Impacts of Work Zone Component Areas on Driver Injury Severity

Mohamed Osman, Ph.D., P.E.[1]; Sabyasachee Mishra, Ph.D., P.E.[2]; Rajesh Paleti, Ph.D.[3]; Mihalis Golias, Ph.D.[4]

[1]Adjunct Professor, Department of Civil Engineering, University of Memphis, Memphis, TN 38152. (Corresponding Author). Email: mosman@memphis.edu, mosman1818@outlook.com
[2]Assistant Professor, Department of Civil Engineering, University of Memphis, Memphis, TN 38152. Email: smishra3@memphis.edu
[3]Assistant Professor, Department of Civil & Environmental Engineering, Pennsylvania State University, University Park, PA, 16802. Email: rzp303@engr.psu.edu
[4]Associate Professor, Department of Civil Engineering, University of Memphis, Memphis, TN 38152. Email: mgkolias@memphis.edu

Abstract: The establishment of work zones along roadways is considered a necessity for the construction of new roadways, the maintenance of deteriorating structures, and to provide access for the installation and maintenance of utilities. This research attempts to investigate the risk factors contributing to driver's injury severity in the different areas that constitutes the formation of roadway work zones. The injury severity outcomes of a crash have a natural and discrete ordering and therefore, this research has adopted the Mixed Generalized Ordered Response Probit (MGORP) model. As compared to the standard Ordered Response Probit model (ORP), which is widely utilized in the injury severity literature, the MGORP framework has the ability to recognize not only the ordering of the injury severity categories, but also allow for the investigation of unobserved effects of risk factors, known in the literature as "unobserved heterogeneity". The empirical analysis was conducted utilizing a database consisting of 10 years of work zone crashes. This database was available through the Highway Safety Information System (HSIS). Elasticity analysis suggests that airbag deployment, alcohol involvement, ejection, seatbelt use, and partial control-of-access are key factors contributing to the likelihood of severe outcomes. Additionally, the effects of several covariates were found to vary across the different work zone-component areas where crashes have occurred.

Author Keywords: work zone safety, injury severity, mixed generalized ordered response probit, heterogeneity, advance warning area, transition area, activity area, termination area

Introduction

The safety of motorists, non-motorists, and workers within a roadway work zone remains a priority for the Federal Highway Administration (FHWA), State Highway Departments, and the traveling public. The formation of a work zone presents a hazardous roadway environment for motorists due to the presence of equipment and machinery, roadway barriers as well as other traffic control devices. According to (FHWA) (FHWA 2016), in recent years, the frequency of work zone-related crashes has been declining, following a nationally similar decreasing trend in highway crashes. However, in 2013 alone, the number of work zone-related crashes was nationally estimated to be 67,523 (FHWA 2016). In 2013, despite the downward annual trend in the frequency of work zone crashes, the number of work zone injuries has increased (FHWA 2016). Approximately 47,758 non-fatal injuries were reported to have occurred in work zones in 2013 (FHWA 2016). In the same year, there were 527 fatal crashes in work zones resulting in 579 fatalities representing reductions of 2% and 6% from those reported in2011 and 2012, respectively (American Road & Transportation Builders Association (ARTBA) Transportation Development Foundation (TDF) 2015; National Highway Traffic Safety Administration (NHTSA), U.S. Department of Transportation 2016.). The number of work zone fatalities in 2013 equates to a work zone fatality every 15 hours.

The Manual on Uniform Traffic Control Devices (MUTCD) classifies the different areas composing a work zone as (Figure 1) advance warning area, transition area, activity area, and termination area. Each of these work zone-component areas serves a specific purpose and typically varies in length and the layout of traffic control devices depending on the nature of activity taking place. Past research on work zone safety mainly focused on crash- risk factors, severity, type, location, rate, and time of occurrence, while some focused on crash frequency (Theofilatos et al. 2017), or generally the impacts of work zones on highway safety (Ozturk et al. 2014). As a result of the wide-range topics on work zones within these past studies, this study will mainly focus on literature related to work zone crash injury severity and risk factors. Within the work zone crash severity literature, some studies have 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 et al. 2002; Khattak and Targa 2004; Li and Bai 2009; Qi et al. 2013; Wang et al. 2010). There have been discrepancies in the literature regarding whether work zone crashes were less or more severe, relative to those occurred in non-work zone areas. Some studies indicated that work zone crashes were 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). As compared to the above methodological approaches addressing work zones in various aspects, some studies conducted comprehensive assessments of such approaches by examining the existing work zone literature that focused on work zone crash-related modeling and analysis for the sake of providing researchers with a complete overview of past studies (Yang et al. 2015). Very few studies undertook analysis at the level of the specific work zone-component area where a crash has occurred. A single previous study analyzed the distribution and characteristics of crashes in work zone–specific component areas and conducted a comparison of work zone versus non-work zone crashes (Garber and Zhao 2002). This previous study concluded that the activity area within a work zone was the most vulnerable to the occurrence of crashes regardless of the type of roadway. The same study also concluded that the termination area had the lowest frequency of crash occurrence. Additionally, this same study found that most work zone crashes at night have occurred in the activity area, but the injury severity of those occurring in the daytime and night time were not expressively different. However, this previous study did not develop an analytical model of injury severity for each of the different work zone-component areas.The determinants and the magnitude-of-impact of the factors affecting the injury severity level of crashes in work zones can vary across different work zone-component areas. The purpose of the current research is to address this gap in the literature through developing an analytical model of driver injury severity in work zone crashes. In addition, the current study explores of the possible interactions between each of the work zone-component areas and the different risk factors associated with the occurrence of a crash. Understanding the different characteristics affecting the injury severity of drivers involved in crashes within the different work zone-component areas will serve as a great advantage enabling transportation engineers, designers, practitioners, and State Highway Departments to alleviate the severity of those individuals, generally involved in work zone crashes or particularly within a specific component-area within a work zone.

The structure of this paper is as follows. The following section presents the modeling framework adopted followed by the data section which presents a discussion of the dataset utilized and the assembly process of the final estimation sample. The empirical analysis section presents a comprehensive overview of the modeling results, tests of the modeling measures-of-fit, and elasticity effects of those variables found statistically significant during the modeling process. Lastly, the conclusion section presents an overall summary of the study as well as its major findings and venues for future research.

Econometric framework

According to previous injury severity literature and based on the type of crash data being utilized, the discrete choice modeling framework best suits the analysis herein. According to the current work zone safety literature, different modeling frameworks have been utilized to analyze crash injury severity data, most of which can be grouped into the unordered framework (Chang and Mannering 1999; Holdridge et al. 2005; Savolainen and Mannering 2007; Shankar et al. 1996; Ulfarsson and Mannering 2004) and the ordered framework (Eluru et al. 2008; Khattak and Targa 2004; Wang et al. 2010; Zhu and Srinivasan 2011a; b; Osman et al. 2018a). In the ordered framework, a function, defined as "latent propensity", is presumed to be collapsed into the observed injury severity outcome based on the estimated value of the propensity function relative to the parameters of thresholds. For modeling identification purposes, the number of thresholds = (the number of possible injury severity outcomes – 1). The latent single propensity function is specified as a function of different factors as well as a stochastic component that allow for considering all unobserved factors that can potentially affect injury severity outcomes. The parameters in both the propensity function and the thresholds are estimated using the Maximum Likelihood (ML) method. Earlier comparison studies for analyzing ordinal discrete outcomes (not necessarily in the context of severity analysis) found that the unordered framework fits data better than ordinal models due to its flexibility in providing additional parameters in the unordered models for each of the outcomes. However, Eluru et al. (2008) developed the Generalized Ordered Response (GOR) model as an extension to the standard ordered response models. The GOR model allows for the relaxation of the parameters of the threshold in order to provide additional flexibility to the ordinal models (Eluru et al. 2008). A recent comparison analysis of unordered and ordered frameworks that considers GOR framework found minor differences between the two models (Anowar et al. 2014), which was not a surprising result considering the similarity in behavior of both frameworks. A recent study on the injury severity of large truck crashes, which conducted a detailed comparison of both ordered and unordered framework found that the GOR models within the ordered framework, are in fact superior to both the standard ordered response model (OR) as well as unordered models (i.e. Multinomial or nested models) (Osman et al. 2016). Injury severity conditional on crash occurrence can depend on a multitude of factors all of which are most certainly not observed in crash databases. Unobserved variable effects are typically referred to as "unobserved heterogeneity". These unobserved factors can affect the influence of other observed covariates in the model leading to variations in the parameter effects across observations. Mannering et al. (2016) describes this issue in greater detail and present alternate modeling techniques, available in the literature, for adequately addressing the problem. Among these methods are the random parameters methods which are most prominent. Consistent with such commendations, this study utilized the random parameters model or the Mixed Generalized Ordered Response Probit (MGORP) model for analyzing the injury severity of drivers involved in work zone crashes. Additionally, the MGORP model allows for investigating the potential additional impacts of the specific work zone-component area where a crash has occurred on the injury severity outcomes. A brief overview of the MGORP model follows.

Mixed Generalized Ordered Response Probit (MGORP) Model

As the MGORP model is considered a generalized version of the standard Ordered Response Probit (ORP) model, the following is an overview of both model and how the MGORP was obtained from ORP. Let $n(n = 1,2, \dots, N)$ be an index representing drivers and $i(i = 1,2, \dots, I)$ is the index representing injury severity outcomes. 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 standard ORP model is (McKelvey and Zavoina 1975):

$$y_n^* = \boldsymbol{\beta}' \boldsymbol{X}_n + \varepsilon_n$$

$$\boldsymbol{y_n = i \; if \; (\psi_{i-1} < y_n^* < \psi_i)} \tag{1}$$

where y_n^* is the latent propensity for occupant n in a given crash, which is rendered into observed injury severity outcomes $\mathrm{y_n}$ through the parameters of thresholds ψ_i. $\mathbf{X}_\mathrm{n}$ is a vector of covariates that is $\mathrm{K} \times 1$ and $\boldsymbol{\beta}$ is its corresponding $\mathrm{K} \times 1$ vector of coefficients; $\psi_\mathrm{i}'\mathrm{s}$ are threshold parameters; $\psi_0 = -\infty$ and $\psi_{\mathrm{I}+1} = \infty$. ε_n is a random error term capturing the effects of unobserved factors on the injury severity propensity. For identification purposes, the error term ε_n is presumed to be independently and identically standard normal distributed across observations which leads to the standard ORP. The model structure mandates that the thresholds be strictly ordered so that the partitioning of the latent risk propensity measure into the ordered injury severity categories is properly achieved $(\mathrm{i.e.}, -\infty < \psi_1 < \psi_2 < \cdots < \psi_{\mathrm{I}-1} < \infty)$ for each driver n.

The generalization of the ORP to a MGORP model is characterized by the enabling $\boldsymbol{\beta}$ vector and ψ thresholds to vary across observations. This is accomplished through subscripting these parameters with the index n. The MGORP theoretical structure is as follows:

$$y_n^* = \boldsymbol{\beta}'_n \boldsymbol{X}_n + \varepsilon_n$$

$$\boldsymbol{y_n = i \; if \; \left(\psi_{n,i-1} < y_n^* < \psi_{n,i}\right)} \tag{2}$$

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

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

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

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 variables related to the i^{th} threshold to exclude 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 $\boldsymbol{\gamma}_i$ and covariance $\boldsymbol{\Omega}_i$. Let $\boldsymbol{\gamma}_n$ and $\boldsymbol{\gamma}$ be the vertically stacked column vectors of all $\boldsymbol{\gamma}_{ni}$ and $\boldsymbol{\gamma}_i$ vectors.

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

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

The unconditional probability can be attained through integrating out the random components as follows:

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

Equation (6) shows an integral that can be calculated using the Monte Carlo simulation method. We carried out the simulation in Gauss programming language, commercially known as (Gauss 15) which is particularly appropriate for the type of econometric modeling being utilized in this study. Equation (6) indicates that these integrals must be evaluated during the estimation of the model. The inference approach of the Maximum Simulated Likelihood (MSL) is based on the approximation of the integral in

Equation (6) which utilizes the Monte Carlo simulation method. The method is based on averaging the integrated function with numerous draws of random components (*i.e.,* $\boldsymbol{\gamma}_n$ and $\boldsymbol{\alpha}_n$). Numerous draws are needed if the integration is done using completely random draws. However, Bhat (2001) developed quasi-random Halton sequences that performed well with fewer draws. Their recommended number of Halton draws can fall between 100 and 200. Therefore, the resulting model was estimated using the MSL inference approach with 150 quasi-random Halton draws (Bhat 2001).

Data

The dataset utilized in current study included 10 consecutive years of work zone crashes (2003-2012) in the State of Minnesota (MN). Crash, roadway, and occupant-level datasets were collected from the Highway Safety Information System (HSIS), which was later analyzed and merged to obtain the final combined dataset for the MGORP model analysis in the current study. The HSIS datasets for MN included separate sub-files for crash, vehicle, occupant, and roadlog files. The crash sub-file included basic crash information on case by case basis such as case numbers, route identification, exact mile-post of crash location, date of crash, type of crash, lighting conditions, weather and surface conditions, number of vehicles involved, work zone and traffic control information, and overall injury severity level of the crash. The overall level of injury severity of the crash is based on the most injured individual, along with several other factors. The vehicle sub-file included information such as case number, vehicle number, driver's age, injury severity, sex, physical condition, make of vehicle, motor body type, number of occupants, and direction of travel along with several other factors. The occupant sub-file included information such as case numbers, age, airbag deployment, alcohol and drug testing, ejection, occupant's injury severity, sex, seating position, and vehicle number. The roadlog sub-file contained information such as roadway access-control, beginning and ending log miles for each segment of each route, average annual daily traffic, roadway description, functional class, widths of lanes, shoulders, and medians, number of lanes, right of way limits, and surface type, along with several other factors. The authors utilized the raw datasets to merge all of the above mentioned sub-files on bases of case numbers, route identification, mile-post, vehicle number, and seating position and obtained one combined dataset that included all necessary factors needed for the current study. Once an initial complete dataset was constructed, the authors excluded incomplete observations from the study, and setup the dataset observations to include all drivers involved in work zone crashes. It should be noted that the final injury severity level of each driver was based on each driver's injury severity level and not the overall severity level of the crash. The final dataset contained 28,358 drivers involved in crashes occurred in work zones. The injury severity level for each driver, as reported by law enforcement, followed a KABCO scale where; K:killed, A:incapacitating injury, B:non-incapacitating injury, C:possible injury, and O:no injury. Table 1 presents the distribution of observations within each injury severity category. The upper section of Table 1 indicates the frequency and percentage of each injury severity category of the original raw data. As a result of the lower frequency of some of the higher injury severity levels, some of these categories were combined. The lower section of Table 1 presents the combined injury severity categories, where fatal, incapacitating, and non-incapacitating injury severity levels are combined into one category "severe injury", while "possible injury" which is referred to as "injury", and the "no injury" categories were kept as originally obtained.

Empirical analysis

Frequency distributions of variables considered in the MGORP modeling process are presented in Table 2. The authors adopted a methodological approach of interacting statistically significant factors with each of the four identified work zone-component areas, driven by the exact location where each crash has occurred. Differential impacts of each independent variable on the severity levels were examined and the final specification for the resulting model was based on the logical process of initially constructing a Generalized Ordered Response Probit (GORP) model. In the modeling process, statistically insignificant factors were excluded from further analysis. In some case, the effects of other factors were combined when found statistically insignificant, thus producing meaningful and intuitive results. During the modeling process, the authors have extensively tested for unobserved heterogeneity effects of the injury severity determinants on the latent injury risk propensity due to potentially unobserved factors. The lack of such important unobserved factors can lead to erroneous specifications through biased parameter estimates (Mannering et al. 2016). Thus, the final model specification became a partially-segmented MGORP. The final modelling estimation and variable choices were mostly guided by and compared to findings of past studies and the intuitiveness of the parameters estimated.

Fig. 2 represents the frequency of crashes within each of the four work zone-component areas in the dataset. In the initial modeling process, each independent variable entered the modeling process as a "standalone" variable to test for the statistical significance of its effect across all work zone-component areas combined. Once a variable was found to be statistically significant, the initial process was followed by the variable's additional interaction effects across each individual work zone-component area. The "termination" work zone-component area served as the base for the remaining three categories for modeling specification purposes. For example, if a standalone variable had a coefficient parameter of +0.50 across all work zone component-areas combined and its interaction with the "activity" work zone-component area had an additional coefficient parameter of +0.15, the combined value of the two parameters (0.50 + 0.15 = +0.65) is the final overall effect of the tested standalone variable in the activity area of a work zone. Similarly, if the interaction of the same "standalone" variable with "transition" had a coefficient parameter of -0.20, the combined effect of the standalone variable in the transition area of a work zone 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-component areas with its positive coefficient value (+0.50). Additionally, relative to the "termination" work zone-component area, as the base category and compared to other work zone areas, "activity" also increased the likelihood of higher injury severity with its positive coefficient (+0.15) for an overall effect of increased likelihood of higher injury severity levels due to this standalone variable while in the activity area (+0.65).

While "transition" had a decreased interaction effect with its negative interaction coefficient (-0.20), as compared to the base category, the overall effect of the standalone variable in the transition area of a work zone still increased that likelihood with its positive combined coefficient (+0.30). This partially-segmented approach uncovers the differences imposed by the different work zone-component areas on the effects of each of the variables initially found statistically significant in the model before the introduction of any interactions.

Estimation results

Estimation results from the MGORP model are presented in Table 3. The first column of Table 3 presents variables' names, while the second and third columns present two sets of variable coefficients corresponding to the different severity levels. The second column presents each variable in the latent risk propensity (excluding a constant) comparing the "no injury" vs. "injury" and "severe injury" outcomes. The third column present variables that entered the specification for the threshold function for the demarcation between the "injury" and "severe injury" outcomes. Each of the estimated parameters t-values are shown in parentheses. Initial and final (at convergence) log-likelihood values, the McFadden R^2, and the total number of observations in the dataset are also presented in Table 3.

In the "variable" column in Table 3, each variable is followed by its potential interactions with each of the work zone-component areas. In the same column, interactions with the four work zone areas are demarcated by the numbers 1 thought 4 at the end of each variable's name; advanced warning area (1), transition area (2), activity area (3), and termination area (4). The "termination area (4)" is considered the base category for all interaction variables throughout the modeling process. It should be noted that not all variables' interactions were found to be statistically significant across all of the work zone-component areas. Therefore, only interactions that were found to be statistically significant were kept in the modeling process. Traditional econometric models do not directly provide the magnitude of effects across the dependent outcomes, and specifically when interaction terms are introduced. So, elasticity effects of variables were calculated and shown in Table 4 following the modeling results. Elasticity effects of variables and their interactions can clearly show how each of the covariates behave across the different work zone-component areas.

Crash-Level Variables

Roadway characteristics

As compared to “level” segments of roadways, work zones on a grade contributed to a decreased likelihood of higher injury severity outcomes (negative coefficient value in the latent risk propensity function). Undivided roadways and roadways with partial- or no control-of-access increased the risk propensity of higher injury severity. The negative threshold coefficient for undivided roadways indicated that crashes were more severe relative to divided roadways. A median would intuitively reduce conflict points. More conflict points are likely to exist in roadway segments without control-of-access. While the interaction of no control-of-access with the advanced warning area still followed the same injury severity direction as the rest of the work zone areas, its negative coefficient in the propensity column indicated that drivers, in this work zone area, sustained less severe injuries than all other work zone-component areas.

Roadways classified as principal and minor arterials were associated with higher driver’s risk propensity for higher injury severity outcomes relative 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. Urban roadways indicated less likelihood of higher injury severity outcomes with its negative risk propensity value. While urban roadways are likely to carry more congested traffic, speeds are typically lowered relative to rural areas in work zones.

Environmental characteristics

Environmental conditions such as adverse weather and wet roadway surfaces were associated with reduced likelihood of higher injury severity levels compared to clear weather and dry surfaces, respectively. It is possible that drivers are more cautious and at lower speeds maintaining safe headways when operating on wet surfaces or in an adverse weather conditions. 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 concluded opposing results for fatal and injury crashes in work zones (Li and Bai 2008a).

Traffic characteristics

Upstream segments of a work zone area when associated with drivers operating at low speeds reduced the risk propensities for drivers crossing the work zone. The positive coefficient in the threshold column for 35-40 mph indicated that if a crash occurred at those speeds, drivers would likely to sustain an injury but not a severe injury. On the other hand, negative coefficients in the threshold function for speed limits of 45 mph or more indicated a higher risk of a severely injured driver. These results were not surprising as the involvement in a crash in a work zone while being subject to distractions and interactions with heavy equipment. Previous work zone crash severity literature found similar results (Li and Bai 2009; Wang et al. 2010).

Work zone characteristics

The traffic control configuration of "lane closure" in work zones was associated with lower likelihood of sustaining higher injury severity outcomes, according to the positive threshold value for this variable. Lane closures are likely to be associated with the reduced speeds due to merged traffic volumes in the non-closed lanes. Intermittent operations were found to be associated with drivers sustaining higher injury severity. Specifically, the negative value of the "intermittent" variable in the threshold function indicated a higher likelihood of "severe injury" relative to "injury". In an intermittent operation, drivers are likely to interact with additional traffic control devices in the work zone as compared to stationary operations areas; such as truck- mounted attenuators, flaggers, and message boards mounted on light or heavy duty trucks directing traffic and protecting workers in the activity area the operation moves ahead. Interactions between the "work zone type" variables and the four areas composing a work zone indicated that the "activity area" of a moving operation has the lowest risk on driver's injury severity among advanced, transition, and termination work zone areas. This is likely due to that fact that in the activity area of a moving operation, drivers have already passed through any needed lane changes and reached their lowest speed through decelerating in the advanced-warning and the transition areas. Also, the activity areas in an intermittent operations work zone are likely to occupy shorter repair segments compared to those of the stationary work zone type. Shorter-in-length activity areas lead to drivers spending less time through the work zone in a moving operation.

Temporal characteristics

Crashes occurring during weekdays were less severe relative to traveling on weekends, according to the MGORP model results. "Weekday" variable showed statistical significance when tested for heterogeneity (S.D. = 0.553). Interactions of "weekend" variable indicated that the advanced-warning and the activity areas decreased driver's risk of high injury severity relative to other work zone areas. Such a behavior was likely due to the fact that most motorists would lower their speeds entering the advanced warning areas but once discovered that the work zone is not operational at the time, drivers are likely to speed through the transition area. The lower risk propensity associated with the activity area is likely due to fewer conflicts with workers and heavy construction equipment during downtime on weekends.

Crashes occurring during daytime travel were associated with reduced likelihood of higher driver's injury severity outcomes in work zones (negative coefficient value in the risk propensity function). Similarly, the positive coefficient in the threshold function indicated that in the event of a crash, a driver would sustain an injury relative to a severe injury. Traveling during the daytime is likely associated with congested roadways; therefore, lower speeds would reduce forceful impacts. Interactions of the time-of-day variable indicated that the advanced warning areas had an increased likelihood of drivers sustaining higher injury severity while the transition area lowered this risk.

Crash characteristics

Crashes involving more than one vehicle were found to be associated with driver's lower risk propensities. Similar results were suggested by earlier research (Qi et al. 2013). Such effect was indicated by both the positive coefficient value of the risk propensity function as well as the negative value of the threshold function. Drivers are likely to operate at lower speeds when crowded by other vehicles within a work zone. In the event of a single-vehicle crash, sudden maneuvers to change lanes or avoid equipment or worker's intrusion in the travel lane are expected. Interaction of the advanced-warning area with "multi-vehicle" indicated the lowest driver's risk propensity relative to other work zone areas.

Occupant/Vehicle-Level Variables

Driver attributes

Drivers operating vehicles out-of-state had lower risk propensities, although the "out-of-state" indicator was heterogeneous when tested with a standard deviation of 0.607. Such results are consistent with previous literature (Harb et al. 2008). Interactions of the "out-of-state" variable indicated that the transition area had the lowest risk propensity relative to other work zone areas. An out-of-state driver is expected to be more cautious paying additional attention to traffic control devices due to possible unfamiliarity with the travelled area. As the transition area starts following the advanced-warning area, and given that drivers are likely already driving at lower speeds, compared to posted speed limits leading to a work zone, it is not surprising that the safest work zone area would be the transition area relative to interacting with the presence of workers and heavy equipment in the activity area, similarly speeding up to normal speeds through the termination areas.

Male drivers crossing a work zone had higher risk propensity (positive coefficient) of more severe outcomes, relative to female drivers. Interestingly, the positive threshold value for the "male" variable has a monotonic effect which indicated that although male driver are more risky, in the event of a crash they would sustain just an injury relative to a severe injury. Physiologically, female drivers are susceptible to higher injury severities. Previous literature have found similar results (Weng and Meng 2011). Gender interactions indicated that females have lower likelihood of sustaining severe injuries in both advanced warning and transition areas.

Younger and older drivers were associated with a lower risk propensity for sustaining higher injury severity relative to mid-age drivers. The negative value in threshold function for older drivers indicated that this age group is likely to sustain "severe injury" relative to "injury" outcomes. Such results could be explained by the reduced risks taken by both age groups compared to the middle age group who would likely take higher risks driving at higher speeds through the work zone. These results are consistent with previous literature (Weng and Meng 2011). Interactions of "older driver" indicated a higher likelihood of higher injury severity outcomes in the activity area relative to all other areas, which could be explained by being in close proximity of distractions such as heavy machinery in the activity area.

The absence or lack-of-use of seat belts was associated with higher driver's injury severity. The negative coefficient value in the threshold function indicated that drivers not using their seat belt have higher likelihood of sustaining "severe injury" relative to "injury" outcomes. The indicator for "alcohol used" indicated that drivers had higher risk propensities when under the influence. Previous literature found similar results (Harb et al. 2008). Drivers ejected from a vehicle, in the event of a crash, had higher risk propensity for higher injury severity outcomes. The negative coefficient value in the threshold function for "ejected" indicated higher risks for severe injuries relative to just an injury. Ejection into a work zone would especially increase the chance of being impacted by machinery, or other devices.

Vehicle characteristics

In the event of a crash, if airbags were deployed, they increased driver's risk propensity outcomes. The airbag "deployed" variable is a unique one in term of the way researchers would interpret it. It is well known that airbags are usually deployed as a result of an impact and not necessarily a contributor to the crash cause. In the context of this study, the authors interpreted airbag deployment as a sign of severe impacts. Previous literature confirmed an assumption that the deployment of airbags would reduce crash fatalities among belted drivers, yet the risk was increased among unbelted drivers (Høye 2010).

Trucks classified as light-duty were associated with a lower driver's risk propensity for sustaining severe outcomes. These results are consistent with the literature (Chang and Mannering 1999). Heavy-duty trucks had higher risks (Chang and Mannering 1999; Dong et al. 2015). 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. Interactions of the “truck-heavy duty” revealed that the activity area had the lowest risk propensity among all other areas. Heavy-duty trucks are likely at their lowest speeds in the activity areas, which would reduce forceful impacts in the event of a crash.

Vehicles that are 10 years of age or more were associated with lower severity levels among drivers. Additionally, the positive threshold coefficient value for vehicle age over 10 years indicated that in the event of a crash, a driver would likely to be injured but not severely. The severity of the driver’s injury is likely associated with the vehicle’s body and frame material composition. The automotive industry and manufacturers have been leaning towards using lighter-weight materials in newer vehicles for better benefits such as better fuel economy, drivability, and performance (Cole and Sherman 1995). It is intuitive that a more solid-built vehicle (i.e. steel or cast iron) would protect its driver from severe impacts relative to light-weight vehicles (i.e. aluminum and magnesium alloy) (Cole and Sherman 1995; Miller et al. 2000). Some previous literature found opposite results (Weng and Meng 2011). Vehicle age variable was found to be statistically significant when tested for heterogeneity (S.D. 0.817).

A crash involving a multi-occupant vehicle was more severe compared to those of a single-occupant. This behavior could be explained by the fact that additional persons in a vehicle represent a distraction to the driver. The positive threshold coefficient value for “multi-occupant” indicated that additional persons in a vehicle led to a driver’s injury relative to severe injury outcomes. Additional passengers in a vehicle might warn the driver of an oncoming danger overlooked by the driver (i.e. another vehicle). Previous literature found similar results (Khattak and Targa 2004). Interactions of “single-occupant” indicated that the advanced warning area had higher risks of severe outcomes compared to other work zone areas. Advanced-warning areas mainly consist of open roadways with reflective signage indicting that a work zone is being approached. Inattentive drivers could miss signage leading to a work zone.

Measures of Fit

To be able to examine the superiority of a statistical model compared to another, it is important to investigate the impacts of the different factors captured in one model and not the other. For the purpose of the modeling structures utilized in this study, a Likelihood Ratio (LR) test is employed. Table 3 indicates that the MGORP has a log-likelihood (LL) value of -13,440.9 at convergence. Comparatively, the model with constants in threshold and no covariates in risk propensity has a LL value of -14,827.8. The MGORP model has 56 additional parameters compared to the constants-only model. The LR test statistic of comparison between the MGROP and the constants-only model was 2773.8, which is greater than the chi-squared critical value of 74.47 (at the 0.05 level of significance), corresponding to 56 degrees of freedom. It should be noted that the MGORP model was specifically designed to test for unobserved heterogeneity within the covariates and if none of the variables were found to be statistically significant for unobserved effects, then the MGORP model collapses to a GORP in the final specification. Therefore, in the process of initially constructing a GORP model as a starting point for the MGORP model, a LR test was also conducted between these two models. The LL value of the GORP model was (-13,457.12) and the LR test statistic of comparison with MGORP model was 32.44. This value is greater than the critical chi-squared value of 9.49 corresponding to 4 degrees of freedom. These tests demonstrate a superior data-fit in the MGORP model and the importance of accounting for unobserved heterogeneity in injury severity models.

Elasticity effects

Elasticity effects are typically beneficial for measuring the percentage of the reaction of a dependent variable to a percentage change in independent variables. Traditional econometric models do not directly provide the magnitude of effects across the dependent outcomes. The MGORP model produces coefficient parameters for each standalone variable as well as each of their subsequent interactions with each of the work zone-component areas, yet does not directly provide the magnitude of the overall behavior of the covariates across each injury severity category. To be able to clearly interpret the impacts of these variables some of which appear in the risk propensity and the threshold functions in the MGORP model, it is necessary to compute their corresponding elasticity effects. Elasticity effects can be interpreted as effect of a 1% change in a given independent variable has on the probability of the injury severity outcomes (Khorashadi et al. 2005). Standard elasticity calculations are not applicable to indicator variables; thus the average direct pseudo-elasticity was calculated (Li and Bai 2008b; Wong et al. 2011; Zhu and Srinivasan 2011a; Osman et al. 2018b). The pseudo-elasticity of a given independent variable represents the average change in percentage in the probability of a discrete outcome category when the variable is changed from 0 to 1 or vice versa. The analysis for elasticity effects for the MGORP model was conducted and the results are shown as follows.

Elasticity Effects of MGORP Model

Variable elasticity effects were calculated for on all injury severity outcomes as depicted in this study. To be able to easily interpret the elasticity results, only results corresponding to the "severe injury" outcome category are presented herein (see Table 4). The first four columns in Table 4 present the results in cases where the elasticity effects vary across different work zone areas whereas the last column shows the elasticity effects for variables whose impact does not vary across different work zone areas.

The first value is the last column of Table 4 corresponding to 'on grade' roadway is -8.79. This indicates that drivers are 8.79% less likely to be severely injured in the event of a work zone crash occurring on "on-grade" relative to "level" roadways. Moreover, this effect does not vary across different work zone areas. Similarly, results corresponding to access control suggest that drivers involved in work zone crashes in "advanced-warning" area are 16.85% more likely to sustain severe injuries compared to crashes in work zone areas with full access control. Furthermore, the effect of access control also varies across different work zone areas. Specifically, drivers involved in crashes at work zones with no access control are 70.40% more likely to sustain severe injuries in "transition", "activity", and "termination" areas compared to 16.85% in "advanced-warning" area.

In a similar fashion, other elasticity effects in Table 4 can be interpreted. Overall, significant variations in elasticity effects across work zone areas were found for the following factors – type of work zone, time of day, number of vehicles involved in the crash, gender, age, and residence status of the driver, and type of vehicle. Also, it is realized that key factors contributing to increased risk of severe outcomes of among drivers involved in work zones crashes are airbag deployment, alcohol involvement, driver ejection out of vehicle, lack of seatbelt usage, and partial access of the work zone.

Implications of Variable Effects and Recommendations

Elasticity effects of variables revealed the different behavior of variables across the different work zone-component areas. As it can be concluded from Table 4, some variables did not statistically vary across the different work zone components while others indicated either major or minor difference in behavior for the different areas. These effects have important implications for the work zone setup and enforcement either for all or specific component-areas of a work zone. Based on these results, these implications could also be extended beyond work zone regulations, such as the training or educations of drivers crossing a work zone.

Across all work zone-component areas, the deployment of airbags in the case of a crash, driving while intoxicated, and the ejection from a vehicle were the highest contributing factors to higher injury severity levels. Although the deployment of an airbag itself may or may not be the main contributing cause of the severe injury, but it is a strong indication of a forceful impact which can be an intuitive result of driving at higher speeds. Driving at higher speeds was also one of the contributing factors to higher injury severity levels. Therefore, to reduce forceful impacts, lower speed limits must be enforced when crossing work zones. Drivers who use alcohol while crossing a work zone are 146% more likely to be severely injured in the case of a crash. This result may in fact be true for all driving and not necessarily crossing a work zone. Alcohol-impaired driving weakens driver’s ability to interpret information supplied by traffic control signs leading or within the work zone and therefore improperly react to them. The presence of law enforcement officers upstream of work zones could be one of the counter measures to spot intoxicated drivers before entering the work zone based on abnormal driving behaviors. Heftier fines and strict legal prosecution should be applied to those who are caught driving under the influence. Driver who do not use their seat-belt and therefore can lead to possible ejection from vehicles during a crash were 36% and 34% respectively, more likely to be severely injured in the case of a crash. Departments of Motor Vehicles should educate drivers, through means of classes for new drivers or refresher sessions for license renewals, generally on the importance of seat-belt usage and specifically when crossing a work zone based of results of work zone safety studies. Those who are caught without a seat-belt should be heavily fines when crossing work zones. Drivers involved in work zone crashes in an undivided roadway segment were 25% more likely to be severely injured. Motorists should be warned about undivided conditions ahead of a work zone segments through means of additional traffic control signage or message boards.

Several different factors behaved differently when interacted with the different work zone-component areas. Some of these factors included no control-of-access, intermittent work zone operations, night time crashes, crashes involving multiple vehicles, out-of-state drivers, females, older drivers, the involvement of heavy-duty trucks, and single-occupant vehicles. It should be noted that regardless the sign of the elasticity effects values, each factor has four values corresponding to the four work zone-component areas considered in this study. These four values essentially compare the factor behavior across the different component areas composing a work zone. Drivers involved with heavy duty trucks in a work zone crash were associated with the highest chances of severe injuries. The advanced-warning, transition, and termination areas were more severe compared to the activity area. The activity area is likely associated with slowest speed among all other work zone-component areas. Work zone designers should seek the detouring of heavy-duty trucks to outside the work zone, if at all possible. In cases where detouring is not an option, heavy-duty trucks should operate at much lower speeds compared to other vehicles, and therefore reduce the impact in the case of a crash. The advanced-warning area posed the least injury severity risk compared to the transition, activity, and termination areas in work zones located in roadway segments without access-control. According to MUTCD traffic control guidelines, most of conflict points between a mainline containing a work zone and side streets generating traffic but not necessarily directly involved in the activity of the work being performed, only require minimal signage, such as a "Road Work Ahead" sign. Traffic joining a mainline containing a work zone in the transition, activity, or termination areas should be given special attention based on the results of this study. Additional traffic control devices are essential and should be provided to drivers upstream of conflict points where new traffic is to join the work zone. Perhaps, specific minimum traffic control devices should be mandated on side streets in non-controlled-access roadways. Intermittent or moving work zone operations should be properly signed with stationary signs at the beginning and ending of the work zone segment as the level of injury severity in the advanced-warning area was as high as the termination area. Visual means, such as dynamic message signs (DMS) or message boards should be utilized to inform drivers of an upcoming mobile operation as well as the termination of a mobile operation. Work zone reduced speed limits are typically introduced through longer periods or stationary work zones, but transportation officials should consider reducing speed limits also during mobile or intermittent operations.

In terms of recommendations for motorists, it is advised that agencies such as Departments of Transportations, Departments of Safety, and private motor vehicle insurance companies to hold training sessions to the public, not only free of charge but with merits to those who attend, to discuss safety topics such as work zones. The majority of the public drivers are unaware of what exactly constitutes a work zone and how the roadway be may affected once the roadway layout is altered in the work zone. The use of social media is crucial to spreading knowledge about work zone safety to the public; this role should be mandated by the federal government on all State DOTs nationwide for safer work zones.

Conclusions

Work zone safety literature is considered sparse in regards of the injury severity of individuals involved crashes in work zones. Specifically, literature addressing crash injury severity within the individual work zone-component areas is non-existent. The efforts in this research aim to fill this gap in the literature by undertaking an extensive empirical analysis of crashes in work zones by utilizing 10 years of work zone crash databases in the State of Minnesota. The authors wish to investigate the most contributing factors affecting the injury severity levels of drivers involved in crashes generally occurring in work zones and particularly within specific work zone-component areas. The empirical analysis employs the MGORP model that recognizes the ordinal nature of the data while allowing for the testing for heterogeneity to capture the effects of unobserved factors. The primary reason for utilizing the MGORP model for this study was that fact that it was specifically developed as an extension of the standard ORP model, which is widely utilized in the injury severity literature. The MGORP model also relaxed some of the constraints imposed by the standard ORP model as well as the ability to analyze unobserved effects of heterogeneous factors. The primary focus of this study is to uncover the potential interaction effects that the nature of each work zone-component area imposes on the factors contributing to the level of injury severity of a work zone crash. In doing so, effects of several covariates were taken into consideration while revealing additional effects produced through interactions to finally produce the net effect for each covariate within each specific work zone-component area. In the context of work zone safety, and to our knowledge, this is the first study to explore the factors affecting driver injury severity at the level of the individual work zone-component areas. The MGORP model which accounts for unobserved heterogeneity and threshold heterogeneity across observations was found to fit the data significantly better than the standard ORP and GORP models. Elasticity effects of covariates indicate that high-impact crashes involving airbag deployment, alcohol, driver ejection, lack of seatbelt usage, and partial control-of-access are key factors and conditions that increase the risk of severe outcomes among drivers involved in work zones crashes.

In term of risk factors that varied across work zone-component areas, significant differences were observed in the effects of the following factors – type of work zone, time-of-day, number of vehicles involved in the crash, gender, age, and residence status of the driver (in-state/out-of-state), and type of vehicle.

A limitation of this study was that the dataset utilized was obtained from one source and for one State, which may have influenced the results according to the nature of the work zones types in the State of Minnesota. A multi-state dataset can provide more confidence in the results of the study which can also allow for the extension of such results nationwide. In terms of future research, the collection of data that specifically pertains to the layout and features of a work zone, such as work zone-specific lane, shoulder, and median widths, lengths of the areas composing a work zone, and specific work zone speed limits, could be beneficial in providing more insights as for the design of ideal work zone parameters and generally for the enhancing work zone traffic safety.

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Appendix

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