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Road Work Zone Safety: Investigating Injury Severity in Motor Vehicle Crashes Using Random Effects Multinomial Logit Model

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KEYWORDS:

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ABSTRACT:

Work zones serve the purpose of facilitating maintenance and rehabilitation activities on roadways. However, these areas can also present unforeseen conditions to drivers, including narrowed right-of-way, lane shifts, and traffic disruptions. These conditions frequently contribute to vehicular crashes within work zones, resulting in property damage, injuries, and even loss of life. This paper aims to highlight work zone related crash data insights and presents statistical estimates of significant determinants of injury severity by analyzing ten-year crash data (2008-2018) from Nebraska, USA. The examination of crash data helped in highlighting work zone attributes that are empirically associated with serious injury crashes and fatalities. Crash data analysis evaluated the relationship of injury severity in work zones with key crash variables such as time of crash, road classification, crash location, road surface conditions, weather conditions and road characteristics. The crash data revealed that 2016 had the highest (1326/11.28%) whereas 2011 had the lowest (739/6.3%) recorded work zone crashes. Also, most of work zone crashes were recorded in activity and transition areas. A standard multinomial logit model and random effects multinomial logit model was estimated and compared. The estimated model showed that higher crash injury severity was associated with highways and interstates, curved and steep road conditions, lane closure and intermittent type work zones, activity and termination areas in work zones, presence of workers, time of day and certain crash attributes. Identifying these key factors related to work zone crashes helped suggest several mitigation strategies to reduce the severity of such incidents. This research is exploratory in nature, and the findings are anticipated to contribute to future studies on work zone safety.

Road Work Zone Safety: Investigating Injury Severity in Motor Vehicle Crashes Using Random Effects Multinomial Logit Model

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1 INTRODUCTION

The United States (US) highway infrastructure requires constant maintenance and capacity expansion to meet increasing travel demand. Work zones enable maintenance and construction activities, but they also present unexpected driving conditions to drivers. Sometimes drivers are unable to cope with those unexpected conditions resulting in motor vehicle crashes. With increasing work zones, there has been a cumulative increase in work zone injuries and fatalities (Thapa & Mishra 2021). According to a survey of highway construction firms, work zone crashes have increased over the years, with 67% of construction firms in the US experiencing at least one work zone crash in 2019, up from 39% in 2016 (Highway Work Zone Safety Survey 2019). In 2010, there were reportedly 37,400 injuries and 586 fatalities; however, the reported numbers in 2018 increased substantially, with 45,400 injuries and 754 fatalities (Work Zones-Injury Facts-National Safety Council 2020). A plausible reason of higher work zone crashes is a substantial increase in vehicle miles travelled (VMT). With an increase in VMT, the existing highway infrastructure bears a greater burden, resulting in a greater demand for highway asset rehabilitation and the capacity expansion. Because of the emphasis on repair and highway reconstruction, work zones in the US are likely to increase in number, duration, and length (Khattak et al. 2002).

During peak roadway construction season in the US, approximately 20% of highways are under construction, and active work zones account for approximately twelve billion vehicle miles, with travellers expecting to encounter a work zone every one-hundred miles on highways (FHWA 2009). Reduced road widths, lane changing dilemmas, slow vehicle movement, and poor road conditions on active work zones are major concerns because they put road users and construction workers at risk of collisions (Sze & Song 2019; FHWA 2019). Active work zones cause approximately 24 percent of non-periodic delays and 10% of overall delays on freeways. When datasets from local roads are considered, the delays become even more concerning (FHWA 2009). To evaluate operational and safety issues caused by work zones, national transportation agencies are using optimized planning and scheduling, advance intelligent technological applications and operational mechanisms. Work zone-related research and practices are typically focused on several major interrelated areas such as, work zone typology, driver behaviour and interaction, environmental conditions, and work zone traffic operations. In particular, this study focuses on evaluating crash injury severity of work zone crashes in Nebraska, USA. The objectives of this study are to (a) investigate if road type, characteristics and classification has any impact on crash injury severity; and (b) empirically estimate how environmental and weather-related parameters control different levels of crash injury severity in work zones in Nebraska. For this purpose, ten-year crash data (2008-2018) were acquired from the Nebraska Department of Transportation (NDOT) and after extensive data assessment and filtration, key crash variables were utilized to estimate standard multinomial logit (MNL) and random effects MNL models. Because of having panel data spanning ten years, the purpose of estimating random effects MNL models was to account for unobserved heterogeneity in the sample while also allowing crash severities to be treated as mutually exclusive events. This effort is unique in that it used a large dataset of work zone crashes as well as crash and injury parameters for several locations across Nebraska with different environmental and weather-related attributes that had not previously been studied.

A literature review follows section 1, which is followed by a section discussing the research approach adopted for this study. The next section describes data acquisition, data filtration, and sample summary statistics. The ensuing section describes estimation of the two MNL models and presents significant covariates of work zone-crash injury severity and other important modelling results. The last section provides conclusions and proposes suitable suggestions.

2 LITERATURE REVIEW

Over the last five decades, researchers have widely investigated work zone safety. The major past studies have concentrated on descriptive analysis of crash data to investigate long-term work zone characteristics such as crash injury severity, crash rate, time of the day, type and location etc. Many researchers have investigated statistical characteristics and policy-sensitive variables of work zone crashes as part of efforts to reduce the number of fatalities and injuries on work zones (Khattak et al. 2002; Scriba et al. 2005; Ullman et al. 2009; Li & Bai 2009; Weng et al. 2014; Yang et al. 2015; Liu et al. 2016; Osman et al. 2018; Awolusi & Marks 2019). Longer work zone duration, according to Khattak et al. (2002) significantly increases both injury and non-injury crash frequencies. With respect to the size of the problem, Weng et al. (2014) developed a rear-end crash risk model to point out that the cars following a truck in active work zones are more likely to be involved in rear-end crashes. Chen et al. (2014) analysed detailed work zone crash data using random parameters and random effects models, revealing that winter months are a significant detriment to work zone crashes. Li & Bai (2009) used logistic regression and frequency analysis techniques to assess risk factors for severe crashes in work zones and discovered that drivers' age and gender have a significant impact on the likelihood of causing severe crashes.

Injury severity of passenger-car crashes in different work zone configurations was studied by Osman et al. (2018). Among other vehicles, heavy duty trucks were the focus for different work zone layouts and their lane shift elasticities were evaluated. An ordered-probit mixed generalized model was estimated that suggested a significant association of higher injury severity with crashes on curved roadways and during evening times and weekends; demonstrating that temporal characteristics do, in fact, influence the severity of work zone crashes (Osman et al. 2018; Farooq 2023). Zhang and Hassan (2019) in a similar study, utilized past seven years crash data by estimating a mixed multinomial logit model to determine how night-time hours affect injury severity in work zone crashes. Qiu & Nixon (2008) found rainfall to be responsible for sever crashes. Furthermore, foggy weather and over speeding trends are also found to be major detriments of severe crashes in work zones during the night hours (Adomah et al. 2021). Significant differences in injury severity among work zone and non-work zone crashes was examined by Zhang et al. (2018) by utilizing two-sample Kolmogorov-Smirnov tests. The findings revealed that single vehicle, head-on, angle oncoming, and side impact 90-degree crashes in work zones were more severe than those in non-work zones.

Wong et al. (2011) used a variety of statistical models such as multiple correspondence analysis, Cox proportional hazard regression, Logistic regression, and Poisson regression to identify variables responsible for severe injuries to workers involved in work zone crashes. The findings highlighted that time of the day, location of work zone, duration and workers' activity were significantly associated with risk of severe injuries in workers. Furthermore, Harb et al. (2008) extensively studied driver and vehicle characteristics as covariates of work zone crashes, demonstrating that driving under the influence of drugs and alcohol could be lethal in work zones. There has been a significant improvement in the methodological development of crash modelling over the last two decades. Lord & Mannering (2010) and Savolainen et al. (2011) introduced a variety of new statistical models for crash frequency and injury severity. Furthermore, Mannering & Bhatt (2014) provided a comprehensive overview as well as a future course of action for analysing crash data and interpreting the results. Lord & Mannering (2010) identified several issues with crash frequency analysis and how to deal with them. In most of crash frequency studies, the problem of over-dispersion is discussed when using negative binomial models. Past studies have seen that few important temporal covariates and varying effects are not properly addressed due to data deficiencies and under-reporting. By relaxing the assumption of having fixed parameters, the use of mixed models with random parameters can help to fix the problems caused by varying effects (Lord & Mannering 2010). For studies where key variables are omitted, random parameters also help to explain the unobserved heterogeneity. Recent methodological advances, such as the application of random parameter models to better understand work zone data, can provide an opportunity to learn more about highway work zone safety (Mannering & Bhatt 2014).

The MNL model and its generalizations are one of the widely used regression models in crash data analysis to indicate graded crash severity outcomes (Savolainen et al. 2011; Abdel-Aty et al. 2011; Xie et al. 2012; Manner & Wünsch 2013; Zhang & Hassan 2019; Farooq & Khattak 2023). The model has been extensively utilized to predict injury severity in truck crashes (Dong et al. 2015), motorcycle crashes (Geedipally et al. 2011), crossover and rollover crashes (Hu and Donnell 2011), rural single vehicle crashes (Xie et al. 2012) and night-time crashes (Manner & Wünsch-Ziegler 2013). Furthermore, it has been used to estimate the factors influencing injury severity in pedestrian (Kim et al. 2008) and farm vehicle crashes (Gkritza et al. 2010). The fixed parameter values for all measurements in the sample are a basic assumption of non-random parameter models (Washington et al., 2011). Although this assumption is useful for estimating the model and predicting the dependent variable value, it creates a major flaw in such models. For different observations, same variables might have varied effects on response variable due to unexplained heterogeneity (Chen et al. 2014). For instance, as compared to young drivers, the effect of low impact speed on an elderly driver is dramatically fatal. Model misspecification can result from omitting a driver's age and physical condition from the model and forcing a fixed value on the parameter associated with impact speed (Chen et al. 2014). In this respect, random parameter and random effects models are more versatile, and they are thought to be better at handling unexplained heterogeneity than fixed parameter models (Chen et al. 2014; Farooq et al. 2021).

In summary, introducing work zones increases the likelihood of crashes due to the disruptions in traffic flow and the resultant unusual roadway conditions. The severity of the injuries caused by these crashes is determined by several factors, including driver characteristics, roadway conditions, time of day, weather, and environmental factors. Injury crashes that occur at night appear to be more severe than those that occur during the day. In addition, duration of work zone and inclement weather conditions such as snow, hail, and fog are positively associated with injury severity. When compared to non-work zones, work zones have more rear-end and sideswipe crashes however, for control access highways the likelihood of severe crashes is reduced significantly. While the existing literature provides valuable insights, there remains a substantial research gap in work zone safety research due to the absence of extensive work zone datasets and deficiencies in the data recording process in the event of a crash. Moreover, a comprehensive single-model estimation has not yet been employed to quantify the impacts of roadway conditions, driver behaviour, environmental factors, and weather-related variables on crash injury severity in work zone crashes in Nebraska.

3 DATA DESCRIPTION

The primary objective of this research is to ascertain the key factors that influence the varying degrees of injury severity resulting from work zone crashes in the state of Nebraska. The dataset used in this study was acquired from the NDOT, spanning the period from 2008 to 2018. The initial unfiltered data revealed that 2016 had the highest (1326/0.025%), whereas 2011 had the lowest (739/0.147%) recorded work zone crashes. As the study focused on work zone crashes involving injuries, an extensive data filtration process was carried out by considering variables of interests associated to work zones; data were reduced from an initial 565,944 reported crashes to 3,290 crashes in work zones. Further, 'Property damage only' crashes were omitted from the dataset, and only 'Possible injury', 'Visible injury', 'Suspected serious injury', and 'Fatal' crashes were retained for analysis. The severity level of a crash is determined by the single most serious injury sustained. When there is a reported fatality in data, the crash is labelled as 'Fatal,' and when there is a reported serious or disabling injury, the crash is labelled as 'Suspected serious injury.'

Table 1 presents the summary statistics for Nebraska work zone crashes. In the filtered-data subset, most work zone crashes were reported on highways (42.6%), followed by local roads (38.9%). Approximately 80% of the reported crashes occurred during daylight conditions however, dark roadways with lighted conditions accounted for 9.5 % of work zone crashes. Furthermore, 24% of work zone crashes occurred on straight roads with slope. In a similar fashion, the dataset had the highest number of crashes on two-lane highways (40%), followed by four-lane highways (39.1%). Based on crash type, rear-end crashes were the highest among all other work zone crashes (Approximately 48%). In addition, the summary statistics reveal that approximately 32% of work zone crashes occurred in the presence of workers (Table 1).

4 RESEARCH METHODOLOGY

Crash severity is classified into discrete categories which describe the injury level of the most severely injured road user involved in a crash. These categories are usually ordered from the most severe crash (fatal) to the least severe crash (property-damage-only). Modelling is usually based on either ordered response models due to the ordinal nature of the dependent variable (Kockelman & Kweon 2002; Khattak et al. 2002; Farooq 2023) or unordered response models that allow covariates to possess a non-monotonic effect on the predicted variable. The multinomial logit model is an example of the latter (Shankar & Mannering 1996; Ulfarsson & Mannering 2004).

A multinomial regression uses a linear prediction function $f\ (k, i)$ to predict the likelihood outcome k with i observations. The regression follows the general form.

$$f\ (k, i) = \beta_{0,k} + \beta_{1,k}x_{1,i} + \beta_{2,k}x_{2,i} + \cdots + \beta_{M,k}x_{M,i} \tag{1}$$

Where $\beta_{M,k}x_{M,i}$ is a regression coefficient associated with mth explanatory variable and kth outcome. The regression coefficients and independent variables are normally distributed into vectors of size $M + 1$, to compact the predictor function.

Table 1. Summary statistics for Nebraska work zone crashes (N= 3,290)

Variable	Crashes	Pct. (%)	Mean	S.D.
Road Classification				
Highway (If road classification is highway =1, otherwise = 0)	1404	42.67	0.42	0.49
Highway ramp (If road classification is highway ramp =1, otherwise = 0)	11	0.33	0.003	0.05
Highway rest area/scale (If road classification is highway rest area/scale =1, otherwise = 0)	3	0.09	0.0009	0.03
Inter-state mainline (If road classification is interstate mainline =1, otherwise = 0)	524	15.93	0.15	0.36
Interstate ramp (If road classification is interstate ramp =1, otherwise = 0)	56	1.70	0.017	0.12
Local road or street (If road classification is local road or street =1, otherwise = 0)	1280	38.91	0.38	0.48
Recreation road (If road classification is recreational road =1, otherwise = 0)	12	0.36	0.0006	0.02
Light Conditions				
Dark lighted roadway (If light condition is dark with lighted roadway =1, otherwise = 0)	311	9.45	0.09	0.29
Dark roadway not lighted (If light condition is dark with roadway not lighted =1, otherwise = 0)	192	5.84	0.05	0.23
Dark unknown roadway lighting (If light condition is dark with unknown roadway lightning =1, otherwise = 0)	5	0.15	0.001	0.03
Dawn (If roadway is lighted because of dawn =1, otherwise = 0)	78	2.37	0.02	0.15
Daylight (If roadway is lighted because of daylight, otherwise = 0)	2641	80.27	0.80	0.39
Dusk (If roadway has lightning conditions during dusk, otherwise = 0)	63	1.91	0.02	0.12
Road Characteristics				
Curved and level (If roadway is curved and level, otherwise = 0)	131	3.98	0.04	0.19
Curved and on hilltop (If roadway is curved and on hilltop, otherwise = 0)	9	0.27	0.002	0.05
Curved and on slope (If roadway is curved and on slope, otherwise = 0)	101	3.07	0.03	0.17
Straight and level (If roadway is straight and level, otherwise = 0)	2272	69.0	0.69	0.46
Straight and on hilltop (If roadway is straight and on hilltop, otherwise = 0)	75	2.28	0.02	0.14
Straight and on slope (If roadway is straight and on slope, otherwise = 0)	792	24.0	0.24	0.40
Road surface Type				
Asphalt (If road surface type is asphalt, otherwise = 0)	1281	38.94	0.38	0.47
Brick (If road surface type is brick, otherwise = 0)	4	0.12	0.001	0.03
Concrete (If road surface type is concrete, otherwise = 0)	1955	59.42	0.59	0.49
Dirt (If road surface type is dirt, otherwise = 0)	10	0.30	0.003	0.05
Gravel (If road surface type is gravel, otherwise = 0)	40	1.22	0.01	0.10
Road Surface Condition				
Dry (If road surface condition is dry, otherwise = 0)	2828	85.96	0.85	0.34
Ice (If road surface condition is ice, otherwise = 0)	54	1.64	0.01	0.12
Sand or mud (If road surface condition is sand or mud, otherwise = 0)	37	1.12	0.01	0.09
Slush (If road surface condition is slush, otherwise = 0)	10	0.30	0.003	0.05
Snow (If road surface condition is snow, otherwise = 0)	34	1.03	0.01	0.10
Water (If road surface condition is water, otherwise = 0)	11	0.33	0.003	0.05
Wet (If road surface condition is wet, otherwise = 0)	316	9.60	0.09	0.29
Number of Lanes				
One lane (If roadway has one lane on each side, otherwise = 0)	198	6.02	0.06	0.24
Two lanes (If roadway has two lanes on each side, otherwise = 0)	1316	40.0	0.40	0.48
Three lanes (If roadway has three lanes on each side, otherwise = 0)	197	5.99	0.05	0.23
Four lanes (If roadway has four lanes on each side, otherwise = 0)	1289	39.18	0.39	0.47
Five lanes (If roadway has five lanes on each side, otherwise = 0)	76	2.31	0.02	0.15
Six or more lanes (If roadway has six or more lanes on each side, otherwise = 0)	214	6.50	0.06	0.24
Median Type				
Barrier (If opposite lanes are separate with a barrier, otherwise = 0)	360	10.94	0.10	0.31
Grass (If opposite lanes are separate with a grass median, otherwise = 0)	516	15.68	0.15	0.36
No Median (If there is no median, otherwise = 0)	1083	32.92	0.32	0.46
Painted (If opposite lanes are separate with a painted median, otherwise = 0)	453	13.77	0.13	0.34
Raised (If opposite lanes are separate with a raised median, otherwise = 0)	878	26.69	0.26	0.44
Direction of Crash				
Rear end (If a crash is rear end =1, otherwise =0)	1593	48.42	0.48	0.49
Sideswipe-opposite direction (If a crash is sideswipe in opposite direction =1, otherwise =0)	35	1.06	0.01	0.10
Sideswipe-same direction (If a crash is sideswipe in same direction =1, otherwise =0)	179	5.44	0.05	0.22
Angle/Backing/ Head-on (If direction of the crash is angle/backing/head-on=1, otherwise =0)	1379	41.91	0.42	0.48
Accident Location in Work zone				
Activity area, adjacent to actual work area (If crash occurred in activity area adjacent to actual work area, otherwise =0)	1671	50.79	0.51	0.50
Advance warning area after the first warning sign (If crash occurred in advanced warning area, otherwise =0)	593	18.02	0.18	0.38
Before the first work zone warning sign (If crash occurred before the first warning sign, otherwise =0)	276	8.39	0.08	0.27
After warning sign (If crash occurred after warning sign, otherwise =0)	70	2.13	0.02	0.17
Termination area after the activity area (If crash occurred in termination area after activity area, otherwise =0)	196	5.96	0.06	0.23
Transition area where lanes are shifted (If crash occurred in transition area where lanes are shifted, otherwise =0)	484	14.71	0.15	0.35
Type of Work zone				
Intermittent or moving work (If work zone type is intermittent or moving work = 1, otherwise = 0)	385	11.70	0.12	0.32
Lane closure (If work zone type is lane closure = 1, otherwise = 0)	1632	49.60	0.50	0.50
Lane shift/crossover (If work zone type is lane shift or crossover = 1, otherwise = 0)	432	13.13	0.13	0.33
Other types (For other unspecified types of work zones = 1, otherwise = 0)	474	14.41	0.14	0.36
Work on shoulder or median (If work zone type is shoulder or median = 1, otherwise =0)	367	11.16	0.11	0.31
Road Users				
Workers present in work zone (If workers are present in work zone = 1, otherwise = 0)	1036	31.48	0.31	0.46
Crash Injury Severity				
Possible injury	2009	61.06	-	-
Visible injury	889	27.02	-	-
Suspected serious injury	339	10.30	-	-
Fatal	53	1.61	-	-

$$f\ (k,i) = \ y_{ij}^{*} = \ x_{ij}' * \ \beta_k + \epsilon_j \tag{2}$$

$$\beta_i \sim g\ (\beta \,|\, \theta) \tag{3}$$

Where $i \in$ I is a set of categories, j = 1, 2,...., n is the index of observations, y_{ij}^{*} is the dependable variable for observations i, β_k is a vector of regression coefficients, x_{ij}' is a vector for independent variables, and error term is represented by ϵ_j, which is assumed to follow an extreme value distribution type I (Zhang & Hassan 2019).

For K possible outcomes, running K-1 independent logistic regression models, in which one outcome is chosen as a "pivot" and then the other K-1 outcomes are separately regressed against the pivot outcome. This would proceed as follows, if outcome K (the last outcome) is chosen as the pivot

$$\ln \frac{P_r(\ Y_i = K-1)}{P_r\ (\ Y_i = K)} = \ \beta_{K-1} * \ X_i \tag{4}$$

The outcome probability densities for standard multinomial logit model follows the expression

$$P_r(\ Y_i = K-1) = \frac{e^{\beta_{K-1} * X_i}}{1 + \sum_{k=1}^{K-1} e^{\beta_{K} * X_i}} \tag{5}$$

The probability density of the parameters is often assumed to be the normal distribution, that is:

$$\beta_k \sim g\ (\beta|\theta) = N\ (\beta_k, \sigma_k^2) \tag{6}$$

The model converges to the fixed-parameter multinomial logit form for variance $\sigma_k^2 = 0$. Simulated (Bayesian) maximum likelihood estimation (SML) is usually utilized to determine coefficients of independent variables with random effects. Given normally distributed random errors in the multinomial logit model, exponentiation of those random errors yields a set of lognormally distributed disturbances, with means and variances well defined. Let $Y_{i\,j}$ represents an ordinal categorical variable with (K + 1) levels (in our case, crash injury severity) associated with a crash event i at time j. Random effects models differ from random parameter models in that they mandatorily require panel data. The random parameter model, on the other hand, can be estimated using both cross-sectional and panel data (Mannering et al. 2014). This study used past ten years panel data as crash entities were observed at two or more points in time. For random effects multinomial logit model, the probability that Yij = k (k = 1, … ,K) for a crash i at time j is given by:

$$P_{ijk} \ = \ P_r\left(\ Y_{i\,j} \ = k \,\middle|\, x_{ij}\right) = \ \left[\sum_{l=1}^{k} \exp\left(\boldsymbol{x_{ij}}\,\beta_l\right) \exp\left(\boldsymbol{v_{il}}\right)\right]^{-1} \exp\left(\boldsymbol{x_{ij}}\,\beta_l\right) \exp\left(\boldsymbol{v_{il}}\right) \tag{7}$$

where $\boldsymbol{x_{ij}}$ is the vector of independent variables including the intercept. Likewise, βk is the vector of unknown regression parameters to be estimated, and $\boldsymbol{v_{il}}$ is the between-crashes random effect assumed to be distributed as $N(0, \sigma^2)$. In random effects multinomial logit regression, 200 Halton draws are typically performed, which provides better coverage than pseudo-random number generators. The marginal effects give the change in independent variable that is caused by a unit change in dependable variable. For indicator variables, marginal effects indicate how probabilities of crash injury severity are affected if independent variables change from zero to one. The marginal probability effect for indicator variables is given by:

$$X_j = \ \varphi\ (X_{1i}^T\, \beta) - \ \varphi\ (X_{0i}^T\, \beta) \tag{8}$$

5 RESULTS

In this study, Nebraska work zone crash injury severity for 2008-2018 is estimated by using standard MNL and random effects MNL models. The purpose of estimating random effects for panel crash-data is to obtain more accurate inferences by explicitly accounting for observation-specific variations in crash injury severity caused by the effects of influential factors (Mannering et al. 2014). The categories of crash severity were 'possible injury' (coded as 0), 'visible injury' (coded as 1), and 'suspected serious injury' (coded as 2) and 'fatality' (coded as 3). 'Possible injury' is chosen as base category and the parameters estimated compare the results of target categories with base categories. As shown in Table 1, a total of 48 indicator variables are used in the model estimation process where a final model is obtained by undergoing a backward elimination process. To check for collinearity among indicator variables, variance inflation factors (VIF) are computed and only those variables are kept for model estimation with VIF values from 1.02 to 3.8 (Zhang & Hassan 2019; Farooq et al. 2021; Khattak & Farooq 2023). Table 4 presents average marginal effects to describe the effect of a unit change in independent variable on crash injury severity. For indicator variables, marginal effects give estimates of change in crash injury severity when covariates change from zero to one. The parameters estimated in Table 1 were statistically significant at a significance level of 0.05 (or higher). The estimated random effects multinomial logit model retained an overall 31 statistically significant variables. Based on Akaike information criterion (AIC) and Bayesian information criterion (BIC) comparison between the two models is presented in Table 3 and random effects MNL model is chosen as the final model because of better estimates (Farooq 2023; Farooq & Khattak 2023, Khattak et al. 2023). A likelihood ratio test is also performed to test the null hypothesis that the standard MNL model is statistically similar to the random effects MNL model. The chi-square statistic is presented as

$$X^2 = -2[L_{MNL}(\beta) - L_{REMNL}(\beta)] \tag{10}$$

where $L_{MNL}(\beta)$ is the log-likelihood at convergence of standard multinomial logit model and $L_{REMNL}(\beta)$ is the log-likelihood at convergence of the random effect multinomial logit model. For two degrees of freedom, the chi-square statistic in likelihood ratio test gives a confidence limit based on one-tailed p-value greater than 95% (X^2 = 11.69, df = 2), indicating that random effects multinomial logit model is statistically better than standard multinomial logit model. Table 4 displays marginal effects to show the change in crash injury severity probabilities due to unit changes in significant covariates. The statistically significant variables are discussed in subsections below.

5.1 ROAD ATTRIBUTES

According to the model results, road classification has a significant impact on crash injury severity because highways and interstate mainlines are more likely to have severe crashes and fatalities than local roads and streets. For crashes that occur on highways and interstate mainlines, the model estimated a higher likelihood of visible and serious injuries compared to possible injuries. According to Table 4, the likelihood of sustaining visible and serious injuries increases by 0.009 and 0.054 on highways, and by 0.024 and 0.085 on interstate mainlines. There is also a higher likelihood of fatalities in highway and interstate crashes compared to possible injuries, as the results show a positive coefficient for fatality occurrence on highway and interstate crashes. The marginal effects show that crashes on highways and interstates increase the likelihood of fatality by 2.22% and 3.33%, respectively when compared to local roads and streets. The results are consistent with past findings as road classification is a key element in crash injury severity and busier and highspeed roads are more hazardous compared to minor and local roads (Renski et al. 1999; Davis et al. 2006; Lee et al. 2006; Mussone et al. 2017). Furthermore, model estimates revealed that the number of lanes is a significant factor influencing crash injury severity, with a two-lane highway having a higher likelihood of serious injuries than roads with a single lane on each side. Table 4 shows that two-lane roads increase the likelihood of serious injuries to 1.37%, which is consistent with previous findings because the number of lanes is a key factor influencing crash injury severity and as the number of lanes increases operating speeds are increased that may result in over speeding in drivers consequently causing severe injury crashes (Elhenawy et al. 2019).

5.3 ROAD GEOMETRY & PAVEMENT TYPE ATTRIBUTES

Crashes on curved and steep roads are more likely to cause visible and serious injuries as compared to possible injuries as modelling estimates indicate that for curved and steep roads, the likelihood of visible and severe injuries increases by 0.494 and 0.264 (Table 4). Pavement type is also crucial as the material used for pavement can affect its skid resistance, macro and micro texture which are essential factors for safe stopping. Under different environmental and weather conditions, lower skid resistance and pavement texture (macrotexture or microtexture) may increase braking distance. A vehicle traveling at the same speed would have to travel a greater distance to come to a complete stop on roads with low pavement macrotexture than on roads with high pavement macrotexture (Liu et al. 2009). For gravel roads the model estimates indicate that the probability of serious injury is increased to 8% as compared to possible injuries making gravel roads more hazardous to road users as compared to asphalt and concrete pavements. The number and severity of crashes are controlled by the type of median, as studies have shown that roads with grass or no medians have a higher likelihood of severe crashes than roads with painted, raised, or barrier medians (Donnell & Mason et al 2006; Hu & Donnell 2011; Zou & Tarko 2016). Model estimates showed that there is lower likelihood of visible, severe, and fatal crashes on highways with barrier medians as marginal effects estimation (Table 4) indicates that the presence of barrier median reduces the likelihood of visible, severe and fatal crashes to 1.6%, 3.4% and 1.4% respectively.

Table 2. Estimation results for random effects multinomial-logit model

Variable	Coeff	P-value
Means for random parameters		
Constant (VI)	-12.51	0.000
Constant (SI)	-25.01	0.000
Constant (F)	-9.181	0.000
Road Attributes		
Highway indicator (If road classification is highway =1, otherwise = 0) [VI]	1.740	0.000
Highway indicator (If road classification is highway =1, otherwise = 0) [SI]	6.64	0.000
Highway indicator (If road classification is highway =1, otherwise = 0) [F]	2.35	0.000
Interstate mainline indicator (If road classification is highway =1, otherwise = 0) [VI]	3.10	0.000
Interstate mainline indicator (If road classification is highway =1, otherwise = 0) [SI]	10.22	0.000
Interstate mainline indicator (If road classification is highway =1, otherwise = 0) [F]	3.70	0.000
Two-lane indicator (If roadway has two lanes on each side, otherwise = 0) [SI]	1.44	0.005
Road Geometry & Materials Attributes		
Curved and on slope indicator (If roadway is curved and on slope, otherwise = 0) [VI]	2.54	0.005
Curved and on slope indicator (If roadway is curved and on slope, otherwise = 0) [SI]	6.28	0.000
Gravel indicator (If road surface type is gravel, otherwise = 0) [VI]	11.71	0.000
Gravel indicator (If road surface type is gravel, otherwise = 0) [SI]	11.16	.0000
Barrier indicator (If opposite lanes are separate with a barrier, otherwise = 0) [VI]	-1.81	0.001
Barrier indicator (If opposite lanes are separate with a barrier, otherwise = 0) [SI]	-3.88	0.000
Barrier indicator (If opposite lanes are separate with a barrier, otherwise = 0) [F]	-1.77	0.020
Environmental and weather Attributes		
Daylight indicator (If roadway is lighted because of daylight, otherwise = 0) [VI]	-5.11	0.000
Daylight indicator (If roadway is lighted because of daylight, otherwise = 0) [SI]	-4.46	0.000
Snow indicator (If it is snowing in an event of crash = 1, otherwise = 0) [F]	2.74	0.004
Work Zone Attributes		
Median indictor (If accident relation to road is 'Median' =1, otherwise = 0) [SI]	3.026	0.037
Median indictor (If accident relation to road is 'Median' =1, otherwise = 0) [F]	1.926	0.028
Intermittent or moving work indicator (If work zone type is intermittent or moving work = 1, otherwise = 0) [VI]	5.467	0.000
Intermittent or moving work indicator (If work zone type is intermittent or moving work = 1, otherwise = 0) [SI]	2.751	0.000
Lane closure indicator (If work zone type is lane closure = 1, otherwise = 0) [VI]	-3.59	0.000
Lane closure indicator (If work zone type is lane closure = 1, otherwise = 0) [SI]	-1.64	0.002
Activity area, adjacent to actual work area indicator (If crash occurred in activity area adjacent to actual work area, otherwise =0) [VI]	4.22	0.000
Activity area, adjacent to actual work area indicator (If crash occurred in activity area adjacent to actual work area, otherwise =0) [SI]	1.44	0.000
Activity area, adjacent to actual work area indicator (If crash occurred in activity area adjacent to actual work area, otherwise =0) [F]	1.18	0.005
Termination area after the activity area indicator (If crash occurred in termination area after activity area, otherwise =0) [VI]	7.07	0.000
Termination area after the activity area indicator (If crash occurred in termination area after activity area, otherwise =0) [SI]	4.38	0.000
Crash attributes		
Sideswipe-same direction indicator (If a crash is sideswipe in same direction =1, otherwise =0) [VI]	-9.56	0.000
Sideswipe-same direction indicator (If a crash is sideswipe in same direction =1, otherwise =0) [SI]	-3.04	0.000
Workers present indicator (If workers are present in work zone = 1, otherwise = 0) [SI]	3.61	0.000

Note: Variable are significant at Alpha (α) = 5%. Parameters are defined for: [VI] Visible injury; [SI] Serious injury; [F] Fatality.

5.2 ENVIRONMENTAL ATTRIBUTES

Among various factors affecting highway safety, adverse weather is known to be a major element. The US Department of Transportation defines adverse weather to be conditions such as as, rain, snow, sleet, cloudy, severe crosswinds, fog, or some combination of these conditions. While snowfall has an impact on crash occurrence, it is also linked to increased crash injury severity (Khattak & Knapp 2001; Anderson et al. 2020). The model estimates a positive coefficient for fatal crashes in snow conditions, indicating how dangerous snowy roads are for users. The marginal estimates (Table 4) show that snow can increase the likelihood of a fatal crash to 2% which is an intuitive finding because snow contributes to severe and fatal traffic crashes in many ways such as from reduced visibility, loss of friction between vehicle tires and roadway surface and loss of stability due to high winds/gusts etc. (Anderson et al. 2020). As the driving behavior is significantly different for day and night times, past research has shown that work zone crashes are more severe during nighttime compared to those occurring during the day (Zhang & Hassan 2019). The model also estimates intuitive coefficients for daytime crashes, which show that when compared to possible injuries in daytime work zone crashes, the probability of visible and serious injuries occurring during the daytime decreases by 0.05 and 0.031, respectively.

5.3 WORK ZONE ATTRIBUTES

The type and location of work zone has a significant impact on the severity of crash injuries (Daniel et al. 2000; Weng at al. 2011). Crash data revealed that crashes occurred in a variety of work zones, including intermittent or moving work zones, lane closures, lane shift/crossover, and construction on the shoulder and median type work zones. In addition, the location of the crash in work zone is important in determining the severity of the injuries. The model estimates show that intermittent type work zones are associated with visible and serious injuries than possible injuries, as their covariates have positive coefficients. Lane closures, on the other hand, are more likely to cause possible injuries than visible or serious injuries (Table 2). According to marginal effects, the probability of having visible and serious injury increases by 0.067 and 0.017 for intermittent type work zones but decreases by 0.004 and 0.009 for lane closures (Table 4). The findings are intuitive, as previous research has shown that lane closure crashes are less severe than intermittent or moving type work zone crashes, because the impact of route familiarity on drivers is critical in decision making and moving type work zones may cause hesitant driving behavior, which increases the risk of severe crashes (See 2008; Itini et al. 2016; Edara et al. 2017).

Table 3. Estimation results for random effects multinomial-logit model

Model Statistics	MNL model with fixed effects	MNL model with random effects
Number of Observations	3290	3290
Restricted Log-likelihood	-3143.46	-3146.46
Like-likelihood at Convergence	-3022.12	-3010.43
Akaike Information Criterion (AIC)	6126.90	6124.69
Bayesian Information Criterion (BIC)	7124.45	7122.12
Number of Parameters	47	48

The estimates indicate that crashes at activity areas and termination areas are more likely to cause serious injuries and fatalities as compared to possible injuries and the marginal effects show that the probability of visible injury, serious injury and fatality increases by 0.051, 0.006 and 0.009 for crashes that are likely to occur on activity areas. Moreover, the probability of severe injury and fatality increases by 0.092 and 0.025, respectively, in termination areas. Crash relation to the road is also a key variable determining crash injury severities and the data show that crash relation to road could be median, gore, beyond left and right shoulder, on roadway, shoulder, and off roadway. Model estimates show that crashes on work zones where vehicles hit medians are more likely to be severe in nature than crashes where vehicles move off the roadway or towards the shoulder. The marginal effects show that for crashes where median is hit by the vehicles, the likelihood of causing a serious injury and fatality increases to 3.3% and 1.8%, respectively.

Table 4. Estimated marginal effects averaged over individuals

Variables	Possible injury	Visible injury	Serious injury	Fatality
Highway indicator (If road classification is highway =1, otherwise = 0) [VI]	-0.0860	0.0090	0.0540	0.0220
Interstate mainline indicator (If road classification is interstate mainline =1, otherwise = 0)	-0.1430	0.0240	0.0850	0.0330
Two-lane indicator (If roadway has two lanes on each side, otherwise = 0)	-0.0141	-0.0070	0.0130	0.0070
Curved and on slope indicator (If roadway is curved and on slope, otherwise = 0)	0.7751	0.4940	0.2640	-1.5301
Gravel indicator (If road surface type is gravel, otherwise = 0)	-0.2421	0.1510	0.0810	0.0090
Barrier indicator (If opposite lanes are separate with a barrier, otherwise = 0)	0.0640	-0.0160	-0.0340	-0.0142
Daylight indicator (If roadway is lighted because of daylight, otherwise = 0)	0.0890	-0.0580	-0.0310	0.0080
Snow indicator (If it is snowing in an event of crash = 1, otherwise = 0)	-0.0610	0.0280	0.0120	0.0200
Median indictor (If crash relation to road is 'Median' =1, otherwise = 0)	-0.0650	0.0130	0.0330	0.0180
Intermittent or moving work indicator (If work zone type is intermittent or moving work = 1, otherwise = 0)	-0.0800	0.0670	0.0170	-0.0041
Lane closure indicator (If work zone type is lane closure = 1, otherwise = 0)	0.0560	-0.0401	-0.0091	-0.0061
Workers present indicator (If workers are present in work zone = 1, otherwise = 0)	-0.0280	-0.004	0.0321	0.0010
Activity area, adjacent to actual work area indicator (If crash occurred in activity area adjacent to actual work area, otherwise =0)	-0.0660	0.0510	0.0060	0.0090
Termination area after the activity area indicator (If crash occurred in termination area after activity area, otherwise =0)	-0.1190	0.0920	0.0250	0.0020
Sideswipe-same direction indicator (If a crash is sideswipe in same direction =1, otherwise =0)	0.1380	-0.1181	-0.013	-0.0061

5.4 CRASH ATTRIBUTES

Crash types on work zones include angled, backing, head-on, left-turn leaving, read-end, and sideswipe (opposite direction/same direction). Past research has indicated that work zones are more likely to have severe rear-end crashes and less severe side-swipe crashes (Khattak et al. 2002; Salem 2006; Akepati & Dissanayake 2011; Weng et al. 2015). The recent findings are intuitively comparable to the past studies as model estimates show that side swipe crashes are not severe in nature as they are more likely to cause possible injuries as compared to visible and severe injuries (Table 2). Moreover, Table 3 indicates that the probability of visible and severe injuries decreases by 0.118 and 0.013 for side swipe crashes in same direction as compared to the probability of causing possible crashes. The model also estimated a positive coefficient of severe injuries in work zone crashes with workers present, and marginal effects show that for events of workers present in work zones the probability of serious injuries increases to 3.21% (Table 4).

6 CONCLUSIONS

Highway work zones are hazardous locations for both construction workers and roadway users. Both the number of crashes and fatalities in the work zones in the US have grown over the years. It is useful to understand the characteristics of work zones that are related to crashes with severe injuries and identify countermeasures to improve work zone safety. These crashes occur due to many risk factors, some of them might not have been studied recently. Past crash data provides comprehensive knowledge of these key crash factors by giving insights of variables that are critical for determining the severity of work zone crashes. These key variables are typically focused on several major interrelated areas such as, work zone typology, location and type of work zone, driver behavior and interaction, environmental conditions, road attributes and work zone traffic operations. The objectives of this study were to (a) investigate if road type, characteristics, and classification have any impact on crash injury severity; and (b) empirically estimate how environmental and weather-related parameters control different levels of crash injury severity in work zones in Nebraska. For this purpose, 2008-2018 data were obtained from NDOT, and key crash variables were designated to estimate the standard MNL and the random effects MNL model after extensive data filtration. The goal of estimating random effects MNL models was to account for unobserved heterogeneity in the sample while also allowing crash severities to be treated as mutually exclusive events due to having panel data spanning the past ten years.

Study results revealed that there is a higher likelihood of serious injuries and fatalities in work zone crashes that occur on highways and interstates as compared to minor roads and local streets. Also, road geometry demonstrated a crucial impact on the likelihood of serious injuries because curved and steep roads in work zones are expected to be more serious in nature. Furthermore, the number of lanes is a significant factor influencing crash injury severity, with a two-lane highway having a higher likelihood of serious injuries than roads with a single lane on each side. For daytime crashes, there is a lower likelihood of occurrence of serious injuries as compared to possible injuries. Also, the probably of visible and serious injury decreases for side-swipe crashes on work zones that occur in the same direction. When opposite work zone lanes are separated by barriers, crash severity is reduced. In addition, there is a higher likelihood of severe crashes in intermittent type work zones as compared to lane closures and location of work zone is determined to be a key factor because crashes on activity areas and termination areas are severe in nature and can likely result in fatalities. There is a lower likelihood of serious injuries in work zone crashes during the day; however, events of snow on the roads can increase the likelihood of fatalities in work zone crashes.

The study suggests taking a number of measures to reduce the number and severity of work zone crashes such as initiating new technologies like flagger audible warning system, enforcing the use of worker-activated panic button warning system, mandatory provision of illuminant flaggers during nighttime, establishing escape routes for workers incase of an emergency, maximizing the installation of mobile barrier median in work zones, using channelizing devices to clearly display sharp edges during night hours, reducing posted speed limits for work zones with gravel roads, providing more pavement markers and rumble strips in activity and termination areas and ensuring safe stopping sight distances for work zones on steep and curve roads. In the events of adverse weather like hail or snow etc., the responsible agency is suggested to introduce new renaissance technologies that establish totally integrated portable remote-control traffic management systems for work zones. Instant advisories can be broadcasted via the Internet or cell phones by remotely controlling roadside signs, flagger warning systems, detectors, cameras, and advisory radio signals, allowing users to safely plan ahead of time when approaching work zones.

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