HIGHWAY SAFETY MANUAL:

ENHANCING THE WORK ZONE

ANALYSIS PROCEDURE

FINAL REPORT

SOUTHEASTERN TRANSPORTATION CENTER

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16. Abstract

Highway infrastructure requires periodic maintenance, reconstruction and rehabilitation. As a result, highway users have to deal with work zone activities such as lane closures and lane shifts or crossovers that increase safety risks. The Highway Safety Manual (HSM) quantifies expected crashes in work zones and potential reductions in crashes due to work zone strategies. Specifically, Crash Modification Factors (CMFs) capture the effects of work zone attributes such as work zone duration reduction on crash frequency. However, reductions in injury severity are not captured in current HSM procedures. This study focuses on expanding the HSM work zone procedure by exploring correlates of injury severity. Modeling results show that driver injury severity in work zone crashes was higher by about 10% if a driver committed improper actions or a violations pertaining to speeding, following too closely, and disregarding officers, flaggers, signals, and signs. The results quantify expected impacts of safety improvements, especially reductions in work zone injury risks due to effective speed enforcement. An illustrative example demonstrates the development of a CMF for injury severity.

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EXECUTIVE SUMMARY

Highway infrastructure requires periodic maintenance, reconstruction and rehabilitation, and upgrading. As a result, highway users have to deal with work zone activities such as lane closures and lane shifts or crossovers, lowering their ability to drive safely through work zones. The Highway Safety Manual (HSM) provides a procedure to quantify expected crashes in work zones by providing Crash Modification Factors (CMFs). However, the current CMFs only capture reductions in crash frequencies due to work zone strategies such as duration reduction. This study focuses on expanding the HSM work zone procedure to include reductions in injury severity due to work zone strategies such as enforcement of speed and traffic rule regulations in work zones. Specifically, this study provides additional crash modification factors that can improve work zone performance from the perspective of crash severity, supporting safety decisions that relate to work zone strategies.

Using a large-scale statewide crash database from the Virginia Department of Transportation, this study explores correlates of injury severity, given crashes that have occurred in work zones. The study accounts for injury severity of each driver involved in a crash by estimating rigorous hierarchical models. The correlates of driver injury severity are nested in crashes. Modeling reveals that for work zone crashes injury severity is higher by 9.94% to 10.33% if a driver intentionally commits an improper action or a violation, while for non-work zone crashes, the chance of injury is higher by only 1.72% to 5.73%. Such actions and violations mainly include speeding, following too closely, and disregarding officers, flaggers, signals, and signs. The correlations between pre-crash actions and injury severity deliver insights into safety improvements that can reduce injury risks in work zones. Information generated by this study can be converted to CMFs related to injury severity in work zones. To explicate, an illustrative example is presented.

INTRODUCTION

Highway safety is a societal concern in the United States, given that surface transportation is still the dominant mode for personal daily travels in most areas of the country. To meet the growing travel demands (*1*), highway infrastructures require periodic maintenance, reconstruction and rehabilitation, and even upgrading when demand exceeds existing capacity. As a result, highway users have to deal with work zone activities such as lane closure, lane shifts and crossovers, and intermittent or moving work, which disturb regular traffic flows. Consequently, the safety of highway users might be jeopardized while traveling through work zones.

As reported in numerous studies, crash frequencies are typically greater in work zones than on normal road segments (*2-7*). These increases vary from approximately 20% to 120%, compared to segments without work zones, controlling for other factors constant (*4*). According to the latest highway safety statistics, 527 fatal traffic crashes occurred nationally in work zones, resulting in 649 fatalities (*8*). Given the statistical value of a life (about nine million dollars), based on guidance from US Department of Transportation (US DOT) (*9*), work zone crashes in the US would annually cost approximately six billion dollars because of the loss of lives, plus additional costs of personal injuries and damages to vehicles and highway infrastructure. To enhance the safety of traffic operations within work zones, US DOT initiated the Work Zone Mobility and Safety Program at the beginning of this century to deliver the best practices in work zones, and provide strategies and technologies to reduce work zone crashes (*10*).

Highway Safety Manual (HSM) provides a procedure to quantify the influences of work zones on highway traffic safety, in terms of changes of crash rates compared to no work zone, i.e., Crash Modification Factors (CMFs). For example, compared to a road segment without work zones, one with an active work zone is associated with 30% increase in crash rates for all types of crashes, giving a CMF of 1.3 (*4*). However, the Information about crash injury severity is not commonly available. This study explores the correlates of injury severity, given a crash that occurs in work zones. The correlational analysis can provide additional crash modification factors from the perspective of crash severity, supporting safety decision-making about road construction and maintenance activities.

To explore the correlates of the work zone crashes, previously, highway practitioners and scholars chained the work zone safety outcomes (i.e., crash frequency and crash severity) to associated factors of work zone characteristics, road features, crash attributes, and others, through descriptive statistics and modeling tools (*7, 11-17*). However, behaviors that lead to injuries and fatalities in work zone crashes is under-explored. The primary objective of this study is to untangle pre-crash behavior correlates of work zone crash severity.

Many previous studies have separated crashes into single-vehicle and multiple-vehicle crashes (*15, 18-22*). The most severe injury in a crash was often regarded as the safety outcome to simplify analysis (*3, 16*), e.g., ordinal probability models could be easily applied. However, using the most severe injury in a crash as the safety outcome misses important information about injuries to other drivers in multi-vehicle crashes. Also, it does not account for the fact that drivers involved in the same crash have a common set of circumstances. Therefore, this study investigates the injury severities of all drivers involved in crashes, while accounting for nesting of drivers in crashes.

Note that injuries to passengers should also be considered in the framework. This is made possible by adding another level in the hierarchical models. However, given the added complexity and low vehicle occupancy rates (about 1.08 persons per vehicle in the data used for this study), the scope of this study was limited to driver injury severity. This study makes both methodological and empirical contributions to work zone safety by exploring the hierarchies embedded in highway crashes and untangling the role of pre-crash driver actions in work zone crashes.

LITERATURE REVIEW

Crash Frequency and Severity

Many studies have focused on crash frequency and rate as safety performance measures to examine the impacts of work zones. A synthesis of the literature shows that the presence of work zones contributes to a higher crash rate (*3, 4, 11, 23, 24*). Traffic volume, work zone length, and duration were found to be positively associated with crash occurrences (*3*, *6*, *23*). Urban work zones show higher crash rates compared with those in rural areas (*25*); this is true for crash rates in nighttime work zones relative to daytime work zones (*4*).

Other than crash frequency, crash severity is of interest to researchers who are concerned with work zone safety (*3*, *6*, *14*, *16*, *22*, *26*). Most studies on work zone crash severity examine the driver injury severity of single-vehicle crashes (*19, 21, 22*) or the most severe injury in multiple-vehicle crashes (*3, 16*). Findings from these studies show that work zone crash injury severity increases with higher speed limits (*16, 22, 24, 26*-*28*), nightlight driving (*16*, *22*, *27*), driving under impairment (*5*), and truck involvement (*16*, *22*, *27*). The use of airbags and seat belts, some work zone controls such as flaggers, and adverse weather are associated with a lower level of injury severity (*22*, *24*, *26*). Most of these factors were found to have similar correlations with the injury severity in a work zone crash. However, some inconsistencies exist in the literature. For example, Li and Bai (*27*) found that poor lighting is associated with higher injury severity if crashes occurred in work zones, while Weng and Meng (*22*) report that good lighting conditions contributed to higher injury severity. Among many reasons, one is that the data sources used for the investigation are different. Weng and Meng used the FARS (Fatality Analysis Reporting System) database in which all crashes were fatal (*8*), while Li and Bai analyzed crashes from Kansas Department of Transportation (KDOT) database that contains crashes with all types of injuries.

Driver Behaviors in Work Zones

In addition to the non-behavioral factors mentioned, some studies discuss the role of driver behaviors on work zone safety outcomes. Harb et al. (*15*) examined driver behaviors in work zone crashes by classifying the drivers as at-fault and not-at-fault. The at-fault drivers were identified if they were issued a citation or contributed to improper actions such as speeding and careless driving. They found that male drivers are more likely to be involved in one of the at-fault actions in work zone crashes. Venugopal et al. (*2*) found that some work zone crashes were associated with improper lane change or merging behaviors. Raub et al. (*29*) videotaped driver behaviors while traveling through work zones and found that improper speeds in work zones could contribute to the occurrence of crashes, as could inattentive driving and following too close. In terms of the crash injury severity, Li and Bai (*27*) found that driver errors, such as disregarding traffic control, were highly correlated with injuries. Salem et al. (*30*) reveal that 71% of injury and fatal crashes result from improper driving behaviors in work zones such as following too close, improper lane change, passing, and failing to maintain proper controls. Previous studies often show the likelihood of certain driver actions within work zone crashes. However, a comprehensive analysis of pre-crash driver behaviors and how they associate with injury severity of different drivers is under-researched. Further, researchers who investigate driver behaviors normally ignore the effect of other vehicles involved in the same crash on driver injury severity. For example, if there were a two-vehicle collision and one of the drivers was speeding, the other driver may also be injured because of the speeding behavior even though that driver was not speeding at all. In this light, this study takes into account the driver behaviors from two sides of a collision for multiple-vehicle crashes.

Crash Modeling for Crash Severity

Unlike studies on work zone crash rate and frequency that use count data modeling techniques, such as Poisson or negative binomial models (*3, 5, 6, 16, 31*), studies that explore the levels of crash severity use different modeling techniques. Binary or ordered logit/probit models are often applied (*16, 22, 24, 27, 28*), based on the number of injury severity levels examined. Weng et al. (*22*) and See (*32*) used a binary logistic model to examine two levels of injury severity in a crash: injury or non-injury. So did Li et al (*27*), but the levels of injury severity they examined were fatal versus injury crashes, and for Elghamrawy (*28*), two level of injuries were examined: injury other than fatal versus injury evident to others or no visible injury. Akepati et al. (*24*) applied an ordered regression model to investigate the injury severity at five levels: no injury, possible injury, non-incapacitating injury, incapacitating injury, and fatal injury, which is quite similar to what Khattak et al. (*16*) investigated using the same model.

As mentioned earlier, to simplify the modeling work, most previous studies on injury severity separated single- or multiple-vehicles crashes. For single crashes, the driver injury severity was discussed in analysis (*19, 21, 22*), while for multiple vehicle crashes, the most severe injury was taken as the crash severity (*3, 16*). With the advancement of modeling techniques and computational power, researchers are able to take advantage of more information available in the data and examine the injury severity of all drivers by applying more nuanced modeling techniques. Given the hierarchical nature of the crash data, i.e., drivers and vehicles nested in a crash, hierarchical modeling provides a better approach to understanding safety outcomes (*33*, *34*). To our knowledge, this technique has not been fully applied to investigate work zone crashes. This study aims to take advantages of hierarchical modeling techniques and extract valuable information on all drivers to disentangle the correlates of injury severity in a crash.

METHODOLOGY

Data

This study used the Virginia 2013 statewide crash database, provided by Virginia Department of Transportation. The database contains all types of crashes that occurred in 2013 on highway facilities within the Commonwealth of Virginia. The database was integrated from the information of individual crashes reported using the Virginia Police Crash Report - FR300 (*35*). Similar to the general structure of highway crash databases (*8*), the final database for analysis includes three files:

1) Crash event file: information about overall crash features (time, location, weather, roadway attributes, crash contexts, etc.);
2) Vehicle file: information about involved vehicles (vehicle body type, vehicle year, etc.); and
3) Person file: information about involved persons including the drivers (age, gender, position in the vehicle, injury type, etc.)

The database contains 121,601 highway crashes that occurred in 2013. There were 222,531 vehicles and 239,683 persons involved in these crashes. For these crashes, the vehicle occupancy rate is 1.08 persons per vehicle, and about 92.84% of persons involved in these crashes were drivers, justifying that the scope of this study covers the majority of injuries. Note that these numbers may not be consistent with the final dataset for data analysis because some observations with missing information were removed from the final dataset.

The work zone crashes were easily recognized according to one of the crash context variables indicating whether a crash occurred in a work zone. Out of the total number of crashes, 2.8% (3,404) occurred in work zones. Compared with recent years (2011~2012) that had on average 3,450 work zone crashes, the number of work zone crashes in 2013 is reasonable. The data were error checked, using descriptive statistics and distributions of variables. It is of reasonably good quality for analysis.

Work zone crashes were compared with non-work zone crashes. Note that this study only discussed driver injury severity in auto-sedans, pick-up trucks, vans, and sport utility vehicles (SUVs) because drivers of trucks and buses are protected differently during a crash compared to passenger vehicle drivers. To account for the influences on passenger vehicle drivers from large vehicles (trucks and buses), a variable was created to indicate whether a passenger vehicle collided with a truck or bus.

Variable Selection

Driver injury severity can be associated with a variety of factors including the crash time, location, crash contexts, vehicle body type, driver actions, and driver socio-demographics. Previous studies focusing on crash injury severity have provided a reference of what variables should be included in the investigation of work zone crashes. Table 1 summarizes a list of variables that were included in previous studies on injury severity in work zones. Most variables that were tested are also available in the VDOT database. Ideally, all tested variables that were shown to be significantly correlated with the injury severity should be re-examined in the present study. Unfortunately, some variables such as the work zone attributes (work zone types, type of work being done, and crash location within work zones) are not available in the released database. Khattak et al. (*16*) and Akepati et al. (*24*) extensively investigated the associations of work zone attributes on injury severity. They did not find substantial correlations between specific work zone attributes and injury severity. Therefore, this study used the work zone indicator to separate work zone crashes from other crashes, conducting a comparative study. The last column of Table 1 shows a list of variables to be tested in the present study.

Pre-crash behaviors are of particular interest to this study. There are 43 types of pre-crash actions stated in police reports, describing driver actions prior to a crash. For modeling purposes and to ensure sufficient variations across observations, these actions are grouped into three categories according to the descriptions:

- *No improper action*, which is already coded in the original database.
- *Non-intentional improper action*, including failing to maintain proper control, avoiding objects, improper turns, backing and passing, over-correction, etc.
- *Intentional improper action or violation*, including speeding, disregarding officers, flaggers, signals and signs, close-following, etc.

Table 1: Model Specification/Variable Selection Based on Previous Studies

	Authors & Reference →	Weng et al. (*22*)	Xie et al. (*19*)	Khattak et al. (*16*)	Li et al.(*27*)	Akepati et al. (*24*)	Variables selected for this study
Key Variables							
Driver and vehicle information	Driver gender	✓	✓		✓	✓	✓
	Driver age	✓	✓		✓	✓	✓
	DUI		✓				✓
	Seat belt	✓	✓			✓	✓
	Airbag & Eject	✓	✓			✓	✓
	Vehicle body type		✓		✓	✓	✓
Highway features	Crash Location (shoulder, etc.)		✓			✓	
	Road surface condition	✓			✓	✓	✓
	Roadway functional class		✓		✓		✓
	Number of lanes	✓			✓		
	Roadway alignment	✓	✓		✓		✓
	Roadway surface pavement		✓		✓		✓
	Two-way/one-way, divided/un.			✓			✓
	Intersection/segment				✓	✓	
	Traffic control	✓		✓	✓	✓	✓
	Urban/rural				✓		✓
	Posted speed limit	✓	✓	✓	✓	✓	
Crash contexts	Weather	✓	✓	✓	✓	✓	✓
	Ambient lighting	✓	✓	✓	✓	✓	✓
	Day of week	✓			✓		
	Time of day	✓			✓		
Crash attributes	Vehicle speed		✓				✓
	Truck involvement	✓		✓	✓		✓
	Harmful event (pedestrian, etc.)	✓					
	Collision type (rear end, etc.)			✓		✓	✓
	Number of vehicles			✓	✓		✓
	Driver actions/errors				✓	✓	✓
Work zone information	Crash location within work zones			✓		✓	✓
	Work zone type (lane closure, etc.)			✓		✓	
	Type of work (construction, etc.)	✓		✓			
	Workers present					✓	

A driver's pre-crash action is hypothesized to be associated with outcomes of a crash. For vehicles in single-vehicle crashes, as shown in Figure 1(i), the driver injury severity is only associated with Vehicle A's driver pre-crash action, if only the driver behavior is discussed. However, for multiple-vehicle crashes (i.e., two or more vehicles in crash), driver injury severity is potentially related to the driver behaviors of other vehicles involved in the same crash. For example, consider the rear-end crash shown in Figure 1(ii). The driver in

Vehicle C (host vehicle) may be injured because of the close-following of Vehicle B (other vehicle), though the Vehicle C driver did nothing improper. Thus, in addition to observing the driver behavior of Vehicle C, this study also takes into account the driver behavior of Vehicle B. A new behavioral variable was created from two sides of a collision. This variable describes the behaviors from the perspective of driver in the observation (i.e., host vehicle driver), having twelve possible attributes shown in Table 2.

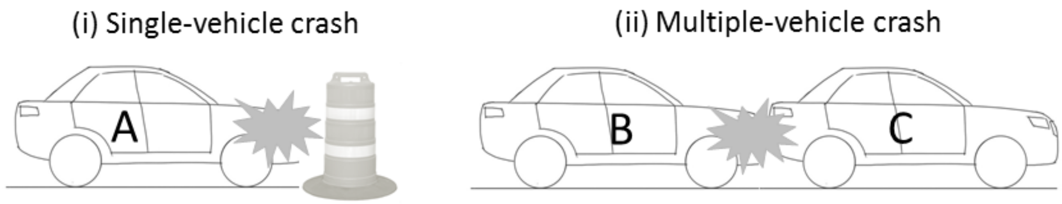

Figure 1: Single vs. multiple-vehicle crash

Table 2: Behavior Combinations and their Codes in Modeling

Behavior code	Host vehicle	Other vehicle*
1	No improper action	N/A
2	Non-intentional improper action	N/A
3	Intentional improper action/violation	N/A
11	No improper action	No improper action
12	No improper action	Non-intentional improper action
13	No improper action	Intentional improper action/violation
21	Non-intentional improper action	No improper action
22	Non-intentional improper action	Non-intentional improper action
23	Non-intentional improper action	Intentional improper action/violation
31	Intentional improper action/violation	No improper action
32	Intentional improper action/violation	Non-intentional improper action
33	Intentional improper action/violation	Intentional improper action/violation

Notes: *Other vehicle* refer to the vehicles (excluding the host vehicle) involved in the same crash. For a single-vehicle crash, *other vehicle's behavior* is N/A. For a multiple-vehicle crash, the driver behavior of other vehicles is captured by the riskiest behavior. This study takes "Intentional improper action/violation" as the riskiest behavior and "No improper action" as the least risky behavior.

The safety outcomes explained by this study are injury severity of each driver within a crash. According to the reported injury types, injury severity can be easily recognized. There were four types of injuries reported separately for each driver: 1) killed, 2) serious injury, 3) minor/possible injury, and 4) no injury.

Data Analysis

Most previous studies have either analyzed correlates of driver injury severity of single-vehicle crashes (*19, 21, 22*) or the most severe injury in a crash (*3, 16*). Thus, for one crash, there was only one response and safety outcome, and traditional regression techniques could be applied. To investigate the injury severity of each driver within a crash, the structure of the data has to be considered. Each crash may have multiple responses or safety outcomes; Figure 2 shows a hierarchical structure of the crash database. Within Crash 1, there was one vehicle and one person (the driver) involved in the crash, while in Crash 2, there were two vehicles and three persons involved. This is a three-level structure: crash event level, driver/vehicle level, and occupant level, which is a layer for future exploration. Note that one vehicle corresponds to one driver only; the driver/vehicle level is a combined level containing information about both driver and vehicle.

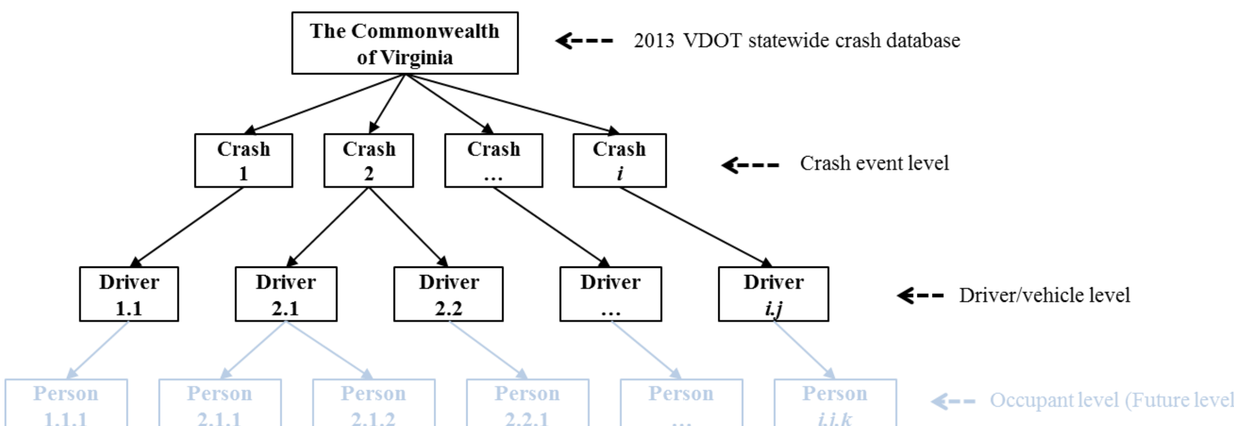

Figure 2: Hierarchical structure of crash data used in the study.

Normally, observations are required to be independent from each other, which is the assumption of conventional regressions (*36*). However, drivers within the same crash are not fully independent from each other. For instance, drivers involved in one crash had a common set of factors at the crash event level: roadway alignment, roadway surface conditions, weather, and ambient lighting conditions. This non-independence violates the assumption of conventional logistic regressions. Also, conventional models do not take into account all the information about injuries available in the database. Therefore, this study uses the hierarchical technique (*37-39*) to model nested relationships between drivers/vehicles and crash events. This technique can account for the non-independence of observations, and explain inter-driver variation (i.e., differences between drivers within the same crash) and between-crash variations (*40*). Thus, given the ordered nature of the injury severity and the multi-level structure of the data, a hierarchical ordered logistic model is estimated.

As shown in Figure 2, the two-level data structure can be described as driver j was involved in the crash i, where $i = 1, 2,\ldots, M$, and $j = 1, 2,\ldots N_i$. There were, $c = 1, 2, 3$, and 4 ordered injury response categories. Note that, the coded values for injury severity in modeling are: 1 = no injury (property damage only); 2 = minor injury; 3 = serious injury; and 4 = killed. For a driver j in crash i, the probability of $y_{ij} = c$, is given by (*41*)

$$p_{ij} = \Pr\left(y_{ij} = c \middle| X_{ij}, v_j\right) = \frac{1}{1+\exp\left(-\gamma_c+X_{ij}\beta+Z_{ij}v_i+\epsilon_{ij}\right)} - \frac{1}{1+\exp\left(-\gamma_{c-1}+X_{ij}\beta++Z_{ij}v_i+\epsilon_{ij}\right)} \quad (1)$$

Where,

y_{ij} = injury severity of driver j involved in crash i;

c = injury severity level, c = 1, 2, 3, and 4;

X_{ij} = a $(1 \times p)$ vector of covariates corresponding to fixed effects;

β = fixed effects parameter for covariates X_{ij};

Z_{ij} = a $(1 \times q)$ vector of covariates corresponding to random effects;

v_i = random effects parameter at crash event level;

γ_c = threshold value for injury severity level c, $\gamma_0 = -\infty$ and $\gamma_4 = +\infty$;

ϵ_{ij} = model residuals $\epsilon_{ij} \sim N(0, \delta^2)$.

Assume that the prior distribution of v_j is multivariate normal with mean 0 and $q \times q$ variance matrix Σ, thus, the log likelihood of the entire dataset can be obtained by

$$L(\beta, c, \Sigma) = \sum_{i=1}^{M} \left\{(2\pi)^{-q/2} |\Sigma|^{-1/2} \int [\exp(h(\beta, c, \Sigma, v_i)] dv_i \right\} \quad (2)$$

Where,

$$h(\beta, c, \Sigma, v_i) = \sum_{j=1}^{N} \{I_k(y_{ij}) \log(p_{ij})\} - \frac{v_i' \Sigma^{-1} v_i}{2} \quad , \quad I_k(y_{ij}) = \begin{cases} 1 & \text{if } y_{ij} = c \\ 0 & \text{otherwise} \end{cases}$$

The model parameters were estimated by maximizing likelihood. Stata software was used for the hierarchical modeling (*41*). The modeling outputs have three parts: fixed effects β, random effects v_i, and model goodness-of-fit. Fixed effects β reveal the correlations between explanatory variables (covariates) and the driver injury severity. Random effect v_i is estimated to account for the non-independence between observations, i.e., drivers within the same crash. In addition to conventional goodness-of-fit measures (e.g., number of observations, log likelihood, and χ^2 test), a likelihood ratio test is also performed to compared the hierarchical ordered logistic model with regular ordered logistic model. The likelihood ratio test is similar to regular χ^2 test, which compares the null model with the alternative model. The assumption for the likelihood ratio test is that there is no substantial improvement made by hierarchical models from regular models. The ratio of log likelihoods of the hierarchical model and the regular model is calculated by (*42*)

$$LR = -2Ln\frac{L_{regular}}{L_{hiearchial}} \tag{3}$$

Where, $L_{regular}$ refers to the log likelihood of regular ordered logistic model and $L_{hiearchial}$ is the log likelihood of the hierarchical model. LR has an approximate χ^2 distribution with *k* degrees of freedom. *k* is the number of parameters in the model. The likelihood ratio test rejects the assumption if χ^2 is larger than a χ^2 distribution 95 percentile with the same degrees of freedom. A *p*-value is provided to show the likelihood ratio test results.

Further, the marginal effects are also estimated according to the hierarchical modeling outputs. The marginal effects can be estimated by (*43*),

$$\frac{\partial \Pr(y_{ij} \leq c|\beta X_{ij})}{\partial X} = \frac{\exp(\gamma_c - X_{ij}\beta - Z_{ij}v_i - \epsilon_{ij})}{[1 + \exp(\gamma_c - X_{ij}\beta - Z_{ij}v_i - \epsilon_{ij})]^2}\beta' \tag{4}$$

Marginal effects provided more intuitive interpretations about the correlations between driver injury severity and associated factors, indicating the change of probability from a lower level of injury severity to a higher level with a unit change in the explanatory variable.

RESULTS

Descriptive Statistics

Table 3 presents the descriptive statistics of variables that were selected for descriptive analysis and modeling (work zone crashes versus non work zone crashes). The data were error checked, and observations with missing information (except driver gender) or erroneous values were removed. Note the information of driver gender was missing in nearly 40% of observations. To keep these observations, a new category (in addition to female and male) was used in the data analysis, indicating whether the observation contains driver gender information. Finally, 189,484 drivers and vehicles from 111,966 crashes were used for analysis.

The numbers of observations (N) were different at the driver/vehicle level and crash level, given the hierarchical structure; specifically, 6,108 drivers were involved in 3,208 work zone crashes, and for crashes at non work zones, 183,376 drivers were involved in 108,758 crashes. In terms of driver injury severity, no substantial differences were found between work zone crashes and non-work zone crashes, as shown in Figure 3. Compared with non-work zone crashes, drivers involved in work zone crashes were slightly less likely to be injured seriously (1.75% vs. 2.57%) or be killed (0.15% vs. 0.2%).

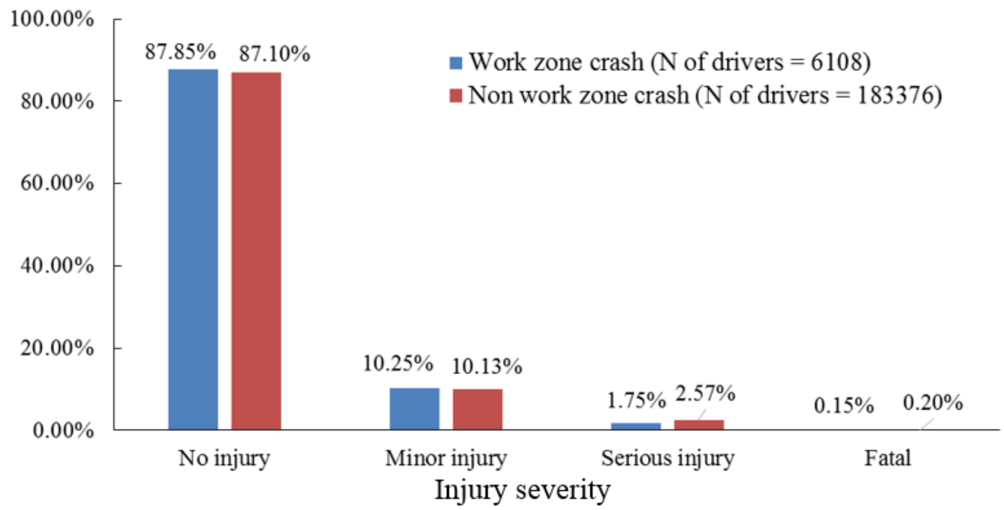

Figure 3: Injury severity distribution of drivers involved in work zone and non-work zone crashes

At the driver/vehicle level, factors related to driver behaviors and driver/vehicle characteristics were discussed. In terms of pre-crash actions, a great number of crashes occurred not because of the host driver's improper actions, but other drivers' faults (including non-intentional and intentional improper actions). About 14.3% of work zone crashes occurred only because of the other drivers' non-intentional improper actions, and 34.1% of crashes occurred in work zones because of other drivers' intentional improper actions or violations. These two proportions were greater than non-work zone crashes.

The information of driving under impairment (DUI) indicates that there was a smaller proportion of work zone crashes that involved DUI (1.8%), compared with other crashes (2.9%). Airbags were less likely to be deployed in work zone crashes (12.8 % vs. 16.9%), indicating that work zone crashes may occur at lower speeds and are relatively less severe than non-work zone crashes (*16*). Regarding the vehicle body type, SUVs had a relatively higher proportion in vehicles in work zone crashes, compared with vehicles in non-work zone crashes.

At the crash level, a higher proportion of work zone crashes (85.9%) occurred when the roadway surface was dry. Remarkably, more than 60% of work zone crashes in the database occurred on interstates, relative to 14.7% of non-work zone crashes, implying that work zone activities on interstates are a major concern. Since interstates are two-way roads, divided, and with fully controlled access, a larger proportion of work zone crashes (61.4%) occurred on divided two-way roadways with access control. About 15.4% of work zone crashes involved a truck or bus, while trucks and buses were involved in only 5.3% of non-work zone crashes. Truck and bus involvement might be a serious issue for work zone safety. In terms of collision types, rear-end crashes (59.1%) dominate work zone crashes, which is consistent with previous studies (*5, 26, 44*).

Table 3: Descriptive Statistics for Work Zone and Non-Work Zone Crashes

Structural Level	Variable	Work Zone Valid N	Work Zone Mean or Proportion	Non Work Zone Valid N	Non Work Zone Mean or Proportion	Diff. in Proportion
Driver/vehicle level	Pre-crash driver action					
	1 = Non-improper action	6108	0.8%	183376	4.6%	-3.8%
	2 = Non-intentional improper action	6108	4.6%	183376	10.4%	-5.8%
	3 = Intentional improper action/violation	6108	0.6%	183376	1.7%	-1.1%
	11 = Non-improper vs. Non-improper	6108	1.1%	183376	1.5%	-0.3%
	12 = Non-improper vs. Non-intentional	6108	14.3%	183376	13.4%	0.9%
	13 = Non-improper vs. Intentional	6108	34.1%	183376	27.7%	6.4%
	21 = Non-intentional vs. Non-improper	6108	11.0%	183376	10.6%	0.4%
	22 = Non-intentional vs. Non-intentional	6108	2.7%	183376	3.4%	-0.8%
	23 = Non-intentional vs. Intentional	6108	0.9%	183376	0.9%	0.0%
	31 = Intentional vs. Non-improper	6108	25.4%	183376	23.3%	2.1%
	32 = Intentional vs. Non-intentional	6108	1.2%	183376	1.0%	0.2%
	33 = Intentional vs. Intentional	6108	3.2%	183376	1.4%	1.8%
	Driver age	6108	39.71	183376	39.31	-
	Driver gender					
	1 = Male	6108	33.2%	183376	33.5%	-0.3%
	2 = Female	6108	21.3%	183376	26.7%	-5.4%
	3 = Not available	6108	45.5%	183376	39.8%	5.8%
	Driving under impairment (1 = yes, 0 = otherwise)	6108	1.8%	183376	2.9%	-1.1%
	Seat belt applied (1 = yes, 0 = otherwise)	6108	98.8%	183376	97.2%	1.5%
	Airbag (1 = deployed , 0 = otherwise)	6108	12.8%	183376	16.9%	-4.1%
	Ejected from vehicle (1 = yes, 0 = otherwise)	6108	0.4%	183376	0.5%	-0.1%
	Vehicle body type					
	1 = Passenger car	6108	62.3%	183376	62.0%	0.3%
	2 = Pick-up truck	6108	11.2%	183376	13.0%	-1.8%
	3 = Van	6108	6.5%	183376	6.2%	0.2%
	4 = Sport Utility Vehicle (SUV)	6108	20.1%	183376	18.7%	1.3%
	Vehicle speed (mph)	6108	23.80	183376	24.84	-
Crash event level	Roadway surface condition (1 = dry, 0 = otherwise)	3208	85.9%	108758	77.5%	8.4%
	Interstate (1 = yes, 0 = otherwise)	3208	60.8%	108758	14.7%	46.1%
	Roadway alignment					
	1 = Straight - level	3208	77.0%	108758	71.0%	6.0%
	2 = Curve - level	3208	3.5%	108758	7.9%	-4.5%
	3 = Straight - grade	3208	13.0%	108758	11.6%	1.4%
	4 = Curve - grade	3208	3.1%	108758	5.6%	-2.5%
	5 = Otherwise	3208	3.4%	108758	3.8%	-0.4%
	Roadway pavement type (1 = asphalt, 0 = otherwise)	3208	94.1%	108758	94.1%	0.0%
	Roadway configuration					
	1 = Two-way, undivided	3208	14.5%	108758	42.4%	-27.9%
	2 = Two-way, divided, no control of access	3208	17.2%	108758	27.4%	-10.2%
	3 = Two-way, divided, with control of access	3208	61.4%	108758	17.7%	43.7%
	4 = One-way, undivided	3208	3.7%	108758	3.8%	-0.1%
	5 = Otherwise	3208	3.3%	108758	8.6%	-5.4%
	Traffic control					
	1 = Yes - working	3208	92.2%	108758	80.1%	12.1%
	2 = Yes - not working somehow	3208	6.2%	108758	18.5%	-12.3%
	3 = No traffic control	3208	1.6%	108758	1.4%	0.1%
	Rural area (1 = yes, 0 = otherwise)	3208	11.6%	108758	26.1%	-14.6%
	Weather (1 = clear/cloudy, 0 = otherwise)	3208	87.6%	108758	80.2%	7.4%
	Ambient lighting (1 = non-daylight, 0 = otherwise)	3208	30.8%	108758	33.1%	-2.3%
	Truck/bus involvement (1 = yes, 0 = otherwise)	3208	15.4%	108758	5.3%	10.1%
	Collision type					
	1 = Rear end	3208	59.1%	108758	33.7%	25.4%
	2 = Angle	3208	12.3%	108758	25.8%	-13.5%
	3 = Head on	3208	1.1%	108758	2.4%	-1.3%
	4 = Sideswipe	3208	14.3%	108758	8.3%	6.0%
	5 = Fixed object	3208	10.2%	108758	19.5%	-9.4%

6 = Otherwise	3208	3.1%	108758	10.3%	-7.2%

Note: Total valid N = 189,484 at driver/vehicle level, and 111,966 at crash even level.

Modeling Results

Hierarchical models estimated both fixed effects (i.e., coefficients of variables) and random effects (i.e., variations of coefficients at a higher level - crash event level). Normally, fixed effects, showing correlations between response variable and associated factors, are of interest. The random effects were estimated to answer whether there is substantial variation of correlations across the groups. Table 4 shows the modeling outputs for work zone crashes versus non-work zone crashes. The full model presents estimates of all variables and the final model gives estimates of variables that were statistically significant at 95% confidence level with p-value < 0.05.

The goodness-of-fit for the models seemed reasonable, at 0.115 for the work zone model and 0.147 for the non-work zone model. For the four models, the estimated random effects were significantly greater than zero, indicating substantial variations between crashes. Further, the likelihood ratio test indicated significant improvement (p-value <0.05) due to hierarchical ordered models over regular ordered models. Examining the fixed effects, coefficients generally have the expected signs and most of the selected variables were significantly correlated with driver injury severity at 95% confidence level. It was no surprise that models for non-work zone crashes had more significant parameter estimates, given their large number of observations used for modeling.

To interpret the parameter estimates, marginal effects were calculated using the hierarchical modeling outputs. Table 5 shows the marginal effects for work zone crashes. Note that the full list of marginal effects for non-work zone crashes is not presented in this paper, given the limited space, but available from the authors. Only marginal effects for the change in the probability of non-injury are presented for non-work zone crashes in Table 5, to compare them with work zone crashes.

Table 4: Hierarchical Modeling Results for Work Zone and Non-Work Zone Crashes

Variable	Work Zone Crash		Non Work Zone Crash	
	Full Model	Final Model	Full Model	Final Model
Pre-crash driver action				
1 = Non-improper action	Base	Base	Base	Base
2 = Non-intentional improper action	2.290**	2.279**	1.639***	1.639***
3 = Intentional improper action/violation	1.635	1.641	1.581***	1.580***
11 = Non-improper vs. Non-improper	2.135*	2.131*	0.506***	0.506***
12 = Non-improper vs. Non-intentional	2.469**	2.498**	1.265***	1.265***
13 = Non-improper vs. Intentional	2.937**	2.992**	1.559***	1.558***
21 = Non-intentional vs. Non-improper	1.525	1.548	0.525***	0.524***
22 = Non-intentional vs. Non-intentional	1.896	1.902	0.947***	0.947***
23 = Non-intentional vs. Intentional	2.941**	2.951**	1.289***	1.288***
31 = Intentional vs. Non-improper	1.357	1.408	0.479***	0.478***
32 = Intentional vs. Non-intentional	2.956**	2.987**	0.732***	0.731***
33 = Intentional vs. Intentional	1.526	1.564	0.868***	0.867***
Driver age	0.007**	0.008**	0.012***	0.012***
Driver gender				
1 = Male	-0.355***	-0.365***	-0.177***	-0.178***
2 = Female	Base	Base	Base	Base
3 = Not available	0.043	0.050	0.207***	0.207***
Driving under impairment (1 = yes, 0 = otherwise)	0.920***	0.891***	0.351***	0.352***
Seat belt applied (1 = yes, 0 = otherwise)	-2.148***	-2.219***	-2.025***	-2.025***
Airbag (1 = deployed, 0 = otherwise)	1.665***	1.664***	1.689***	1.689***
Ejected from vehicle (1 = yes, 0 = otherwise)	1.743***	1.784***	2.046***	2.046***
Vehicle body type				
1 = Passenger car	Base	Base	Base	Base
2 = Pick-up truck	-0.395**	-0.369**	-0.203***	-0.203***
3 = Van	-0.162	-0.151	-0.180***	-0.180***
4 = Sport Utility Vehicle (SUV)	-0.017	-0.012	-0.070***	-0.070***
Vehicle speed (mph)	0.013***	0.013***	0.010***	0.010***
Roadway surface condition (1 = dry, 0 = otherwise)	0.403		0.135**	0.166***
Interstate (1 = yes, 0 = otherwise)	0.827**	0.876***	-0.019	
Roadway alignment				
1 = Straight - level	Base		Base	Base
2 = Curve - level	-0.214		0.254***	0.254***
3 = Straight - grade	-0.126		0.177***	0.177***
4 = Curve - grade	0.315		0.384***	0.385***
5 = Otherwise	-0.452		0.132**	0.132**
Roadway pavement type (1 = asphalt, 0 = otherwise)	-0.265		-0.164***	-0.163***
Roadway configuration				
1 = Two-way, undivided	0.697*	0.773**	0.029	0.042
2 = Two-way, divided, no control of access	0.841**	0.869**	0.036	0.049
3 = Two-way, divided, with control of access	Base	Base	Base	Base
4 = One-way, undivided	-0.397	-0.417	-0.308***	-0.305***
5 = Otherwise	0.659	0.672	-0.295***	-0.283***
Traffic control				
1 = Yes - working	Base		Base	Base
2 = Yes - not working somehow	-0.231		-0.312***	-0.311***
3 = No traffic control	-0.255		-0.359***	-0.359***
Rural area (1 = yes, 0 = otherwise)	0.244		0.651***	0.651***
Weather (1 = clear/cloudy, 0 = otherwise)	-0.306		0.036	
Ambient lighting (1 = non daylight, 0 = otherwise)	-0.096		-0.138***	-0.139***
Truck/bus involvement (1 = yes, 0 = otherwise)	1.010***		0.829***	0.828***
Collision type				
1 = Rear end	0.007	-0.020	0.073	0.072
2 = Angle	-0.006	-0.055	0.218***	0.219***
3 = Head on	1.038*	0.941	1.104***	1.104***
4 = Sideswipe	-0.790	-0.826*	-0.469***	-0.469***
5 = Fixed object	0.258	0.277	0.639***	0.638***
6 = Otherwise	Base	Base	Base	Base

Table 4: Hierarchical Modeling Results for Work Zone and Non-Work Zone Crashes (continued)

Variable	Work Zone Crash		Non Work Zone Crash	
	Full Model	Final Model	Full Model	Final Model
Threshold 1	4.174***	3.681***	3.369***	3.376***
Threshold 2	6.684***	6.208***	5.741***	5.748***
Threshold 3	9.551***	9.074***	9.099***	9.107***
Variance of random effects at crash event level	1.930	1.966	2.682	2.682
Likelihood ratio test: Hierarchical Vs. Regular Ordered	72.93***	74.97***	2854.19***	2855.50***
Number of observations (i.e., drivers/vehicles)	6108	6108	183376	183376
Number of groups (i.e., crashes)	3208	3208	108758	108758
Log likelihood intercept only	-2612.46	-2612.46	-84091.49	-84091.49
Log likelihood at convergence	-2306.28	-2311.18	-71759.45	-71759.72
Pseudo-R^2	0.117	0.115	0.147	0.147
Prob. > χ^2	0.000	0.000	0.000	0.000

Notes: *** = significant at 99% level; ** = significant at 95% level; and * = significant at 90% level.

Pseudo-R^2 = (Log likelihood intercept only - Log likelihood at convergence)/Log likelihood intercept only

Discussion of Key Factors

Pre-Crash Actions

As mentioned earlier, pre-crash actions refer to the driver's behavior or vehicle maneuvering prior to the event of a crash. Pre-crash actions, as one of human factors, have been recognized as the main contributor to highway safety outcomes (*45*, *46*). They represent critical decisions drivers make according to their driving needs and the instantaneous driving contexts (*47*). This study took into account all drivers' behaviors in a crash by observing driver behaviors of both the host and other vehicles involved in the same crash. The modeling results in Table 3 show that pre-crash actions were significantly associated with the level of driver injury severity. Compared with the base action, non-improper action, all other combinations of behaviors were linked with higher injury severity (positive coefficients indicating greater probability of injury). The magnitudes of coefficients in the work zone model were greater than those in the non-work zone model, indicating stronger correlations between pre-crash behaviors and injury severity in work zone crashes.

	Injury Severity of Work Zone Crash				Non work zone
Variable	No Injury	Minor Injury	Serious Injury	Fatal	No Injury
Pre-crash driver action					
1 = Non-improper action	Base	Base	Base	Base	Base
2 = Non-intentional improper action	-5.07%	4.63%	0.41%	0.03%	-6.30%
3 = Intentional improper action/violation	-2.47%	2.26%	0.20%	0.01%	-5.88%
11 = Non-improper vs. Non-improper	-4.33%	3.96%	0.35%	0.02%	-1.06%
12 = Non-improper vs. Non-intentional	-6.37%	5.81%	0.52%	0.03%	-3.96%
13 = Non-improper vs. Intentional	-10.33%	9.39%	0.89%	0.05%	-5.73%
21 = Non-intentional vs. Non-improper	-2.21%	2.02%	0.17%	0.01%	-1.11%
22 = Non-intentional vs. Non-intentional	-3.36%	3.07%	0.27%	0.02%	-2.49%
23 = Non-intentional vs. Intentional	-9.94%	9.04%	0.85%	0.05%	-4.08%
31 = Intentional vs. Non-improper	-1.85%	1.69%	0.15%	0.01%	-0.98%
32 = Intentional vs. Non-intentional	-10.29%	9.35%	0.88%	0.05%	-1.72%
33 = Intentional vs. Intentional	-2.25%	2.06%	0.18%	0.01%	-2.19%
Driver age	-0.04%	0.03%	0.00%	0.00%	-0.05%
Driver gender					
1 = Male	1.71%	-1.56%	-0.14%	-0.01%	0.69%
2 = Female	Base	Base	Base	Base	Base
3 = Not available	-0.28%	0.26%	0.02%	0.00%	-0.96%
Driving under impairment (1 = yes, 0 = otherwise)	-6.64%	6.00%	0.60%	0.04%	-1.77%
Seat belt applied (1 = yes, 0 = otherwise)	28.26%	-24.78%	-3.28%	-0.21%	21.05%
Airbag (1 = deployed, 0 = otherwise)	-15.00%	13.46%	1.46%	0.09%	-12.72%
Ejected from vehicle (1 = yes, 0 = otherwise)	-19.65%	17.47%	2.05%	0.13%	-22.14%
Vehicle body type					
1 = Passenger car	Base	Base	Base	Base	Base
2 = Pick-up truck	1.66%	-1.51%	-0.14%	-0.01%	0.84%
3 = Van	0.74%	-0.68%	-0.06%	0.00%	0.75%
4 = Sport Utility Vehicle (SUV)	0.06%	-0.06%	-0.01%	0.00%	0.31%
Vehicle speed (mph)	-0.06%	0.06%	0.01%	0.00%	-0.04%
Roadway surface condition (1 = dry, 0 = otherwise)					-0.69%
Interstate (1 = yes, 0 = otherwise)	-4.13%	3.76%	0.35%	0.02%	
Roadway alignment					
1 = Straight - level					Base
2 = Curve - level					-1.17%
3 = Straight - grade					-0.79%
4 = Curve - grade					-1.89%
5 = Otherwise					-0.58%
Roadway pavement type (1 = asphalt, 0 = otherwise)					0.75%
Roadway configuration					
1 = Two-way, undivided	-4.40%	4.00%	0.38%	0.02%	-0.19%
2 = Two-way, divided, no control of access	-5.18%	4.70%	0.45%	0.03%	-0.22%
3 = Two-way, divided, with control of access	Base	Base	Base	Base	Base
4 = One-way, undivided	1.37%	-1.25%	-0.11%	-0.01%	1.15%
5 = Otherwise	-3.65%	3.32%	0.31%	0.02%	1.08%
Traffic control					
1 = Yes - working					Base
2 = Yes - not working somehow					1.39%
3 = No traffic control					1.23%
Rural area (1 = Yes, 0 = otherwise)					-3.37%
Weather (1 = clear/cloudy, 0 = otherwise)					
Ambient lighting (1 = non daylight, 0 = otherwise)					0.58%
Truck/bus involvement (1 = yes, 0 = otherwise)	-7.70%	6.96%	0.70%	0.04%	-5.12%
Collision type					
1 = Rear end	0.11%	-0.10%	-0.01%	0.00%	-0.28%
2 = Angle	0.29%	-0.27%	-0.03%	0.00%	-0.91%
3 = Head on	-7.84%	7.07%	0.73%	0.04%	-7.01%
4 = Sideswipe	3.18%	-2.90%	-0.26%	-0.02%	1.42%
5 = Fixed object	-1.72%	1.56%	0.15%	0.01%	-3.23%
6 = Otherwise	Base	Base	Base	Base	Base

By examining the largest marginal effects (which are statistically significant), it was found that in work zones a driver who did not make any improper actions was 10.33% more likely to be injured if the other drivers (in the same crash) committed an intentional improper action or violation such as speeding or following too close, while in other places, the chance was increased by 5.73%. Also in work zones, a driver who made a non-intentional improper action was 9.94% more likely to be injured if the other drivers (in the same crash) committed an intentional improper action; in non-work zone places, the chance was increased by 4.08%. If a driver made an intentional improper action and another driver made a non-intentional improper action, the first driver was 10.29% more likely to be injured in a work zone crash; the chance for injury in the same situation for crashes in non-work zones was 1.72%. Therefore, in work zones, the harm can either be caused by other drivers' actions or the driver's own intentional improper actions or violations.

Other Driver-Related Factors

In a crash, older drivers were more likely to be injured, though the magnitude of the marginal effect was small. Compared with females, male drivers were associated with a lower probability of being injured, by 1.71%. Note that nearly 40% drivers reported in the data did not have their gender specified. The modeling did not show a significant correlation between this group of drivers and injury severity, indicating that missing observations were randomly distributed in the data.

Individuals driving under impairment were 6.64% more likely to be injured. For non-work zone crashes, the chances of driver injury were 1.77% higher, if they were driving under impairment. Thus, the DUI problem seems to be more serious for work zone crashes and needs further investigation. Drivers who did not use seat belts were more likely to be injured, by 28.26%, in work zone crashes, and by 21.05 % in non-work zone crashes. The use of seat belts was highly correlated with the crash outcomes, consistent with previous studies (*19*, *22*, *24*).

Vehicle-Related Factors

The deployment of airbags and driver ejection systems can be used as one of the indicators of crash severity. Normally, crashes where airbags were deployed and drivers ejected are more severe, compared with other crashes (*22*), which is confirmed by this study. For work zone crashes, the chance of driver injury was increased by 15%, if an airbag was deployed, and by 19.65% if the driver was ejected from the seat, as compared with their bases (without airbag deployment, injury severity would be even worse, on average). For non-work zone crashes, the chances were increased by 12.72% and 22.14%, respectively.

Among passenger vehicles, body type did not show much correlation with driver injury severity in work zone crashes. In general, pick-up trucks, vans, and SUVs were associated with a smaller chance of injuries for all types of crashes (work zone and non-work zone). As expected, vehicle speed prior to the crash was positively correlated with the driver injury severity.

Truck and Bus Involvement

As expected, crashes that involve trucks or buses were likely to be more severe, especially due to mass differentials in multi-vehicle crashes (*27*). Drivers in work zone crashes with truck or bus involvement were 7.7% more likely to suffer injuries, compared with drivers in single passenger vehicle crashes. For non-work zone crashes, the chances were 5.12% higher. Truck and bus involvement is associated with injuries of even greater severity if the crash occurs in a work zone.

Collision Type

As expected, head-on were the most severe in both work zones and non-work zone areas. However, in terms of the correlations between collision type and driver injury severity, this study did not reveal substantial correlations in work zone crashes.

Roadway Characteristics

Crashes in interstate work zones seemed to be more severe than non-interstate work zone crashes. Drivers involved in interstate work zone crashes were 4.13% more likely to be injured than those involved in other work zone crashes. Roadway configuration is another factor significantly associated with driver injury severity. Undivided two-way roads or divided roads without access control in the median were associated with a higher injury severity, compared with the base. Other roadway characteristics, including pavement type, alignment, rural versus urban, and traffic control, were not significantly correlated with driver injury severity in a work zone crash.

INCORPORATING MODELING RESULTS IN HSM

Currently, the Highway Safety Manual (HSM) provides a procedure to quantify the effects of work zones on highway traffic safety, in terms of changes of crash frequency. For example, compared to a road segment that does not have a work zone, one with an active work zone is associated with 30% more crashes, given a Crash Modification Factor of CMF of 1.3 (*4*). However, information about crash injury severity is not commonly available. This study explored the correlates of injury severity, given a crash that occurs in work zones. The correlational analysis provides additional crash modification factors from the perspective of crash severity. For example, modeling reveals that for work zone crashes driver injury severity is higher by 9.94 to 10.33% if a driver intentionally commits an improper action or a violation that pertains to speeding, following too closely, or disregarding officers, flaggers, signals, and signs. If effective speed enforcement and adherence to traffic rule regulations are implemented, then such actions and violations may be eliminated in work zones, lowering the injury severity by approximately 10% (even if the crash rates in work zones are higher by 30%). Thus, information generated in this study can be converted to a CMF related to injury severity related to work zones.

Table 6 gives an example to illustrate the procedure for developing a CMF for injury severity. This example integrates the changes in crash rates revealed by Ullman et al. (*4*) and injury severity relationships uncovered by this study. Suppose there are 100 crashes occur on a road segment if no work zone is present. Initiating a work zone on this segment is expected to increase crashes by 30%, totaling 130 crashes. The initial proportion of injury crashes at no work zone is approximately 13%, as shown in Figure 3. Therefore, among 100 crashes on this segment, 13 are expected to be injury crashes and 87 are property damage only (PDO) crashes. With a work zone, the distribution will be 16.9 injury (=130 × 13%) and 113.1 PDO crashes (=130 – 16.9), assuming that the percentage of injury crashes stays the same at 13%, i.e., it does not change from no work zone to work zone. If effective speed and traffic rule regulations are enforced, then injury severity is expected to be lower by 10%, meaning that the new percentage of injury crashes in work zones will be 11.7% (=13% × (100% – 10%)); the modified distribution of crashes in work zones will be 15.21 injury (=130 × 11.7%) and

114.79 PDO crashes (=130 – 15.21). In general, the distribution of expected injury and PDO crashes after countermeasure implementation can be given by the following equations (*45*):

Expected Number of Injury Crashes-After $= (CMF \times N) \times P_{Inj} \times (1 - CMFSEV)$ (13)

Expected Number of PDO Crashes-After $= (CMF \times N) - (CMF \times N) \times P_{Inj} \times (1 - CMFSEV)$ (14)

Where,

CMF = Crash Modification Factor;

N = Number of crashes before implementation of countermeasure;

P_{Inj} = Probability of injury, between 0 and 1 before countermeasure implementation;

CMFSEV = Crash Modification Factor for injury severity.

Table 6: Illustrative Example of Developing Crash Modification Factor for Injury Severity

Countermeasures in work zone	No work zone present	Work zone without speed and traffic rule regulations enforcement	Work zone with speed and traffic rule regulations enforcement
CMF (*4*)	1.3		
CMFSEV	0.9		
Steps for crash injury distribution modification	Number of crashes before work zone	Number of crashes during work zone before countermeasure implementation	Number of crashes during work zones with modified injury severity distribution
Number of Crashes	100	130	130
P_{Inj}	13%	13%	11.7%
Number of Injury	13	16.9	15.21
Number of PDO Crashes	87	113.1	114.79

LIMITATIONS

The results presented in this study are highly dependent on the accuracy of police crash reports. This is especially true for drivers' pre-crash actions because they rely on honest reporting to officials by the involved drivers about their pre-collision actions. Thus the possible discrepancies between reported values and actual values may be a threat to the validity of the analysis results; however, this threat is common to all studies of police reported crashes. In addition, the injury severity scale used is based on police officers' assessments, which can vary across individuals.

The presented analysis included several key factors that were hypothesized to be correlated with the driver injury severity. Some were found to be statistically significantly associated with driver injury severity. However, some unselected factors (e.g., vehicle defects, roadway design features) might also be important to injury severity. This study is limited by the factors selected for modeling.

CONCLUSIONS

This study investigated correlates of driver injury severity in work zone crashes, as compared to non-work zone crashes. Unlike most previous studies that were limited to analyzing one response for one crash, (driver injury severity of single vehicle crashes (*19, 21, 22*), or the most severe driver injury of multiple vehicle crashes (*3, 16*)), this study took account of the injury severity of all vehicle drivers involved in crashes. Thus, for multiple injury severities within a crash, this study applied an appropriate hierarchical modeling methodology to explain the correlates nested in hierarchies, i.e., driver/vehicle characteristics nested in the overall crash attributes. Among the driver characteristics, this study focused on pre-crash driver actions, exploring how drivers' pre-crash actions were associated with driver injury severity.

Pre-crash actions have been recognized as significant contributors to safety outcomes (*45*, *46*), (*47*). Drivers are slightly more severely injured in work zone crashes than non-work zone crashes. Intentional improper actions and violations seem to be an issue in work zones because they are associated with higher chances of injuries, compared to non-work zones. Such actions mainly include speeding, following too closely, and disregarding officers, flaggers, signals, and signs. Effective speed enforcement and enforcement of traffic rule regulations should be explored as options to reduce driver injury severity in work zones.

In addition to the pre-crash actions, other driver/vehicle related factors were explored. Driving under impairment (DUI) and not using seat belts are two key reasons that drivers can be seriously injured in a crash. Such drivers stand an even greater chance of injury in work zone crashes. Further, this study confirms that crashes with deployed airbags and driver ejections are more severe (*22*), and as expected, vehicle speed prior to a crash is positively correlated with driver injury severity.

Several crash attributes were examined in this study: truck or bus involvement, collision type, and roadway characteristics. Truck or bus involvement is likely to increase the severity of crashes (*27*), especially for crashes that occur in a work zone. Head-on collisions are the most severe crashes, in both work zones and non-work zone areas. However, no substantial differences were found between work zone and non-work zone crashes, in terms of the correlations between collision type and driver injury severity. Also, interstate work zone crashes were found to be more severe than non-interstate work zone crashes. Some roadway characteristics, including pavement type, alignment, rural versus urban, and traffic control, are not significantly correlated with driver injury severity in a work zone crash. An example demonstrates how HSM procedures can use CMFs for injury severity, based on findings from this study.

This study explored the hierarchies embedded in highway crashes, and untangled the correlates of driver injury severity in work zone crashes versus non-work zone crashes, focusing on driver's pre-crash actions. Further research is needed to answer why some drivers undertake certain actions prior to a crash and what are the contributing factors to a particular action, given that this action is associated with a higher level of injury. The Virginia statewide crash database used in this study contains rich information that was not fully explored by this study. For example, the geo-coordinates of crashes allow us to define the geographic distributions of crashes within the whole state. The spatial patterns of work zone crashes can be explored using geo-spatial modeling techniques, providing insights of developing local safety recommendations for work zones in a particular region.

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