contributing factors for crashes in work zones on interstates versus non-interstates. The results indicate that the factors are different. For interstates, the significant factors are three or more vehicles, rear-end collision, location before the first work zone sign, and weekdays. For non-interstates, the significant factors are SC or US primary roadways, activity area of the work zone, at-fault drivers under 35, sideswipe collision, presence of workers in the work zone, and collision with fixed objects. The differences could be due to interstate projects being "significant projects". A significant project is defined "as one that, alone or in combination with other concurrent projects nearby, is anticipated to cause sustained work zone impacts that are greater than what is considered tolerable based on State policy and/or engineering judgment" [12].

Another way of assessing the difference between interstate and non-interstate factors is to examine the coefficients or marginal effects of the factors that are significant in both models: female at-fault drivers, driving too fast for conditions, and dark lighting conditions.

The marginal effects of driving too fast for conditions and female at-fault drivers are lower for interstates. This finding corresponds to expectations since interstate projects or significant projects must have a transportation management plan (TMP) and a temporary traffic control (TTC) plan that addresses traffic safety and control through the work zone. TMPs are designed to ease work zone impacts and inform those affected by the project of the expected work zone impacts and changing conditions. An example of a difference between the TTC of an interstate project and non-interstate project is that interstate work zones are required to have a minimum clear zone of 10 feet on each side of the road to allow for a recovery area for vehicles that veered off course. Conversely, non-interstate work zones require only a clear zone of 4–6 feet. Furthermore, interstate work zones may require additional measures such as more advanced warning signs, larger and more conspicuous work zone signs, more TTC devices, and more effective traffic management strategies [38]. For the dark lighting conditions factor, its marginal effects are higher for interstates. One possible explanation for this is that given the same illumination for the two roadway types, drivers on interstates have higher risks because of their higher traveling speeds. The takeaway from this finding is that light conditions in work zones on interstates need to be brighter compared to those on non-interstates.

6. Conclusions

This study investigated factors that contribute to injury in truck-involved crashes in work zones in South Carolina. Using South Carolina statewide crash data from 2014 to 2020, it was found that having two separate posted speed limit models provides more insight than a single aggregate model. This is supported statistically by the parameter transferability tests. Consequently, two mixed logit models were developed, one for posted speed limit less than 60 mph (representing non-interstates) and one for posted speed limit greater than or equal to 60 mph (representing primarily interstates). Based on the model estimation results, the factors that contribute to injury at the 90% confidence level for both models include dark lighting condition, female (at-fault) drivers, and driving too fast for roadway conditions. Significant factors that apply only when the speed limit is less than 60 mph are crashes occurring on SC or US primary roadways, activity area of work zone, drivers under 35 years old, sideswipe collision, presence of workers in the work zone, and collision with fixed objects. Significant factors that apply only when speed is greater than or equal to 60 mph are crashes that involve more than three vehicles, rear-end collision, location before the first work zone sign, and crashes occurring on weekdays. Lastly, two random parameters were found to be significant for two speed limit categories: exactly two vehicles involved in crashes for posted speed less than 60 mph and crashes occurring in the shoulder or median of the roadway for posted speed limit greater than or equal to 60 mph. Based on the findings of this study, the factors that highway agencies have control of and should target first to improve safety are driving too fast for conditions and dark lighting conditions.

This study filled a research gap in truck-involved crashes in work zones. It is the first study to investigate the factors that contribute to injury for two posted speed limit categories, less than 60 mph and greater than or equal to 60 mph. Similar to other prior studies in safety analysis, this study has some limitations that should be taken into account when interpreting and applying the findings. The most important limitation is that the crash data came from a single US state. The finding can be generalized if the future study uses crash data from multiple states. Along this line, a larger dataset would allow for the consideration of multiple injury-severity levels instead of just two. Future work could explore other demarcation speed values to generalize the findings. In addition to roadway posted speed limits, collision speeds could also be considered. Lastly, drivers' attitudes toward work zones represent an understudied area that could be explored in future work.

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