Analysis of Passenger-Car Crash Injury Severity in Different Work Zone Configurations

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Abstract

Work zone safety remains a priority to the Federal Highway Administration, State Highway Departments, highway engineers, and the traveling public. Work zones create a hospitable environment for crashes; an issue that gained tremendous share of attention in recent years. Therefore, every effort should be sought out to reduce the injury severity of crashes in work zones. In this paper we attempt to investigate factors contributing to the injury severity of passenger-car crashes in different work zone configurations. Considering the discrete ordinal nature of injury severity categories, a Mixed Generalized Ordered Response Probit (MGORP) modeling framework was developed. The model estimation was undertaken by compiling a database consisting of 10 years of crashes that involved at least one passenger car, and occurred in a work zone. Revealing the underlying factors contributing to injury severity levels for different work zone configurations will allow for distinguishing mitigation methods for higher severity outcomes that best suit each of the depicted work zone layouts. This can be accomplished through the implementation of specific safety measures based on the specific configuration of a work zone as a potential crash location. Elasticity analysis suggests that partial control of access, roadways classified as rural, crashes during evening times, crashes during weekends, and curved roadways are key

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factors that increase the likelihood of severe outcomes. Also, the effects of several covariates were found to vary across the different work zone configurations.

Keywords: passenger car, work zone safety, injury severity, mixed generalized ordered response probit, heterogeneity

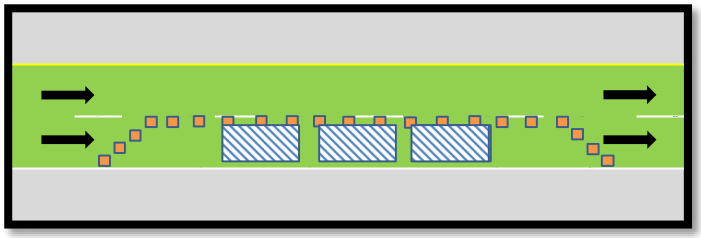
1. Introduction

Work zone safety remains a priority to the Federal Highway Administration (FHWA), Departments of Transportation (DOTs), highway engineers, and the traveling public. The presence of heavy machinery, barriers, traffic control devices, and generally the alteration of the roadway layout in a work zone creates an intimidating environment to the traveling motorists.

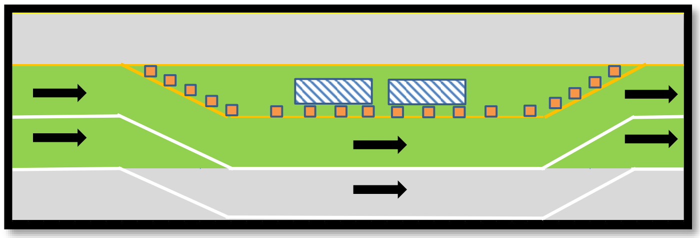
According to FHWA facts and statistics, 67,523 crashes were nationally reported to have occurred in work zones in 2013 (FHWA, 2016). Compared to 2012, the frequency of work zone crashes in 2013 was reduced, however higher severity levels were reported (FHWA, 2016). In 2013 alone, approximately 47,758 non-fatal injuries were reported in work zones (FHWA, 2016). In the same year, there were 527 fatal crashes in work zones resulting in 579 fatalities (FHWA, 2017). The number of work zone fatalities in 2013 equates to one work zone fatality every 15 hours. On average, 85% of fatalities in work zones were drivers or occupants of passenger cars (FHWA, 2016).

The development of a temporary traffic control plan (TTC) for work zones typically depict the type of work zone configuration that is suitable for the specific proposed work activity to be accomplished. A TTC plan serves as an application that ultimately shapes the layout and type of work zone to be formed. Nationally, FHWA mandates such applications through the Manual on Uniform Traffic Control Devices (MUTCD) to specify the minimum TTC requirements needed for the different work zone configurations ("Manual on Uniform Traffic Control Devices (MUTCD)," 2009). Although there are numerous detailed typical TTC applications published by the MUTCD, the State of Minnesota (MN) has adopted a special work zone crash reporting technique allowing the summarization of the different TTC applications into five major types based on the specific work zone configuration where a crash has occurred. The Highway Safety Information System (HSIS) maintains the MN crash database under contract with the FHWA. HSIS presents the MN work zone crashes to have occurred in one of five categories: (1) Lane Closure, (2) Lane Shift/Crossover, (3) Shoulder or Median, (4) Intermittent/Mobile, or (5) Other. For illustration purposes and inspired by the 2009 edition of the MUTCD, Fig. 1 demonstrates generic versions of each of the work zone configurations; categories (1) through (4) of such TTC layouts are shown (Fig. 1 (a) though (d)), except for the "Other" category. Fig.1 (a) corresponds to a one lane closed on a mainline where traffic from the closed lane merges with other open lanes. Fig.1 (b) corresponds to a lane shift where both lanes remain open and shifted around the activity area. Fig.1 (c) corresponds to a lane crossover configuration where one direction of traffic is completely closed and traffic crosses the median to utilize roadway from opposing traffic. Fig.1 (d) corresponds to activities in the shoulder or median while mainline traffic stays unaffected. Fig.1 (e) corresponds to an intermittent or mobile activity which typically moves along the same direction of travel at a slower speed.

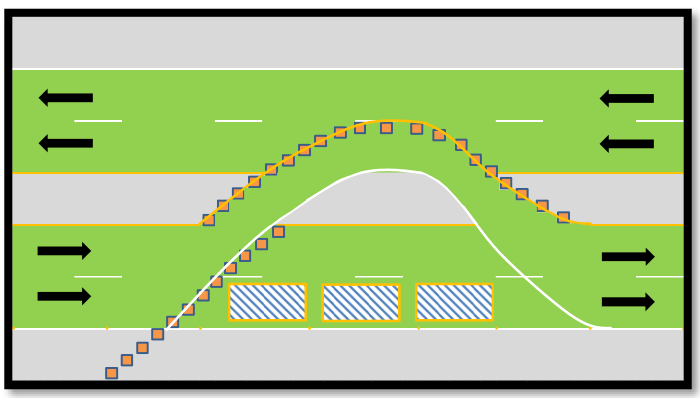
Each of these work zone configurations may vary in size and location depending on the nature of the work activity taking place. Earlier studies on work zone safety focused on different aspects including crash risk factors, severity, type, location, rate, and time frame. Due to the broad nature of these past studies, this study will mainly focus on studies related to work zone crash severity and risk factors. Within the work zone crash severity literature, some studies mainly focused on fatal crashes (Arditi et al., 2007; Daniel et al., 2000; Schrock et al., 2004), other studies discussed on both fatal and injury crashes (Elghamrawy et al., n.d.; Li and Bai, 2008a), and some conducted injury severity analyses (Akepati and Dissanayake, 2011; Khattak and Targa, 2004; Khattak et al., 2002; Li and Bai, 2009; Qi et al., 2013; Wang et al., 2010). There have been inconsistencies in the literature regarding whether work zone crashes are more severe relative to those occurring in non-work zone areas. Some studies indicated that work zone crashes were in fact more severe (Bédard et al., 2002; Garber and Zhao, 2002; Meng et al., 2010; Pigman and Agent, 1990; Ullman et al., 2006), while others disagreed (FHWA, 2016; Hargroves and Martin, 1980; Nemeth and Migletz, 1978; Nemeth and Rathi, 1983; Rouphail et al., 1988).



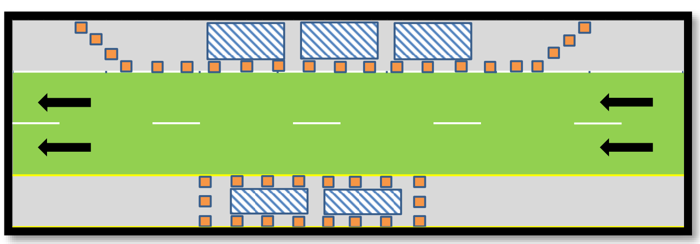
a. Lane Closure



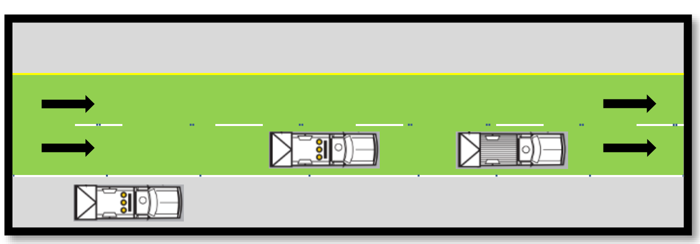
b. Lane Shift



c. Crossover



d. Shoulder or Median



e. Intermittent/Mobile

Fig. 1 Work zone configurations (adopted from: MUTCD 2009)

According to the work zone safety literature, there have not been any studies that undertook analysis at the level of the specific work zone configuration where a crash has occurred. Most of work zone safety research to date accounts only for the work zone as an entire roadway segment that is under some type of TTC due to road work. Additionally, the potential effects of the different work zone configurations, especially within the context of injury severity analysis, on the severity of crashes were never comprehensively analyzed in the literature. Depending on the nature of the TTC plan pertaining to a specific work zone configuration, the determinants and the magnitude of impact of factors that influence injury severity of crashes that occur in work zones can vary across different work zone configurations. The objective of current study is to develop an analytical model of crash injury severity within each of the work zone configurations previously identified. In doing so, injury severity of the most injured passenger-car occupant within a specific work zone configuration is investigated by exploring the interactions between the identified five work zone configurations and different risk factors. Unobserved heterogeneous effects of the different risk factors are examined and identified through the modeling structure utilized. Understanding the different characteristics contributing to the injury severity of passenger-car most-injured occupant in the different work zone configurations will serve as a great advantage enabling practitioners, designers, and DOT officials to mitigate the severity of those individuals; generally involved in a work zone crash or particularly within a specific work zone configuration. As stated in the 2009 edition of the MUTCD ("Manual on Uniform Traffic Control Devices (MUTCD)," 2009), TTC applications were designed as minimum solutions for the depicted configurations and therefore, work zone designers and DOTs can make informed decision when upgrading TTC plans from those minimums to best suit their needs by possessing advanced knowledge of what factors may or may not affect the injury severity levels of motorists based on the work zone configuration it is.

The remainder of this paper is structured as follows. The next section presents the methodology adopted in this paper. The data section discusses the dataset utilized and the final estimation sample assembly process. The study analysis section presents a detailed overview of the estimation results, statistical measures of fit, elasticity effects, variables strength, and recommendations. Finally, the conclusion section provides a summary of this research along with major findings, limitations, and future scope of research.

2. Methodology

Several different modeling methods have been used to analyze crash severity data. Typically these methods can be grouped into two categories – unordered (Chang and Mannering, 1999; Holdridge et al., 2005; Savolainen and Mannering, 2007; Shankar et al., 1996; Ulfarsson and Mannering, 2004) and ordered (Eluru et al., 2008; Wang et al., 2010; Zhu and Srinivasan, 2011a). In the ordered framework, a single latent propensity function is assumed to be translated into the observed severity outcome depending on the value of the propensity function relative to threshold parameters (number of thresholds = number of possible severity outcomes – 1). The latent propensity function is specified as a function of different factors along with a stochastic component to account for all unobserved factors that influence injury severity. The parameters in the single propensity equation and the thresholds constitute the set of parameters that are estimated using methods such as the maximum likelihood (ML). Eluru *et al*. (2008) extended the standard ordered response framework to develop Generalized Ordered Response (GOR) models that allow parameterization of the threshold parameters providing additional flexibility to the ordinal models (Eluru et al., 2008). So, it is not surprising that a recent comparison analysis of unordered and ordered frameworks that considers generalized version of ordered models found minor differences between the two models (Anowar et al., 2014). Although, some studies that specifically conducted comparisons between the different econometric frameworks found that the ordered framework is superior to the unordered framework in the context of injury severity analysis (Mannering et al., 2016; Osman et al., 2016; Ye and Lord, 2014). Moreover, Osman *et al.* (2016) concluded that within the ordered framework, the GOR modeling structure outperformed the standard Ordered Probit (ORP) model. The ORP, which is a widely utilized ordered discrete choice model in the literature of injury severity, imposes certain constraints. The ORP model is constrained to finding only one coefficient for each independent variable. The single coefficient has a parallel effect across the different categories of the dependent variable (injury severity), either towards higher severity or towards lower severity. It is not impossible to utilize the random parameter approach in ordered models but the ordering constraint remains (Kim et al., 2013).

Another aspect of considerable importance in injury severity analysis is unobserved heterogeneity. Injury severity conditional on crash occurrence can depend on numerous factors all of which are most certainly not observed in crash databases. These unobserved factors can moderate the influence of other observed covariates in the model leading to variation in the parameter effects across different observations. This unobserved variation in covariate effects is referred to as *unobserved heterogeneity*. Mannering *et al.* (2016) describes this issue in greater detail and presents alternate modeling methods available in the literature for handling this problem (Mannering et al., 2016). Among these methods, the random parameters methods are the most prominent. Consistent with the previous studies and the recommendations of this study, we adopted the "random parameters" or Mixed GOR Probit (MGORP) model for analyzing injury severity of most-injured passenger car occupant involved in work zone crashes. The MGORP model, as a generalized version of the standard ORP model, has the flexibility of overcoming the constraints imposed by the latter while allowing for the testing of unobserved heterogeneity of the covariates (Eluru et al., 2008). All the notations used are presented below followed by brief overview of the MGORP model:

Notation	**Explanation**
i	Index representing injury severity categories
n	Index that represents the most injured occupant of an involved passenger-car
y_n^*	Latent risk propensity of occupant n in a crash
y_n	Observed severity outcomes
ψ_i	Threshold parameter of injury severity category
$\boldsymbol{X}_n$	Vector of covariates of size $K \times 1$
$\boldsymbol{\beta}$	Corresponding $K \times 1$ vector of coefficients of the covariates in X_n
ε_n	Random error term capturing the effects of unobserved factors on the injury severity
$\boldsymbol{\beta}_n$	Vector is assumed to a realization from a multivariate normal distribution with mean $\boldsymbol{b}$
$\boldsymbol{Z}_{ni}$	Set of exogenous variables associated with the i^{th} threshold excluding the constant
$\boldsymbol{\gamma}_{n.i}$	Corresponding vector of coefficients associated with exogenous variable set $\boldsymbol{Z}_{ni}$
$\alpha_{n,i}$	Parameter associated with injury severity level i $\boldsymbol{Z}_{ni}$

$\boldsymbol{\gamma}_n$	Vertically stacked column vectors of $\boldsymbol{\gamma}_{n.i}$
$\boldsymbol{\alpha}_n$	Vertically stacked column vectors of $\alpha_{n,i}$
$P_n(i\|\boldsymbol{\gamma}_n, \boldsymbol{\alpha}_n)$	Probability of observed injury severity *i* of occupant *n* conditional on $\boldsymbol{\gamma}_n$ and $\boldsymbol{\alpha}_n$
$\boldsymbol{c}_i$	Mean of the multivariate normal distribution
$\boldsymbol{\Omega}_i$	Covariance of the multivariate normal distribution

Let $n(n = 1,2, \dots, N)$ be an index that represents the most injured occupant of an involved passenger-car and $i(i = 1,2, \dots, I)$ is the index representing injury severity categories. In the context of this study, index i will take the value "no injury" ($i = 1$), "injury" ($i = 2$), and "severe injury" ($i = 3$). The MGORP model starts as a standard ORP. The equation system for the ORP model is (McKelvey and Zavoina, 1975):

$$y_n^* = \boldsymbol{\beta}'\boldsymbol{X}_n + \varepsilon_n$$
$$y_n = i \; if \; (\psi_{i-1} < y_n^* < \psi_i) \qquad (1)$$

where y_n^* is the latent risk propensity of occupant n in a crash, which is translated into observed severity outcomes y_n by threshold parameters ψ_i. $\boldsymbol{X}_n$ is $K \times 1$ vector of covariates and $\boldsymbol{\beta}$ is the corresponding $K \times 1$ vector of coefficients; ψ_i is the i^{th} threshold parameters; $\psi_0 = -\infty$ and $\psi_{I+1} = \infty$. ε_n is a random error term capturing the effects of unobserved factors on the injury severity propensity. For model identification purposes, this error term ε_n is assumed to be independently and identically standard normal distributed across the crashes which leads to the ORP model. The model structure requires that the thresholds to be strictly ordered for the partitioning of the latent risk propensity measure into the ordered injury severity categories ($i.e., -\infty < \psi_1 < \psi_2 < \cdots < \psi_{I-1} < \infty$) for each occupant n.

The enhancement of the ORP model to a MGORP is characterized by the enabling $\boldsymbol{b}$ vector and ψ thresholds to vary across observations. This is accomplished through subscripting these parameters with the index n. The MGORP equation system can then be written as follows:

$$y_n^* = \boldsymbol{\beta}'_n\boldsymbol{X}_n + \varepsilon_n$$
$$y_n = i \; if \; \left(\psi_{n,i-1} < y_n^* < \psi_{n,i}\right) \qquad (2)$$

To account for unobserved heterogeneity, the $\boldsymbol{\beta}_n$ vector is assumed to a realization from a multivariate normal distribution with mean $\boldsymbol{b}$ and covariance $\boldsymbol{\Sigma}$. Now, Equation (2) can be re-written as follows:

$$y_n^* = \boldsymbol{\beta}'_n \boldsymbol{X}_n + \tilde{\varepsilon}_n \text{ where } \tilde{\varepsilon}_n \sim N(0, \boldsymbol{X}'_n \boldsymbol{\Sigma} \boldsymbol{X}_n)$$

$$y_n = i \; if \; \left(\psi_{n,i-1} < y_n^* < \psi_{n,i}\right) \tag{3}$$

Also, a specific non-linear functional form was used for parameterizing thresholds to ensure that the ordinal criterion is met ($-\infty < \psi_{\mathrm{n},1} < \psi_{\mathrm{n},2} < \cdots < \psi_{n,I-1} < \infty$) for each driver n:

$$\psi_{n,i} = \psi_{n,i-1} + exp\left(\alpha_{n,i} + \boldsymbol{\gamma}'_{n,i} \boldsymbol{Z}_{ni}\right) \tag{4}$$

where $\boldsymbol{Z}_{ni}$ is a set of exogenous variables associated with the i^{th} threshold excluding the constant; $\boldsymbol{\gamma}_{n,i}$is the corresponding vector of coefficients, and $\alpha_{n,i}$ is a parameter associated with injury severity level $i = 1,2,\ldots,I-1$. $\psi_{n,1}$ is specified as $exp(\alpha_1)$ for identification reasons. Moreover, $\boldsymbol{\gamma}_{n,i}$ vector is assumed a realization from a multivariate normal distribution with mean $\boldsymbol{c}_i$ and covariance $\boldsymbol{\Omega}_i$. Let $\boldsymbol{\gamma}_n$ and $\boldsymbol{\alpha}_n$ be the vertically stacked column vectors of $\boldsymbol{\gamma}_{n,i}$ and $\boldsymbol{\alpha}_{n,i}$, respectively.

The probability of observed injury severity *i* of occupant *n* conditional on $\boldsymbol{\gamma}_n$ and $\boldsymbol{\alpha}_n$ is given by:

$$P_n(i|\boldsymbol{\gamma}_n, \boldsymbol{\alpha}_n) = \Phi\left(\frac{\psi_{n,i} - \boldsymbol{b}'\boldsymbol{X}_n}{\sqrt{\boldsymbol{X}'_n \boldsymbol{\Sigma} \boldsymbol{X}_n}}\right) - \Phi\left(\frac{\psi_{n,i-1} - \boldsymbol{b}'\boldsymbol{X}_n}{\sqrt{\boldsymbol{X}'_n \boldsymbol{\Sigma} \boldsymbol{X}_n}}\right) \tag{5}$$

The unconditional probability can be obtained by integrating out the random components as follows:

$$P_n(i|\boldsymbol{\gamma}_n, \boldsymbol{\alpha}_n) = \int\limits_{\boldsymbol{\gamma}_n, \boldsymbol{\alpha}_n} \left[\Phi\left(\frac{\psi_{n,i} - \boldsymbol{b}'\boldsymbol{X}_n}{\sqrt{\boldsymbol{X}'_n \boldsymbol{\Sigma} \boldsymbol{X}_n}}\right) - \Phi\left(\frac{\psi_{n,i-1} - \boldsymbol{b}'\boldsymbol{X}_n}{\sqrt{\boldsymbol{X}'_n \boldsymbol{\Sigma} \boldsymbol{X}_n}}\right)\right] f(\boldsymbol{\gamma}_n) f(\boldsymbol{\alpha}_n) d\boldsymbol{\gamma}_n \, d\boldsymbol{\alpha}_n \tag{6}$$

The integral in Equation (6) can be evaluated using Monte Carlo simulation method. We undertook the simulation in Gauss programming language that is specifically suited for econometric modeling. It can be seen from Equation (6) that multivariate integrals must be evaluated during model estimation. The maximum simulated likelihood (MSL) inference approach is based on the idea of approximating the integral in Equation (6) using Monte Carlo simulation method by averaging the function that is being integrated at numerous draws of random components (*i.e.*, $\boldsymbol{\gamma}_n$ and $\boldsymbol{\alpha}_n$). Several draws are needed if the integration is done using completely random draws. However, Bhat (2001) developed quasi-random Halton sequences that perform quite well with fewer draws. The typical recommended number of Halton draws is between 100 and 200. So, the resulting model was estimated using the maximum simulated likelihood (MSL) inference approach with 150 quasi-random Halton draws (Bhat, 2001).

3. Data

A dataset consisting of 10 years of work zone crashes (2003-2012) in Minnesota (MN) was collected from the HSIS database. The dataset contained 17,237 unique crashes reported to have occurred in work zones. Due to the fact that approximately 85% of fatalities in work zones were drivers or occupants of passenger cars (FHWA, 2016), and that the factors influencing the level of injury severity of involved individuals vary significantly among truck versus non-truck crashes (Chang and Mannering, 1999), this study will mainly focus on crashes that included only passenger-cars. Although, truck involvement was accounted for as a binary variable in the modeling process in order to investigate whether it is in fact a risk factor contributing to the injury severity levels of occupants of passenger-cars in those cases involving both types of vehicles. Therefore, all crashes involving only large trucks were excluded from the dataset. The final sample of crashes was adjusted to 14,351 unique passenger-car crashes in work zones within the time frame depicted in this study. The distribution of observations by injury severity is presented in Tables 1. The upper section of Table 1 shows the percentage of each injury severity category of the original dataset. The injury severity level followed the KABCO injury severity scale where K=killed, A=incapacitating injury, B=non-incapacitating injury, C=possible injury, and O=no injury. Due to the low frequency of some of the severity levels, some of the severity categories were combined. The combined injury severity categories are also shown in Table 1 Fatal, incapacitating, and non-incapacitating severity levels were combined into one severity level called “severe injury”. “Possible injury” which is referred to as “injury” and “no injury” categories were kept as is.

TABLE 1 Frequency Distribution of Initial and Final (combined) Dependent Variable

Injury Severity Category	Count	(%)
Fatal (K)	63	0.44
Incapacitating Injury (A)	127	0.88
Non-Incapacitating Injury (B)	1,099	7.66
Possible Injury (C)	3,021	21.05
Property Damage (O)	10,041	69.97
Total	14,351	100.00%
Combined Injury Severity Category		
Severe Injury (K,A,B)	1,289	8.98
Mild Injury (C)	3,021	21.05
No Injury (O)	10,041	69.97
Total	14,351	100.00%

4. Data Analysis

As previously mentioned, the MGORP model is considered an extension to the standard ORP where the MGORP allows for the parameterization of the threshold parameters providing additional flexibility and therefore overcome the ORP constraint of finding only one coefficient on each variable that is in one direction, either towards higher severity or towards lower severity. So, prior to the development of the MGORP, a standard ORP and a GORP model were developed and used as the bases in estimating the MGORP model. The building of the ORP model was done in a stepwise fashion where statistically insignificant variables were removed from following runs. As indicated in earlier studies, Osman *et al.* (2016) compared unordered and ordered discrete choice frameworks to include: multinomial logit (MNL), nested logit (NL), ordered logit (ORL), and generalized ordered logit (GORL) models in injury severity analysis and found that the GORL model was superior to all other utilized models (Osman et al., 2016). Moreover, Eluru *et al*. (2008) discussed in details the superiority of the GORP/MGORP to the standard ORP (Eluru et al., 2008).

Table 2 indicates the frequency distribution of the explanatory variables entered the MGORP modeling process. The authors adopted a methodological approach of interacting statistically significant factors with each of the five depicted work zone configurations, based on the specific work zone layout reported by the law enforcement agency investigating the crash. Differential impacts of the independent

TABLE 2 Frequency Distribution of Explanatory Variable

Explanatory Variable	(%)	Explanatory Variable	(%)
Roadway		**Work Zone**	
Geometric design		Work zone area	
Access control		Advanced-warning	11.20
No control	36.14	Transition	21.18
Partial control	9.33	Activity	64.05
Full control	54.53	Termination	3.57
Inclination		Work zone type	
On grade	24.15	Lane closure	38.90
Level	75.85	Lane shift/crossover	21.86
Alignment		Shoulder or Median	23.46
Curved	17.89	Intermittent	6.92
Straight	82.11	Other	8.86
No. of lanes		Presence of workers	
Two-lane	14.38	Workers present	32.28
Multi-lane	85.62	Workers not present	67.72
Roadway classification		**Temporal**	
Functional class		Day of the week	
Principal arterial	75.40	Weekday	79.23
Minor arterial	18.26	Weekend	20.77
Other (collector, local systems)	6.34	Time of day	
Area type		Daytime	73.39
Urban	85.14	Evening	19.93
Rural	14.86	Late night	6.68
Environmental		**Crash**	
Weather condition		No. of vehicles	
Adverse	35.84	Single-vehicle	21.73
Clear	64.16	Multi-vehicle	78.27
Roadway surface condition		Truck involvement	
Wet	18.83	Heavy-duty	3.87
Dry	81.17	Light-duty	33.56
Traffic		None	62.57
Speed limit		Location	
< 35	14.13	On-bridge	6.56
35-40	9.13	Not on-bridge	93.44
45-50	17.93		
55-60	52.02		
65-70	6.79		

variables on the severity level were examined and the final specification for the presented model was based on a logical process of building a generalized ordered response probit (GORP) model while removing the statistically insignificant variables and combining other variables when their effects were statistically insignificant. Due to the complex process of crash occurrences to include, but certainly not limited to, interactions of vehicles, roadway conditions, traffic factors, and environmental conditions, it is considered almost impossible to gain access to all of the data contributing to the occurrence of a crash or its corresponding severity level. The lack of such important data can lead to erroneous specifications through biased parameter estimates (Mannering et al., 2016). This problem is typically referred to as "unobserved heterogeneity" in the crash analysis literature. We extensively tested for unobserved heterogeneity effects of the injury severity determinants on the latent injury risk propensity due to potential unobserved factors. Thus, our final model specification became a mixed generalized ordered response probit (MGORP) model. The final model estimation process was, in large part, guided by findings of past research and intuitiveness of the parameters estimated. It terms of investigating the potential effects imposed by the specific work zone configuration where a crash has occurred, we followed a systematic approach of interacting all statistically significant variables with each of the five work zone configurations depicted in this study.

Figure (2) represents the frequency of crashes within each of the five work zone configurations in the dataset. In the initial modeling process, each independent variable was regressed as a "standalone" variable to test for the statistical significance of its effect across all work zone configurations, followed by potential additional effects produced through interaction terms across each individual work zone configuration. The "other" work zone configuration served as the base for the remaining four categories for modeling specification purposes. For example, if a standalone variable had a coefficient parameter of +0.50 across all work zone configurations and its interaction with the "lane closure" configuration had an additional coefficient parameter of +0.15, the combined value of the two parameters (0.50 + 0.15 = +0.65) is the final effect of "lane closure" on this variable. Similarly, if the additional variable effect through the interaction of the same "standalone" variable with the "shoulder or median" work zone configuration had a coefficient parameter of -0.20, therefore the combined effect for "shoulder or median" would be (0.50 - 0.20 = +0.30). This example can be interpreted as the "standalone" variable increased the likelihood of higher injury severity levels across all work zone configurations in the dataset with its positive coefficient value (+0.50). Relative to the "other" work zone configuration as the base category and compared to other work zone configurations, "lane closure" also increased the likelihood of higher

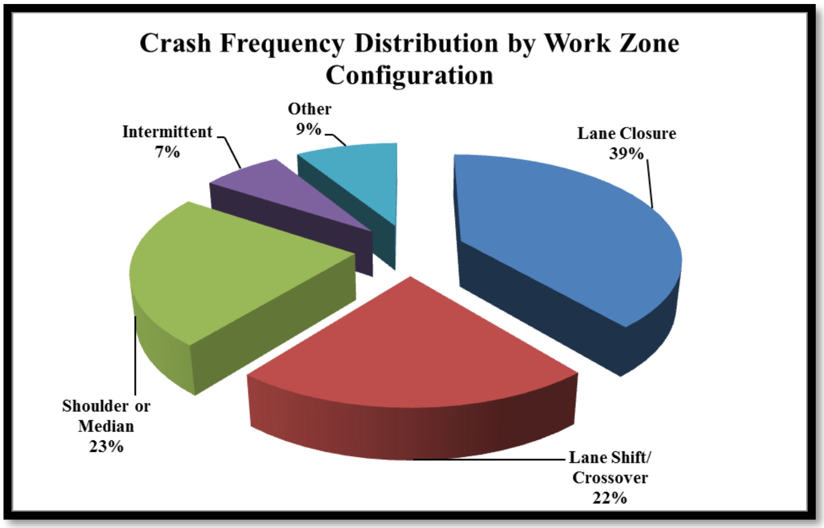


Fig. 2 Crash frequency distribution by work zone configuration

injury severity with its positive coefficient (+0.15). While "shoulder or median" also increased that likelihood with its positive coefficient (+0.30), it decreased the likelihood of higher injury severity levels relative to "other" work zone configurations with its negative interaction coefficient value (-0.20). This incremental effects approach uncovers the differences imposed by the different work zone configurations on each of the variables initially found statistically significant in the model before the introduction of any variable interactions.

5. Study Results

Table 3 presents the estimation results of the MGORP model. The first column of Table 3 shows the name of each variable entered the estimation process, while the second and third columns present two sets of variable coefficient parameters corresponding to the different injury severity levels. The second column presents each variable in the latent risk propensity function (excluding a constant) comparing the "no injury" vs. "injury" and "severe injury" outcomes. Eluru et al. (2008) demonstrated the predicted probability of the different injury severity levels between the appropriate thresholds as a logistic curve (Eluru et al., 2008). The third column of Table 3 presents variables entered the threshold specification function between "injury" and "severe injury" outcomes. Positive (+) parameter values indicate larger region of "injury" vs. "severe injury" under an injury severity curve, while negative (-) parameter values indicate larger “severe injury” vs. “injury” outcomes (Eluru et al., 2008). The respective t-values of the estimated coefficients are shown in parentheses. Table 3 also presents the initial log-likelihood value (restricted model with no covariates), the log-likelihood value at convergence (unrestricted model), the McFadden pseudo R^2 value (predictive ability of the model; see (McFadden, 1973)) , and the total number of observations in the dataset.

In the “variable” column, each variable is followed by its potential additional effects through interactions with each of the different work zone configurations depicted in this study. For modeling specification reasons, the “other” category is considered the base for the remaining four work zone configurations throughout the modeling process. In the first column of Table 3, the four work zone configurations are demarcated by the numbers 1 thought 4 at the end of each variable’s name; lane closure (1), lane shift/crossover (2), shoulder or median (3), and intermittent/mobile (4).

5.1. Roadway characteristics

Relative to access-control “full control”, the positive parameters of “no control” and “partial control”, (propensity = +0.241, +0.175 respectively), indicated the increased risk propensity of higher injury severity outcomes. The negative threshold for “partial control” (threshold = -0.088) further indicated the increased proportion of “severe injury” relative to “injury” outcomes. Roadways with no access-control are likely to have more conflict points. While some studies indicated that full-control of access may contribute to the frequency of crashes in work zone (Khattak et al., 2002), there has not been any studies found in the work zone safety literature to address the accessibility of a roadway from an injury severity standpoint. Additional effects of interactions between the “no control” variable with the different work zone configurations indicated that crashes occurred in lane closures were more severe (threshold = -0.083), while intermittent/mobile operations were associated with less injury severity (propensity = +0.241-0.149 = +0.092) relative to other work zone configurations. Lane closures in work zones with full-access to the roadway are likely to be associated with higher vehicular density in lanes open to traffic.

Intermittent work zones in fully-accessed roadways are likely to be associated with lower vehicular

TABLE 3 MGORP model results

Explanatory Variables	MGORP	
	Latent Propensity	Threshold: injury | severe injury
Roadway		
Geometric design		
Access control (base: full control)		
No control	0.241 (6.92)	-
No control-1	-	-0.083 (-1.38)
No control-4	-0.149 (-2.04)	
Partial control	0.175 (4.28)	-0.088 (-1.53)
Inclination (base: level)		
On grade	-	-0.057 (-1.42)
Alignment (base: straight)		
Curved	-	-0.136 (-2.86)
No. of lanes (base: multi-lane)		
Two-lane	0.117 (2.56)	-
Two-lane-1	-0.109 (-1.47)	-
Roadway classification		
Functional class (base: collector, local system)		
Principal arterial	0.070 (1.12)	-
Principal arterial-3	0.236 (3.80)	-
Minor arterial	0.218 (3.07)	-
Standard Deviation	0.343 (2.13)	
Minor arterial-1	-0.118 (-1.87)	-
Collector/local system-3	0.395 (3.36)	-
Area type (base: urban)		
Rural	-	-0.269 (-5.69)
Environmental		
Weather condition (base: clear)		
Adverse weather	-	0.111 (2.97)
Roadway surface condition (base: dry)		
Wet	-0.225 (-4.07)	-
Standard Deviation	0.314 (1.76)	
Wet-3	0.081 (1.20)	-
Traffic		
Speed limit (mph) (base: 45-60)		
< 35	-0.324 (-5.09)	-
Standard Deviation	0.592 (4.81)	
< 35-2	0.136 (1.45)	-
35-40	-	0.092 (1.69)
45-50-2	0.135 (2.28)	-
45-50-3	-0.243 (-3.48)	-
55-60-3	-0.185 (-2.91)	-
65-70	0.063 (1.38)	-

Note: Interaction variables ending in 1-4 (1=lane closure, 2=lane shift/crossover, 3=shoulder or median, 4=intermittent/mobile)

TABLE 3 Continued

Explanatory Variables	MGORP	
	Latent Propensity	Threshold: injury | severe injury
Work Zone		
Work zone area (base: transition)		
Advanced-warning	0.205 (4.51)	0.065 (1.28)
Advanced-warning-3	-0.172 (-1.75)	
Activity	0.067 (2.10)	
Termination	0.115 (1.48)	-0.130 (-1.46)
Termination-3	0.160 (1.13)	
Termination-4	0.311 (1.57)	
Work zone type (base: shoulder/median, intermittent, other)		
Lane closure	-	0.073 (1.65)
Lane shift/crossover	-	0.090 (2.01)
Presence of workers (base: not present)		
Present	0.074 (2.28)	
Present-1	-0.050 (-1.10)	
Temporal		
Day of the week (base: weekday)		
Weekend	0.152 (5.43)	
Time of day (base: daytime)		
Evening	0.088 (2.96)	-0.104 (-2.46)
Late night	0.068 (1.28)	-0.287 (-4.06)
Late night-3	0.153 (1.42)	-
Crash		
No. of vehicles (base: multi-vehicle)		
Single-vehicle	0.069 (2.00)	-
Single-vehicle-1	0.183 (3.14)	-
Multi-vehicle-2	-0.077 (-1.97)	-
Truck involvement (base: none, light-duty)		
Heavy-duty	0.537 (6.93)	-0.213 (-2.59)
Heavy-duty-2	0.149 (1.10)	-
Heavy-duty-3	-0.308 (-2.26)	-
Location		
On-bridge (base: not on-bridge)		0.079 (1.21)
Constants		
Threshold 1 (no injury | injury)	-0.146 (-1.75)	
Threshold 2 (injury | severe injury)	-0.074 (-2.07)	
Log-Likelihood at zero	-11,399.9	
Log-Likelihood at convergence	-11,070.9	
McFadden R^2	0.0289	
Number of observations	14,351	

Note: Interaction variables ending in 1-4 (1=lane closure, 2=lane shift/crossover, 3=shoulder or median, 4=intermittent/mobile)

speeds which can reduce forceful impacts at conflict points.

For all work zone configurations, roadways on-grade and curved segments, as compared to “level” and “straight” respectively, increased the likelihood of higher injury severity outcomes (negative parameter values in the threshold function for both variables; thresholds = -0.057, -0.136 respectively). Although some studies indicated the both curved and on-grade roadways increased the likelihood of single vehicle crash occurrences in work zones (Harb et al., 2008), yet there has been no comparative evidence to the findings of this study for the injury severity of crashes on both roadway alignments. Drivers are likely to be more cautious on a grade or a curved roadway, yet an unanticipated crash can lead to severe outcomes. The number of lanes variable indicated that crashes occurring on two-lane roadways were associated with higher risk propensity (propensity = +0.117) of injury severity compared to multi-lanes roads. This finding is consistent with past literature for work zone crashes (Li and Bai, 2009). Additional effects through interactions between the number of lanes with the different work zone configurations indicated that although crashes in the lane closure configuration were still associated with higher injury severities, yet the negative propensity (propensity = +0.117-0.109 = +0.008) specified that compared to other work zone configurations, lane closures reduced the severity of crashes. This is likely due to that fact that lane closures on a two-lane road is usually controlled with a temporary signal at the beginning and end of the work zone area so that one direction of traffic is traveling at a time across the work zone reducing conflicts with oncoming traffic. While considering rear-end crashes Qi et al. (2013) found similar associations of crashes with “shoulder/median” activity in work zones (Qi et al., 2013).

Principal and minor arterials indicated an increased risk propensity towards higher injury severity outcomes (propensity = +0.070, +0.218 respectively) compared to collectors and local systems. Previous studies (Li and Bai, 2008a; Qi et al., 2013) found similar results, which could be explained by higher speeds in the upstream area of a work zone. The standard deviation for the “minor arterial” variable (SD = 0.343) indicated the presence of unobserved heterogeneity during the modeling process. Compared to all depicted work zone configurations, shoulder/median activity on a principal arterial indicated higher risk towards higher injury severity levels (propensity = +0.070+0.236 = +0.306). Although lane closures on a minor arterial still contributed to higher injury severity levels, its negative propensity (propensity =

+0.218-0.118 = 0.100) indicated the reduced risk compared to other work zone configurations. Minor arterials are likely to have lower speed limits and higher vehicular density in work zones relative to principal arterials. Shoulder and median work on collectors or local system was associated with higher injury severity levels (propensity = +0.395) compared to other work zone configurations. This could be explained by the reduced availability of areas to maneuver (lack of shoulder or median) in a crash developing situation while likely traveling at maximum allowable speeds through the work zone in fully functional lanes adjacent to work area.

Crashes occurring on roadways classified as "rural" indicated that in the event of a crash, the likelihood of the "severe injury" vs. "injury" outcomes is much higher (threshold = -0.269). This was indicated by the negative coefficient parameter between both outcomes in the threshold function. This is likely due to higher speeds leading to a work zone area compared to an urban roadway. This finding is consistent with past work zone injury severity literature (Li and Bai, 2009; Qi et al., 2013; Wang et al., 2010) and work zone crash frequency literature (Khattak et al., 2002).

5.2. Environmental characteristics

Adverse weather and wet surfaces were associated with lower likelihood of severe injury crashes compared to clear weather conditions. It seems as if drivers are more cautious driving at lower speeds and maintaining safe headways when driving on wet surfaces or in an adverse weather situation. Other work zone studies found that wet surface had no impact on the severity of a crash relative to non-work zone areas (Harb et al., 2008; Li and Bai, 2009). Another study has found opposing results for fatal and injury crashes in work zones (Li and Bai, 2008a). Although traveling on wet surfaces in a work zone involving work on shoulder or median reduced the risk of severe crashes, it appeared to be associated with least risk among other work zone configurations.

5.3. Traffic characteristics

Lower speeds upstream of work zones reduced risk propensities of higher severity crashes. This is indicated by the negative propensity of speeds under 35 mph. The positive coefficient in the threshold column for 35-40 mph indicated that if a crash occurred at those speeds, the most injured occupant would likely to sustain an injury but not a severe injury. When tested for unobserved heterogeneity, the standard deviation of 30 mph or less indicated strong statistical significance. On the other hand, positive coefficients in the risk propensity function for speed limits of 60 mph or more indicated a higher risk of a severe injury crashes. Previous work zone crash severity literature found similar results (Li and Bai, 2009; Wang et al., 2010). Additional effects of interactions between the different speed limit categories with the different work zone configurations indicated that speeds of 50 mph or less were associated with higher severity outcomes in the event of a crash in lane shifts or crossovers compared to other work zone configurations. Lane shifts or crossovers are considered to be more complex work zone configurations relative to other types and are likely to be associated with potential distraction with machinery and workers ahead in the driver's line of sight. Speed limit range of 45-60 mph reduced the risk propensity of higher injury severity outcomes through work zones involving activity in the shoulder or median. Work outside the travel lane (i.e. shoulder or median) when balanced with mid-range speeds can lead to more attentive driving while allowing time and distance to come to a stop in a crash developing situation.

5.4. Work zone characteristics

Advanced-warning, activity, and termination areas of a work zone were all associated with higher injury severity crashes indicated by the positive risk propensity coefficient values for all three variables as compared to the transition area. Motorists in the transition area are likely to have already lowered their speeds after passing through advanced signage leading to the upcoming work zone and therefore, forceful impacts are reduced in the event of a crash. The activity area is likely to be associated with driver's distraction with work zone equipment and the presence of workers, while the termination area is likely to be associated with higher speeds exiting the work zone. No comparative evidence was found in the work zone injury severity literature to support or contradict such findings. One previous study concluded that the activity area was more susceptible to crashes regardless of the road type while the termination area had the lowest frequency (Garber and Zhao, 2002). Work on shoulder or median was associated with the least risk propensity of severe crashes in the activity area compared to other work zone configurations, yet increased the risk of those occurred in the termination area. This can be explained by the fact that drivers are likely to reduce their speeds approaching the advanced waning area of a work zone and easily gain speeds in the termination area especially when realized that actual work zone activity is not in the traveled lanes. The termination area of an intermittent/mobile operation was associated with higher risk propensity for higher severity outcomes compared to lane closures or lane shifts. Motorists are likely to encounter large pieces of moving equipment especially when merging into reopened lanes at the end of a moving work zone.

Compared to work on shoulder or median, intermittent/mobile, and "other" work zone configurations, lane closures and lane shifts were associated with injuries but not severe ones in the event of a passenger-car crash. This behavior was indicated by the model through the positive coefficient values of both variables in the threshold function. Although this study did not investigate the injury severity of work zone workers, it did account for their presence during the occurrence of a passenger-car crash in the work zone due to potential distraction to the driver. The presence of workers was associated with higher risk propensity of higher injury severity outcomes for passenger-car occupants. Presence of workers in a lane closure had the lowest risk among all other work zone configurations. The presence of workers generally represents a distraction to drivers. Driver are likely to pay more attention to the specific location of workers to avoid striking one in case of possible intrusion of workers into the traveled lanes, and therefore less attention is given to other surroundings such as vehicles and traffic control devices.

5.5. Temporal characteristics

"Weekend" was found to be associated with higher likelihood of higher injury severity across all work zone configurations relative to traveling on the weekdays. Past literature indicated similar results for non-truck involved crashes (Chang and Mannering, 1999; Mishra and Zhu, 2015). Such a behavior is likely due to the fact that most, and certainly not all, work zones are inactive during weekends. Motorists would likely speed through the work zone once discovered it is not operational. Higher speeds will lead to forceful impacts in the event of a crash.

Traveling during evening and late night times increased the propensity risks of severe passenger-crashes in work zones compared to daytime crashes. The positive risk propensities and negative thresholds values, in the MGORP model results indicated such a behavior. The highly significant negative threshold value for “late night” indicated that in the event of a crash, a passenger-car occupant is likely to sustain “severe injury” relative to “injury” outcomes. Past work zone safety studies found similar results for night time crashes (Chang and Mannering, 1999; Harb et al., 2008). This can be explained by poor visibility at late night times and higher speeds due to lower vehicular densities compared to daytime. Although most work zones are inactive during late night times, the work zone configuration of shoulder or median work was associated with the highest risks among other configurations. Shoulder or median work zone configurations involve the least exposure to work zone objects (e.g. cones, barriers, attenuators) in the traveled lanes and therefore motorists are likely to raise speeds due to less intimidation by conflicts.

5.6. Crash characteristics

The “single-vehicle” crash indictor was found to be associated with higher risk propensities for passenger-car crashes in work zones. Single-vehicle crashes in lane closures were associated higher risks compared to other work zone configurations. Single-vehicle crashes usually involve inattentive driving and in the case of lane closures, sudden maneuvers to change lanes or avoid equipment or worker’s intrusion in the travel lane are expected. No comparative evidence in the work zone injury severity literature to support or contradict such findings. Drivers are probably riding at lower speeds especially when crowded by other merging vehicles in a lane shift configuration.

Compared to light-duty trucks and other passenger-cars involved in work zone crashes, the involvement of heavy-duty trucks was found to be highly associated with higher risk propensities. The highly significant value of the “heavy-duty” variable in the risk propensity function indicated such a behavior. The negative threshold value for the same variable further indicated that in the event of a passenger-car crash involving a heavy-duty truck, passenger-car occupants are likely to sustain “severe injury” rather “injury” outcomes. Such a behavior was suggested by past literature (Chang and Mannering, 1999, p.; Harb et al., 2008; Li and Bai, 2009), while another study suggested opposing results, although some of these studies did not control for crashes specifically in work zones (Chen and Chen, 2011, p.; Dong et al., 2015; Wang et al., 2010). Being fatigued or falling asleep is not unusual among truck drivers (Saltzman and Belzer, 2007), although these conditions are not particular to just work zones. Additional effects of interactions between the “heavy-duty” indicator with the different work zone configurations indicated that lane shifts or crossovers were associated with higher risk propensities of severe crashes while work on shoulder/median reduced that risk. Heavy-duty trucks are likely harder to maneuver when shifting lanes compared to other work zone configurations, especially during a sudden reaction to another vehicle or workers in a work zone. Although the MGORP model failed to provide a coefficient in the risk propensity function for “on-bridge”, the positive coefficient value of the threshold function indicated that in the event of a passenger-car crash on a bridge, the outcome is an injury rather than a severe injury. Drivers are likely to lower their speeds crossing an active work zone on a bridge therefore; forceful impacts are unlikely to occur in the event of a crash.

5.7. Measures of fit

In order to examine whether the impacts of contributing factors captured in the MGORP model on the injury severity levels compared to those identified in the standard ORP model, a Likelihood Ratio (LR) test is employed. For more information regarding the LR test, readers are encouraged to refer to (Washington et al., 2003). In comparing two statistical models, the log-likelihood (LL) values at convergence for each unrestricted model (full model with all covariates) are utilized. Similarly, a LR test between an unrestricted model and a restricted model (same model with constants only and no covariates) can be utilized to test the predictive power of a model. The resulting test statistic is chi-square distributed, with degrees of freedom being equal to the difference in the numbers of parameters between the models being compared (Washington et al., 2003).

Given that the MGORP model is a generalized version of ORP model, the two models can be compared using a LR test in the estimation sample. Table 3 indicates that the LL value at convergence of the MGORP is -11,070.9, while the corresponding value of the ORP model (suppressed for the sake of brevity) is -11,137.9. The LR test value for comparing the MGORP and ORP models is 134.1, which is greater than the critical chi-square value with 15 degrees of freedom at any reasonable level of significance (note that the ORP model restricts all the non-constant parameters in the threshold column of Table 3 to 0; there are 15 such parameters).

We also evaluated the predictive performance of the unrestricted MGORP model and its corresponding restricted version. Table 3 indicates that the LL value of the restricted MGORP model (constant-only model with no covariates in the risk propensity) is -11,399.9. The MGORP model has 54 additional parameters compared to the constants only model. The LR test statistic of comparison between the MGROP and the constants-only model was 658.1 which is greater than the critical chi-squared value of 72.1 (at any reasonable level of significance) corresponding to 54 degrees of freedom.

Based on the results of the LR tests conducted, the predictive performance of the MGORP model is superior to both the ORP and the constants-only MGORP. The differences are highly statistically significant at any reasonable level of confidence at the corresponding degrees of freedoms. Overall, the values of all the fit statistics indicate the superior performance of the MGORP model from a data fit standpoint.

6. Elasticity Effects

The magnitude of the effects of the independent variables entering a statistical model on each injury severity outcome is not directly provided through the parameter values produced by the model. To be able to clearly understand the impacts of these variables, some of which appear in both the risk propensity and the threshold functions for the MGORP model, it is necessary to compute their corresponding elasticity effects. Elasticity effects can be interpreted as the percent effect a 1% change in a variable has on the severity outcome probability (Khorashadi et al., 2005). Elasticity calculations are not applicable to indicator variables; therefore average direct pseudo-elasticity was calculated (Li and Bai, 2008b; Wong et al., 2011; Zhu and Srinivasan, 2011b). The pseudo-elasticity of a variable represents the average percent change in the probability of an outcome category when the value of that variable is changed from 0 to 1. The elasticity analysis was undertaken for the MGORP model and the results are shown in the following subsection.

6.1. Elasticity effects of MGORP model

Elasticity effects were calculated for all three injury severity outcomes. For the sake of brevity, only results corresponding to the "severe injury" outcome category are presented herein (see Table 4). The first five columns in Table 4 present the results in cases where the elasticity effects vary across different work zone configurations whereas the last column shows the elasticity effects for variables whose impacts do not have such a variation across the different work zone configurations.

In terms of elasticity effects of variables that do not vary across different work zone configurations, the first value is the last column of Table 4 corresponding to "partial control" is 51.20. This indicates that occupants of passenger-car crashes are 51.20% more likely to be severely injured in the event of a crash occurring in work zones in roadways with access-control "partial control" relative to "full control". Moreover, this effect does not vary across different work zone configurations. In Table 4, elasticities of other variables that do not vary across the different work zone configurations in the last column can be interpreted in a similar fashion. Elasticity effects of variables that vary across work zone configurations indicates, the involvement of heavy-duty trucks is found to impose the highest risk of severe outcomes in "lane shift/crossover" (186.39%) followed by other configurations, while "shoulder/median" has the least risk (47.56%) among all other work zone configurations. In Table 4, elasticities of other variables that varied across different work zone configurations in the first five columns can be interpreted similarly.

TABLE 4 Elasticity effects of MGORP model for "Severe Injury" outcome.

Explanatory Variable	Lane Closure	Lane Shift / Crossover	Shoulder / Median	Intermittent	Other	Main Variable Effects
Roadway						
Geometric design						
Access control (base: full control)						
No control	70.07	51.90	51.90	17.88	51.90	
Partial control						51.20
Inclination (base: level)						
On grade						8.67
Alignment (base: straight)						
Curved						21.23
No. of lanes (base: multi-lane)						
Two-lane	1.43	22.21	22.21	22.21	22.21	
Roadway classification						
Functional class (base: other=collector, local system)						
Principal arterial	13.12	13.12	67.13	13.12	13.12	
Minor arterial	18.84	44.42	44.42	44.42	44.42	
Other	0.00	0.00	88.32	0.00	0.00	
Area type (base: urban)						
Rural						44.03
Environmental						
Weather condition (base: clear)						
Adverse weather						-15.65
Roadway surface condition (base: dry)						
Wet	-33.34	-33.34	-22.53	-33.34	-33.34	
Traffic						
Speed limit (mph) (base: 45-60)						
< 35	-44.46	-28.27	-44.46	-44.46	-44.46	
35-40						-13.35
45-50	0.00	25.43	-35.78	0.00	0.00	
55-60	0.00	0.00	-28.17	0.00	0.00	
65-70						11.47

TABLE 4 Continued

Explanatory Variable	Lane Closure	Lane Shift / Crossover	Shoulder / Median	Intermittent	Other	Main Variable Effects
Work Zone						
Work zone area (base: transition)						
Advanced-warning	40.99	40.99	5.96	40.99	40.99	
Transition	0.00	0.00	-19.01	44.35	0.00	
Activity						12.38
Termination	21.74	21.74	57.39	97.30	21.74	
Work zone type (base: shoulder/median, intermittent, other)						
Lane closure						-10.48
Lane shift/crossover						-12.93
Presence of workers (base: not present)						
Present	4.29	13.54	13.54	13.54	13.54	
Temporal						
Day of the week (base: weekday)						
Weekend						29.68
Time of day (base: daytime)						
Evening						34.73
Late night	12.49	12.49	44.74	12.49	12.49	
Crash						
No. of vehicles (base: multi-vehicle)						
Single-vehicle	52.70	12.88	12.88	12.88	12.88	
Multi-vehicle	0.00	-12.69	0.00	0.00	0.00	
Truck involvement (base: none, light-duty)						
Heavy-duty	134.64	186.39	47.56	134.64	134.64	
Location						
On-bridge (base: not on-bridge)						-11.63

Based on the elasticity effects in Table 4, it can be seen that the key factors and conditions that increase the risk of severe outcomes for the occupants of passenger-cars across all work zones are: partial control of access, roadways classified as rural, crashes during evening times, crashes during weekends, and curved roadways. Other variables such as crashes in the activity area of a work zone, higher speeds of 65-70 mph, and roadways on a grade also contribute to increased risk, but not as much as the variables identified earlier. Variations in elasticity effects of variables across different work zone configurations were found for the following factors – access-control, number of lanes, roadway functional class, roadway surface condition, speed limit, work zone component area, presence of workers in the work zone, time-of-day, number of involved vehicles, and truck involvement.

7. Implications of variable effects and recommendations

Variable effects have important implications for the regulation and use of traffic control devices based on the general configuration of the work zone it is, and generally for planning and design of work zones. These implications could also be extended to the training and education for drivers, work zone workers, and non-motorists. In the context of this research, these implications can be classified into two categories: (1) across all work zone configurations, and (2) across specific work zone configurations.

7.1. Recommendations for all work zone configurations

In terms of TTC regulation and use across all work zone configurations, the modeling results and elasticity effects suggest that on roadways that lacks full control-of-access, additional TTC signage and warning messages are needed in the upstream areas of access-points to advice motorists of such upcoming locations. This recommendation is derived from elasticity effects of this study which indicates that occupants of passenger-cars on partially-controlled access roadways are 51.20% more likely to be severely injured in the event of a crash relative to “full control”. Rural roadways has an elasticity effect value of 44.03%; so a speed limit reduction shall be mandated and enforced, and not just recommended, upstream of work zones on roadways classified as “rural”. Based on an elasticity effect value of 34.73%

for evening crashes, there shall be additional lighting enforcement practices during the evening times, especially if the work zone is active. The condition and reflectivity of TC devices shall be strictly maintained and the usage of additional warning lights to clearly demarcate travel lanes from work areas in the evening times is encouraged. Substantial consequences shall be executed by DOTs towards those who are found in violation. When feasible, means of Intelligent Transportation Systems (ITS) (e.g. digital message boards (DMSs)) shall be employed to communicate operations that are active during the evening times. Heftier fines shall be imposed on speeding motorists despite the fact that a work zone may or may not be operational during weekends (elasticity value of 29.68%). Although most work zones are not operational during weekends, it shall be clearly communicated to motorists if it is in fact active. Direct communication with motorists in the vicinity of a work zone (e.g. message boards, DMSs), or with potential off-site motorists (e.g. social media, radio stations) is encouraged which may divert such motorists from joining the work zone.

7.2. Recommendations for specific work zone configurations

In terms of planning and design, the results suggest that splitting heavy-duty truck traffic from other traffic will reduce conflicts, especially when lane shifts exist within a work zone. Elasticity effects for the heavy-duty truck involvement in a lane shift situation indicate a value of 186.39%. If at all feasible, this suggestion shall be extended to other work zone configurations (elasticity values for lane closure/intermittent/other=134.64%). The results suggest that the transition and termination areas of the intermittent/mobile work zone configuration shall be extended beyond MUTCD recommended lengths; this is to allow clearance distance from any moving equipment so that motorists can make a safer merging maneuver out of an occupied lane or into reopened lanes past the work zone. Enforcing lower speeds in the termination area of the “shoulder or median” configuration shall be assured until the work zone is entirely crossed (elasticity value of 57.39%). This can be established through mandating the presence of law enforcement officers at the end of the work zone; typically all lanes are fully open to traffic in such a work zone configuration. Lower speed limits shall be posted and enforced beyond those recommended by the MUTCD, especially for work zones involving shoulder or median activities on collectors or location systems among all other work zone configurations. The existence of lane closures in roadways with no-access-control shall be clearly communicated to traffic joining the mainline at conflict points. This can be established through the usage of message boards in the upstream area of access points. This practice shall be extended to the “lane shift/crossover”, “shoulder/median”, and “other” work zone configurations which are also associated with increased risks for severe crashes but not as much as lane closures. As compared to all other work zone configurations, shoulder/median activities on principle arterials shall be clearly communicated to motorists in the advanced warning area. Work on shoulder or median are associated with fully functional travel lanes and therefore motorists are likely to speed through the work zone not knowing work exists, but not in the traveled lanes. Additionally, law enforcement presence on principal arterials upstream of the advanced-warning area for “shoulder or median” work activities is recommended for the enforcing of reduced speed limits. On minor arterials, similar practices shall be introduced in all work zone configurations but not necessarily in the “lane closure” configuration which is associated with the least injury severity risks among all. Shoulder or median activities shall be clearly communicated to motorists traveling late at night, which are associated with the highest risk among all other work zone configurations. Work activities on shoulders or medians are not obvious to motorists traveling at late night times as much as other work zone configurations.

In terms of training and education, the results suggest the importance of education for motorists and training for the personnel of the agency overseeing the operation within the work zone. It is essential to install TTC devices that can communicate to the motorist the specific configuration of the work zone being approached. Work zone safety seminars shall be offered to the traveling public to teach them about what may be different once a work zone is erected in their community, and how this may affect their daily commute. FHWA mandates only minimum traffic control applications for different work zones, therefore additional traffic control devices and measures may be warranted especially for unique features of potential configurations. Training for government agency personnel or their representative (e.g. work zone safety classes) shall be mandated vs. recommended; this is crucial in terms of learning about the different factors affecting the severity of crashes within certain work zone configurations. Learning more about these factor will allow for the recognition of potential hazardous situations, and therefore the tailoring of additional counter measures pertaining to the specific work zone configuration in effect. For example, work zone managers should learn the additional TTC signage needed when more than anticipated heavy-duty truck traffic is present in the work zone.

8. Conclusions

This research proposes an econometric structure for injury severity analysis that recognizes the ordinal nature of the severity outcomes, while allowing for capturing the effects of the dependent variables on each ordinal category and revealing potential unobserved heterogeneity in the effects of contributing factors. The model developed here is referred to as the mixed generalized ordered response probit (MGORP) model, which generalizes the standard ordered response probit (ORP) model that is extensively used in the literature of injury severity analysis. The MGORP is applied to analyze the injury severity of passenger-car crashes in work zones by using 10 years of crash databases in the State of Minnesota. The authors wish to investigate the most contributing factors affecting the injury severity level of the most injured occupant of passenger-cars involved in crashes in work zones. The primary focus of this study is to uncover the potential additional variables' effects, through the introduction of interaction terms, which the different common work zone configurations impose on the factors contributing to the crash. In doing so, effects of regressed variables were taken into consideration while revealing additional effects produced through interactions to finally produce the net effect for each variable within each specific work zone configuration. The MGORP model that accounts for unobserved heterogeneity and threshold heterogeneity across crashes was found to fit the utilized dataset while addressing limitations imposed by simpler modeling techniques in past injury severity literature (i.e. ordered probit model (ORP)).

There are several important findings in the current study. The MGORP model elasticity effects indicates that key factors that increases the likelihood of severe crashes includes – partial control of access, roadways classified as rural, crashes during evening times, crashes during weekends, and curved roadways. Other variables such as crashes in the activity area of a work zone, higher speeds of 65-70 mph, and roadways on a grade also contribute to higher risks, but not as much as the variables identified earlier. Although, these variables were common to all work zones.

With regards to variations across the different work zone configurations, significant differences were observed in the effects of the following factors – access-control, number of lanes, roadway functional class, roadway surface condition, speed limit, work zone component area, presence of workers in the work zone, time-of-day, number of involved vehicles, and truck involvement.

One of the limitations of this study was that there were very few variables in the database describing the work zone-specific features (for example, work zone duration, lane and shoulder widths). In terms of future research, the collection of work zone-specific data such as work zone-specific lane, shoulder, and median widths, lengths of areas composing a work zone, work zone duration, and specific work zone speed limits could be beneficial to provide more insights to design ideal work zone parameters for enhancing traffic safety.

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