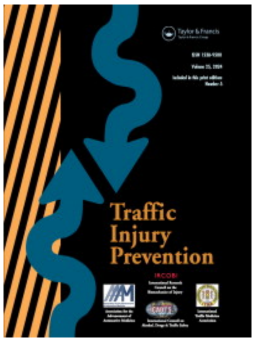

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Assessing the effects of geometry and non-geometry related factors in work-zone crashes

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Assessing the effects of geometry and non-geometry related factors in work-zone crashes

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ABSTRACT

Objective: Work zones are unique in geometry and traffic management, utilizing special traffic signs, standard channelizing devices, appropriate barriers, and pavement markings. These configurations can introduce unexpected driving conditions, potentially posing risks to drivers. This analysis aims to explore potential differences in contributing factors between work-zone crashes where geometry was identified as a factor and those where it was non-geometry factor. To gain insights into driver injury severities in single-vehicle work-zone crashes, this study analyzed work zone crash data from Florida.
Method: This study employed random parameters logit models, accommodating potential variations in parameter estimates' means and variances. The dataset encompassed a wide array of factors known to influence driver injury severity, encompassing crash characteristics, vehicle attributes, roadway features, prevailing traffic volume, driver profiles, and spatial and temporal considerations.
Results: This analysis yielded significantly distinct parameters for work-zone crashes, distinguishing between geometry-related and non-geometry-related factors (primarily the human factors). This distinction suggests a complex interplay between these factors. Notably, the marginal effects of individual parameter estimates exhibited marked differences between these two categories – geometry and non-geometry factors.
Conclusion: These findings contribute to the growing body of research indicating that geometric restrictions within work zones introduce a distinct set of risk factors compared to non-geometry-related factors. Recognizing the significance of geometric restrictions, beyond typical driving conditions, holds the implications for enhancing safety within various work zone configurations and offers valuable insights for crash scene investigators to pinpoint contributing factors accurately.

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Introduction

In Florida, the number of work-zone crashes has been steadily rising since 2014, despite no significant increase in the number of work zones themselves. In 2017, there were 8,494 work-zone crashes compared to just 5,409 in 2014. This means that in 2017, there was nearly one work-zone crash every hour, as opposed to one crash approximately every 1.6 h in 2014. It is worth noting that single-vehicle crashes in work zones account for roughly 20% of all crashes in Florida according to crash statistics. These single-vehicle crashes are of particular interest because they shed light on how the fundamental aspects of work-zone design can influence potential driver errors (Islam et al. 2020). Moreover, as there is a growing emphasis on the maintenance and reconstruction of existing highways and infrastructure, as well as the need for new roadway facilities, work-zone safety has become a critical concern for both workers and motorists.

While there have been several research studies on work-zone safety in general and injury severities in work-zone crashes (Harb et al. 2008; Li and Bai 2008; 2009; Meng et al. 2010; Tarko et al. 2011; Osman et al. 2018; Islam et al. 2020), none of these studies have considered the geometric configuration of work zones as a contributing factor in crash severity models (Osman et al. 2018), despite a consensus that it plays a role. For instance, in Florida, geometry was identified as a contributing factor in approximately 25% of all work-zone crashes from 2012 to 2017. When this study breaks down the proportion of severe (fatal and incapacitating injury), moderate (non-incapacitating and possible injury), and no injury (property damage only) crashes for both geometry-related and non-geometry-related factors in single-vehicle work-zone crashes, it is noteworthy that they account for 8%, 31%, and 61%, and 10%, 31%, and 59% of total work-zone crashes, respectively, in Florida during the same period.

Past research on work zones has approached the topic from various angles. Some studies have primarily focused on fatal crashes (Daniel et al. 2000; Schrock et al. 2004; Arditi et al. 2007), while others have considered both fatal and injury crashes (Li and Bai 2008; Elghamrwy et al. 2010). Some have specifically analyzed injury severity (Li and Bai 2009;

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Wang et al. 2010; Akepati and Dissanayake 2011), and there have been studies examining whether work-zone crashes involving heavy vehicles are more severe compared to non-work-zone areas (Islam 2021). Some of these studies suggested that work-zone crashes tend to be more severe (Bédard et al. 2002; Ullman et al. 2006; Meng et al. 2010), while others have disagreed with this assessment (Nemeth and Migletz 1978; Hargroves and Martin 1980; Nemeth and Rathi 1983; Rouphail et al. 1988; FHWA 2016). However, none of these studies has delved into the role of work-zone geometry as a contributing factor. In real-world investigations of work-zone crashes, work-zone geometry is sometimes identified as a contributing factor, but not in all cases. This raises the question of whether all work-zone crashes should be attributed to geometry that originates from the temporary traffic control plan or not. While most crashes can be attributed to human factors, road geometry, and work-zone activity, specifically traffic signs, markings, and channelization with barrels, can influence drivers' speed adaptation, lane keeping, and overall risk perception.

This analysis aims to explore potential differences in contributing factors between work-zone crashes where geometry was identified as a factor and those where it was not. In this study, the notion of "work zone" encompasses special road section where work zone design (including work configuration with detailed physical dimension) and operational aspect under the roadway factors contribute to work zone related crashes. On the other hand, "none" encompasses the non-geometry factors that characterize human factors or driver actions and also contribute to work zone related crashes. Additionally, this study seeks to provide further insights into how work-zone geometry may impact driver injury severity in work-zone-related crashes in Florida.

Data description

The work zone related crashes in this study were police-reported crashes in Crash Analysis Reporting (CAR) system in Florida from January 1, 2012 to December 31, 2017. Florida ranks third highest from 2012 to 2015 and second highest in 2016 and 2017 with number of fatal work zone crashes in the nation (National Work Zone Safety Clearinghouse). Work zone related crash data (work zone related code = 2) was filtered from the CAR data system and linked with vehicle dataset a unique identifier (e.g., Crash number). The resulting dataset with crash, vehicle and person information from CAR data system provided detailed information about the crash, vehicle and person characteristics involved with work zone crashes in Florida. The linked dataset with 41,894 observations was filtered for single-vehicle involved in work zone crashes, which resulted in a total of 8,430 observations. The single-vehicle work zone related crashes were further filtered for contributing circumstance from road geometry where work zone (Work Zone = 4) was coded with 2,133 and the work zone non-geometry (None =1) with 5,216 observations. The work zone related crashes were determined and coded in the crash form based on the discretion of the police officers investigating at the crash scene. Moreover, their training, experiences, and evidence found at the crash scene in work zones, the determination of Geometry Factors (work zone geometry) and Non-Geometry Factors (non-work zone geometry) was coded and stored in the crash database. This determination could be subjected to the extent of information-available within the scope of the investigation.

The available crash data provides information on crash attributes (for example, year, month, time, day, district, county, roadway class, road surface, weather and light condition, type of work zones, area inside work zones, lane with, shoulder with, median width, location of harmful event, traffic volume, percent of truck volume, and so on), vehicle characteristics (for example, type of vehicle, maneuvering, and most harmful events, and so on), driver attributes (age, gender, usage of safety equipment's, influence of alcohol, drug, driving action prior to crash, and so on). In this analysis, the major focus on estimating severity models to assess the factors leading to work zone geometry crashes from and work zone non-geometry crashes involving single-vehicle reported in Florida. More importantly, this detailed dataset characterizing the work zone crashes by severity can be used to understand any possible risk that may likely to vary between two scenarios: work zone geometry and work zone non-geometry involving single-vehicle in work zone related crashes.Table A1 (supplementary material) presents the descriptive statistics, including mean and standard deviation, for the significant variables identified in both the geometry-related and non-geometry-related factors models. These statistics offer a comprehensive overview of the key parameters under consideration.

Methodology

The study of crash-related injury severity has been approached from various angles, employing a range of discrete outcome models, including ordered logit/probit models, multinomial logit models, dual-state multinomial logit models, nested logit models, latent-class logit models, mixed (random parameters) logit models, Markov-switching models, and more. Recognizing the potential for unobserved heterogeneity within the data, recent research has increasingly turned to methodologies accounting for this variability. These methodologies include random parameter approaches (Venkataraman et al. 2013; Islam and Hernandez 2013a, 2013b, 2016), latent class models (Xiong and Mannering 2013; Behnood et al. 2014; Yasmin et al. 2014), a fusion of both (Islam and Mannering 2021), and consideration of heterogeneity in means and variances (Hang et al. 2022; Islam 2022a, 2022b, 2023a, 2023b, 2024a; Islam and Bertini 2023; Islam et al. 2020; Islam and Mannering 2020, 2021; Islam and Pande 2020; Nasrollahzadeh et al. 2021). Table A2 (supplementary material) presents some of the methodologies used in the work zone safety studies (Ashqar et al. 2021; Gupta et al. 2021; Hang et al., 2022; Islam 2022a, 2022b; Islam et al. 2020; Nasrollahzadeh et al. 2021; Osman et al. 2018).

In this specific investigation, this study adopts a random parameters logit model. This model is designed to accommodate potential heterogeneity in both the means and variances of the random parameters, offering a robust solution for addressing unobserved heterogeneity. In this study, the notion of "work zone" encompasses special road section where work zone design (including work configuration with detailed physical dimension) and operational aspect under the roadway factors contribute to work zone related crashes. On the other hand, "none" encompasses the non-geometry factors that characterize human factors or driver actions and also contribute to work zone related crashes.This modeling journey begins with the formulation of a function that determines injury severity, as outlined in Equation (1):

$$S_{kn} = \boldsymbol{\beta}_k \mathbf{X}_{kn} + \varepsilon_{kn} \tag{1}$$

where S_{kn} is an injury severity function determining the probability of driver injury severity outcome k in work-zone crash n, $\mathbf{X}_{kn}$ is a vector of explanatory variables that affect work-zone injury severity level k, $\boldsymbol{\beta}_k$ is a vector of estimable parameters, and ε_{kn} is the error term. If this error term is assumed to be generalized extreme value distributed, a standard multinomial logit model results as in (Washington et al. 2011):

$$\mathrm{P_n}\left(k\right) = \frac{EXP\left[\boldsymbol{\beta}_k \boldsymbol{X}_{kn}\right]}{\sum_{\forall K} EXP\left[\boldsymbol{\beta}_k \boldsymbol{X}_{kn}\right]} \tag{2}$$

where $P_n(k)$ is the probability that work-zone crash n that will result in driver-injury severity outcome k, and K is the set of three possible injury severity outcomes. To allow the possibility of one or more parameter estimates in the vector $\boldsymbol{\beta}_i$ varying across crash observations, Equation (2) can be rewritten as in (McFadden 1981; Train 2009):

$$\mathrm{P_n}\left(k\right) = \int \frac{\mathrm{EXP}\left(\boldsymbol{\beta}_k \mathbf{X}_{kn}\right)}{\sum_{\forall K} \mathrm{EXP}\left(\boldsymbol{\beta}_k \mathbf{X}_{kn}\right)} f\left(\boldsymbol{\beta}_k \mid \boldsymbol{\varphi}_k\right) d\boldsymbol{\beta}_k \tag{3}$$

where $f(\boldsymbol{\beta}_k|\boldsymbol{\varphi}_k)$ is the density function of $\boldsymbol{\beta}_k$ and $\boldsymbol{\varphi}_k$ is a vector of parameters describing the density function (mean and variance), and all other terms are as previously defined.

To account for the possibility of unobserved heterogeneity in the means and variances of parameters, let $\boldsymbol{\beta}_{kn}$ be a vector of estimable parameters that varies across crashes defined as in (Islam 2021, 2022a, 2022b, 2023a, 2023b, 2024a; Islam and Bertini 2023; Islam et al. 2020; Islam and Mannering 2020, 2021; Islam and Pande 2020):

$$\boldsymbol{\beta}_{\mathrm{kn}} = \beta + \Theta_{kn} \mathbf{Z}_{\mathrm{kn}} + \sigma_{kn}\, EXP\left(\Psi_{kn} \mathbf{W}_{kn}\right)\, v_{kn} \tag{4}$$

where β is the mean parameter estimate across all work-zone crashes, $\mathbf{Z}_{kn}$ is a vector of crash-specific explanatory variables that captures heterogeneity in the mean that affects work-zone injury severity level k, $\boldsymbol{\Theta}_{kn}$ is a corresponding vector of estimable parameters, $\mathbf{W}_{kn}$ is a vector of work-zone crash-specific explanatory variables that captures heterogeneity in the standard deviation σ_{kn} with corresponding parameter vector Ψ_{kn}, and v_{kn} is a disturbance term.

With these parameters expertly estimated, this study computed marginal effects to gauge the impact of explanatory variables on injury severity probabilities. The marginal effect provided insight into how a one-unit increase in an explanatory variable influences injury outcome probabilities in both scenarios

Estimated model results

For a deeper understanding of the findings, this study presented the outcomes of the mixed logit models with heterogeneity in both mean and variance. These results, based on an extensive sampling of 1,000 Halton draws, are thoughtfully compiled in Table A3 (supplementary material) for geometry-related factors and in Table A4 (supplementary material) for non-geometry-related factors. This study also included the average marginal effects in these tables, providing you with a clear and insightful perspective on the implications of this research.

This study conducted rigorous statistical testing to ascertain the presence of significant differences between geometry-related and non-geometry-related factors concerning driver injury severity data. This was confirmed through a series of likelihood ratio tests.

The first test, based on a model estimated using all available work-zone-related data spanning from 2012 to 2017, utilized the following equation:

$$\chi^2 = -2\begin{bmatrix} LL\left(\beta_{Work\ Zone\ related\ crash}\right) - LL\left(\beta_{Geo-metry\ related\ crash}\right) \\ -LL\left(\beta_{Non-geomtry\ related\ crash}\right) \end{bmatrix} \tag{5}$$

In this equation, $LL(\beta_{Work\ Zone\ related\ crash})$ represents the log-likelihood at the convergence of the model using all work-zone-related crash data from 2012–17, $LL(\beta_{Geo-metry\ related\ crash})$ denotes the log-likelihood at the convergence of a model based on work-zone road factors (2012–17), and $LL(\beta_{Non-geomtry\ related\ crash})$ signifies the log-likelihood at the convergence of a model focused on non-geometry factors. The model estimates yielded a χ^2 value of 1551.706, which follows a χ^2 distribution with 17 degrees of freedom (equivalent to the number of parameters found to be statistically significant in the model using all the data from 2012–17). This result grants us a confidence level of 99.99% to confidently reject the null hypothesis that parameters are equal in the geometry-related and non-geometry-related scenarios.

To further test for statistical differences, this study conducted two additional likelihood ratio tests as described in (Islam 2023a):

$$\chi^2 = -2\left[LL\left(\beta_{w_1 w_2}\right) - LL\left(\beta_{w_1}\right)\right] \tag{6}$$

In this equation, $LL(\beta_{w_1 w_2})$ represents the log-likelihood at convergence of a model containing parameters from non-geometry-related work-zone crash data (W_2), while using data from geometry-related work-zone crashes (W_1). On the other hand, $LL(\beta_{w_1})$ denotes the log-likelihood at convergence of the model using geometry-related work-zone crash data (W_1) but with parameters no longer restricted to those from non-geometry-related work-zone crashes (W_2).

Applying the parameters from the non-geometry-related work-zone crash model to the geometry-related work-zone data yielded an χ^2 value of 28.812. With 18 degrees of freedom, this results in a χ^2 confidence level of over 94.9%, allowing us to confidently reject the null hypothesis that the two scenarios are the same. Likewise, when the test was reversed, applying parameters from the geometry-related work-zone model to non-geometry-related work-zone data, an χ^2 value of 113.476 was obtained. With 17 degrees of freedom, this equates to a χ^2 confidence level of more than 99.9%, reaffirming the ability to reject the null hypothesis that the two scenarios are identical.

Table A3 and A4 (supplementary material) present the detailed model estimation results for work-zone crashes attributed to geometry-related and non-geometry-related factors, respectively. Additionally, Table A5 (supplementary material) provides invaluable insights into the marginal effects for these two scenarios. It is noteworthy that in both models, the constant term specific to minor injury was identified as a random parameter with heterogeneity in both mean and variance, leading to statistically significant standard deviations (random parameters).

For the work-zone geometry-related factors (as shown in Table A3), it is observed that the mean of the constant-term parameter decreased when traffic volume on that segment fell below 40,000 vehicles per day. In contrast, the variance of the parameter increased when truck volume accounted for 10% to 20% of the total segment volume. For the work-zone non-geometry-related factors (as indicated in Table A4), the mean of the constant-term parameter increased when the first harmful event occurred on the shoulder, and the variance increased when the harmful event involved a roadside fixed object.

It is important to highlight that the random parameter variable specific to minor injury crashes was found to follow a normal distribution and was statistically significant compared to other distributions considered, such as uniform or triangular distributions. In the work-zone geometry-related model, the constant specific to minor injury crashes had a mean of −3.149 and a standard deviation of 3.206. This suggests that, with a normal distribution, this variable is positive for 16.3% of the observations, thereby increasing the likelihood of minor injury crashes. Conversely, in the work-zone non-geometry-related model, the constant specific to minor injury crashes had a mean of −3.440 and a standard deviation of 3.912. In this case, the normal distribution indicates that this variable is positive for 49.8% of the observations, thereby increasing the likelihood of minor injury crashes.

These findings not only underscore the significance of the random parameter variable but also provide meaningful insights into the distribution patterns and their respective impacts on minor injury crashes. The following subsection emphasizes the significant impact of both geometric and non-geometric factors on the severity of injuries in work zone crashes, by examining the magnitude of their marginal effects on the outcome.

Spatial characteristics

In District 7, which includes Hillsborough, Pinellas, Pasco, Citrus, and Hernando counties, it was observed an alarming increase in severe injury crashes. The average marginal effects were 0.006 for geometry-related factors and 0.009 for non-geometry-related factors. This trend echoes findings from a previous study (Islam et al. 2020). The study reveals that the likelihood of severe driver injuries is 1.4 times higher as a result of geometry-related factors when compared to non-geometry-related factors in District 7. Conversely, District 6, covering Miami-Dade and Monroe counties, exhibited a lower likelihood of severe and minor injury crashes in both scenarios. District 5, comprising Brevard, Flagler, Lake, Marion, Orange, Osceola, Seminole, Sumter, and Volusia counties, had a higher likelihood of severe and minor injury crashes, with an average marginal effect of 0.004 in the non-geometry-related factors model. Figure B1 below shows the relative position of FDOT districts.

Vehicle characteristics

Passenger cars and pickup trucks emerged as statistically significant factors in the geometry-related factors model. Passenger cars were found to decrease the likelihood of severe and minor injury crashes, with average marginal effects of 0.01 and 0.02, respectively. However, they increased the likelihood of crashes resulting in no injuries, with an average marginal effect of 0.03. In contrast, pickup trucks were associated with an increased likelihood of severe injury crashes but a decreased likelihood of minor injury crashes in work zones in both scenarios. Similar results were also found in past studies (Islam et al. 2020; Islam 2022a).

Environmental characteristics

Rainy weather conditions were found to elevate the risk of minor and no injury crashes, with average marginal effects of 0.005 and 0.001, respectively, in the geometry-related factors model. This observation aligns with results from previous studies (Tarko et al. 2011; Osman et al. 2018; Islam et al. 2020) and suggests that drivers exercise caution when navigating work zones in inclement weather conditions. On the other hand, daylight conditions were associated with an increased likelihood of crashes resulting in no injuries. This is likely because drivers tend to be more alert and vigilant in well-lit environments within work zones.

Geometric characteristics

Lane closures within work zones were linked to a heightened likelihood of severe injury crashes and a reduced likelihood of minor injury crashes in the non-geometry-related factors model. This result was consistent with previous studies (Osman et al. 2018; Islam 2022b). In contrast, work on the shoulder and median areas increased the likelihood of severe injury crashes, with average marginal effects of 0.017 and 0.013 for geometry-related and non-geometry-related models, respectively. This is because work on the shoulder or median occurs alongside operational traffic in all lanes, potentially leading to drivers being unaware of ongoing work and increasing anxiety due to limited room for corrections in case of errors. This result is consistent with other studies (Islam et al. 2020; Islam 2022a). The study indicates that the risk of severe driver injuries is 1.3 times higher in work zones configured for shoulder and median work, attributed to geometry-related factors, compared to non-geometry-related factors. Furthermore, a substantial shoulder width, ranging from 1.83 to 3.05 meters (6–10 feet), increased the likelihood of both severe and minor injury crashes. This finding is consistent with previous studies (Tarko et al. 2011; Islam et al. 2020; Islam 2022a). Additionally, a transition area within the work zone amplified the likelihood of minor and no injury crashes in work-zone geometry-related crashes.

Crash characteristics

The location of the first harmful event on the right shoulder raised the likelihood of severe and minor injury crashes by 0.011 in the non-geometry-related model. However, in the geometry-related model, it increased the likelihood of severe injury crashes, with an average marginal effect of 0.010. The study highlights a 1.3 times higher risk of severe driver injuries in incidents occurring on the right shoulder, primarily linked to non-geometry-related factors, when compared to geometry-related factors. Harmful events, such as collisions with roadside fixed objects, heightened the likelihood of both severe and minor injury crashes, with an average marginal effect of 0.005 in the non-geometry-related model. These harmful events occurred on the right shoulder, median, and off-road locations. These results are consistent with a previous study (Islam et al. 2020) although some contrasting results were found for heavy vehicles crashes in work zones (Islam 2022b).

Traffic characteristics

When truck volume accounted for less than 10% of total traffic volume, there was a noticeable increase in minor injury crashes, with average marginal effects of 0.026 and 0.016 for the geometry-related and non-geometry-related models, respectively. This finding mirrors the results of prior studies (Khattak et al. 2002; Tarko et al. 2011; Islam et al. 2020; Islam 2022b). The study emphasizes a 1.8 times higher risk of minor driver injuries associated with low truck volume (less than 10% of total traffic volume), primarily attributed to geometry-related factors, in comparison to non-geometry-related factors.

Driver characteristics

Drivers below the age of 30 exhibited an increased likelihood of minor injury crashes, with an average marginal effect of 0.018 for non-geometry-related work-zone crashes. This age group may be associated with riskier driving behaviors, such as speeding or distractions. Negligent or careless driving behaviors were also linked to an increased likelihood of minor injury crashes, with average marginal effects of 0.027 and 0.016 for the geometry-related and non-geometry-related models, respectively. These results are consistent with the findings from previous studies (Islam et al. 2020; Islam 2022b) and distraction for passenger cars (Islam 2024b), although a contrasting result was found in another study (Islam et al. 2020). The study underscores a 1.6 times higher risk of minor driver injuries linked to negligent driving, primarily due to geometry-related factors, as opposed to non-geometry-related factors.

Discussion

Using single-vehicle crash data from Florida spanning 2012 to 2017, this study employed a random parameter logit model, incorporating heterogeneity in both mean and variance, to explore the disparities in driver injury severities in work-zone crashes attributed to geometry-related and non-geometry-related factors. This study considered three injury levels: severe (including fatal and incapacitating), minor (encompassing non-incapacitating and possible injuries), and no injuries. Although the determination of geometry and non-geometry factors by police officers could be subjective and may be misclassified due to limited information extracted from all possible sources, the mixed logit with heterogeneity in means and variances for these two different categories of datasets uncovered interesting results with statistical significance.

The model results encompassed an array of factors, including spatial characteristics, vehicle characteristics, environmental conditions, geometric features, crash attributes, traffic patterns, and driver traits. These factors are intricately connected with human factors, particularly driver behaviors and characteristics, playing a pivotal role in work-zone crashes tied to geometric and non-geometric attributes.

While some consistencies exist between geometry-related and non-geometry-related factors, eight out of the seventeen statistically significant variables were consistent between both. Moreover, it is essential to note that likelihood ratio tests demonstrated that estimated parameters differed for geometry-related and non-geometry-related factors regarding driver injuries in Florida work-zone crashes during the 2012–2017 analysis period.

The findings revealed intriguing insights, such as, the significance of traffic volume and the location of harmful events, and their varying impact across geometric and non-geometric contexts. These insights provide valuable input for designing safer work zones and improving the understanding of how different factors influence injury outcomes.

The disparities in the magnitude and the factors influencing geometry- and non-geometry-related work-zone crashes hold substantial significance. This is especially true because the impact of crash, traffic, geometry, temporal, spatial, vehicle, and driver characteristics differs significantly between these two scenarios. These complex interactions extend across geographical regions, as exemplified by District

6 and District 7, specific work-zone attributes such as shoulder and median work, distinctive vehicle characteristics like passenger cars and pickup trucks, instances of negligent or careless driving, and low truck volume (defined as truck volume below 10% of total traffic).

Furthermore, there were additional characteristics specific to non-geometry-related work-zone crashes, including driver age below 30 years, adverse environmental conditions like rain, the location of harmful events (on the right shoulder or involving roadside objects), and the nature of work zones (e.g., lane closures). On the flip side, there are characteristics distinct to geometry-related work-zone crashes, such as the location of the work zone (including transition areas), the presence of a large shoulder (typically measuring 1.83–3.05 m (6–10 feet)), environmental attributes like daylight conditions, and the absence of workers at the site.

This research study, characterized by its statistical rigor, holds significant importance in translating its insightful findings into practical applications. This is particularly crucial because work-zone-related crashes continue to require substantial attention, both in Florida and nationally. Despite acknowledging the inherent uncertainties in the model estimation, the study's results offer actionable insights for various stakeholders, including safety professionals, policymakers, and law enforcement agencies. These insights are especially valuable for those involved in work-zone management and data administration, aiding in the identification of relevant factors contributing to work-zone crashes.

The implementation of the study's findings holds particular relevance for stakeholders in the realm of emerging technologies, such as in-vehicle or smart work zone applications (Islam 2022b). These technologies serve as vital tools in advancing safety within work zones, aligning seamlessly with Florida's Strategic Highway Safety Plan, which rightly recognizes work zone safety as a pivotal area of emphasis.

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