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Impact of speed on injury severity in single-vehicle run-off-road crashes: Insights from partially temporal constrained modeling approach

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ABSTRACT

Single-vehicle run-off-road crashes accounts for approximately 35% of all the traffic fatalities in the U.S during the period of 2019–2021. This paper explores the association between driving speed and injury severity outcomes of single-vehicle run-off-road crashes. The single-vehicle run-off-road crash data from 2019 to 2021 on Interstate freeways in Florida are utilized, and categorized into periods of pre-, during-, and post-COVID-19 pandemic. The partially constrained temporal and temporal unconstrained random parameters logit models are developed considering three injury severity outcomes: no injury, minor injury and serious injury/fatality. Multiple variables in terms of driver, vehicle, roadway, environmental, crash, and temporal attributes are observed to significantly affect the injury severity. Moreover, temporal instability and transferability issues are validated through likelihood ratio test and out-of-sample prediction. In the partially constrained models, numerous variables such as indicators of new vehicle, male driver, and restraint-protected driving consistently yield identical parameter values across all periods, whereas various variables clearly illustrate the distinct differences across the three periods and three speed intervals. The marginal effects in the unconstrained models also display the obvious differences across three periods and three speed intervals. Moreover, the findings corroborate the increased risk outcomes linked to larger speed differences and the COVID-19 pandemic period. These results provide better understanding of the risk mechanisms underlying run-off-road crashes and furnish valuable direction for the formulation of effective safety interventions.

1. Introduction

In 2021, there were approximately 1.19 million road traffic deaths worldwide, which equates to 15 deaths per 100,000 people in road traffic crashes (World Health Organization, 2023). Specifically, the crashes that occur due to a vehicle leaving the travel lanes of the road are generally referred to as run-off-road crashes. Approximately 35 % of all the fatalities were the single-vehicle run-off- road crashes resulting in 12,718 fatalities per year in the United States during the period of 2019–2021 (National Highway Traffic Safety Administration, 2021, 2022, 2023). The reason might be that when a vehicle runs off the road while traveling at high speed on a highway, it typically collides with a fixed object at a very high velocity, such as a tree or guardrail. The impact is severe due to the kinetic energy involved, resulting in significant damage to the vehicle and serious injuries or fatalities. In contrast, other types of crashes, such as two-vehicle collisions on urban roads, usually involve vehicles traveling at low speeds, especially at intersections, where speeds are often limited by traffic lights and other traffic control. As a result, the force of impact is lower, leading to relatively minor injuries and damage. Similarly, rear-end collisions, which typically occur at low speeds or in congested traffic, tend to cause minor physical injuries and vehicle damage due to the reduced speed. Additionally, when single-vehicle run-off-road crashes occur at night, in extreme weather conditions or in remote areas, it may not be quickly discovered, leading to delayed rescue efforts and further exacerbating the severity of the crashes (Abdel-Aty and Ding, 2024). Therefore, relevant countermeasures such as lane departure warning and the design consistency of road geometry have been developed to reduce the frequency and the injury severity of run-off-road crashes (Khan et al., 2023; Nilsson et al., 2018). Moreover, there is also a large body of research investigating various potential causal attributes of run-off-road crashes, especially in the injury severity modeling and analysis domain.

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Road traffic safety generally analyzes the related factors of crashes from the aspects of driver-vehicle–road-environment. Similarly, factors involving these aspects were explored for the association with the injury severity of run-off-road crashes, including driver-related variables (e.g., age), vehicle-related variables (e.g., vehicle type), road-related variables (e.g., speed limit), environment-related variables (e.g., weather conditions). Among these, speeding is one of the critical driver-related factors in fatal single-vehicle run-off-road crashes (Liu and Subramanian, 2009). Meanwhile, a growing body of research has revealed the effects of driving speed on crashes from the perspective of average speed at the road section level, as reported by Nilsson (1981, 2004). Nilsson (1981, 2004) proposed using quadratic, cubic, and fourth power functions to describe the impact of speed changes on injury, serious injury, and fatal outcomes. Furthermore, existing studies have stated that speeding is associated with the more severe injury outcome of run-off-road crashes. For instance, Khan et al. (2023) found that speeding increased serious and fatal injuries outcomes by 0.105 and 0.027 units of run-off-road crashes respectively. It can be seen that different speeding values will cause the crash injury severity to change significantly, so the run-off-road crash severity modeling cannot ignore the non-transferability between different speeding intervals. However, most studies explored more about the correlation between speeding/no speeding and the severity of run-off-road crashes (Khan et al., 2023; Lee and Mannering, 2002; Al-Bdairi and Hernandez, 2017). These studies integrated speeding variables and other related variables at the same level to construct models, but ignore the natural connection between run-off-road crashes and speeding, which may lead to analysis bias and are not sufficient to reflect the significant impact of speeding in run-off-road crashes. And this natural connection is that excessive speed increases the braking distance and increases the risk of the vehicle running out of the lane, thereby resulting in a higher likelihood of serious injury of run-off-road crashes (Khan et al., 2023; Gong et al., 2017). Otherwise, the unobserved heterogeneity caused by complex interactions among the various variables, and missing factors, would cause biased and inconsistent parameter estimates (Mannering et al., 2016; Gong et al., 2022; Wang, et al., 2022a; Ding et al., 2024). Therefore, it is necessary to further refine the speeding intervals and conduct injury severity modeling of run-off-road crashes by addressing unobserved heterogeneity. Meanwhile, the non-transferability of the run-off-road crashes between speeding intervals also can be demonstrated and deeply explained.

In addition, Mannering (2018) explores potential causes of temporal instability in crash severity analysis in detail, and a large body of recent work confirms that the influence of variables that determine injury severity may be unstable over time (Cui et al., 2024; Islam et al., 2020; Li et al., 2021; Se et al., 2021; Wang et al., 2023). The temporal instability will result in potential bias in the estimation results of the proposed model in different periods, and ignoring potential temporal instability may adversely affect the inferences drawn by the model and the ability to evaluate the effectiveness of security countermeasures (Mannering, 2018). Meanwhile, the temporal instability in model parameters is generally attributed to changes in driver behavior and driving pattern (Wang et al., 2019). Similarly, the lockdowns brought about by the COVID-19 pandemic have resulted in dramatic changes in transportation pattern and driving behavior, thereby posing new challenges to traffic safety. The National Center for Statistics and Analysis in the United States estimates that vehicle miles traveled (VMT) in the first half of 2020 decreased by 16.6 % compared with the same period in 2019 (Vanlaar et al., 2021). The decreased traffic volume and the reduced law enforcement create a driving environment with more opportunities for speeding, alcohol-impaired, drug-impaired driving (Thomas et al., 2020). For instance, the average speeding during peak hours increased by 10-15mph in California during March and Mayin in 2020 (Hughes et al., 2023). Especially, Doucette et al. (2021) reported that fatal single-vehicle crashes increased by 4.1 times, although motor vehicle collisions and VMT reduced during the 2020 stay-at-home period. Therefore, COVID-19 has caused driver behavior to deviate from historical trends, so it is worthwhile to account for temporal shifts in single-vehicle run-off-road crash severity modeling to ensure model transferability, thereby to have a deep understanding of the impact of relevant variables on single-vehicle run-off-road crashes during different periods of COVID-19.

In summary, existing research ignored to consider the relationship between different speeding intervals and single vehicle run-off-road crashes, and the temporal instability of injury severity of run-off-road crashes caused by COVID-19. To address the existing gaps in knowledge, this study aims to achieve the following objectives: (1) Explore in detail the association between over speeding and injury severity outcomes in single-vehicle run-off-road crashes compared with the non-speeding behavior, three different speeding intervals are defined to conduct the modeling and analysis; (2) Combine the single vehicle run-off-road crashes data before, during and after COVID-19 to analyze the temporal stability of the parameters in the proposed model; (3) Evaluate the performance of partially constrained temporal and unconstrained random parameter logit models, and analyze the stable and unstable indicators which influence the injury severity of run-off-road crashes.

2. Literature review

2.1. Review on related findings concerning the run-off-road crashes

Previous studies explored multiple factors associated with run-off-road crashes severity outcomes, including driver characteristics, environmental characteristics, roadway attributes, vehicle, traffic characteristics. Table 1 summaries the significant variables and corresponding influence on run-off-road crashes severity from the four dimensions. As for the speed, most studies have focused on the relationship between whether the driver is speeding on the different injury severity outcomes in run-off-road crashes, and it has been confirmed that speeding will increase the likelihood of more serious injury outcomes (Khan et al., 2023; Lee and Mannering, 2002; Ding et al., 2024. As explained above, there is a strong positive relationship between driving speed and crashes. Based on this theory proposed by Nilsson (1981, 2004), Fig. 1 shows the percentage increase in crashes of injury severity outcomes, with 50 km/h as the reference speed and incremental changes at 1 km/h intervals. From Fig. 1, we can first find that as the speed increment increases, the crash rates of all the injury severity outcomes gradually increase compared to the reference speed. Second, at the same speed, the crash rates of injuries, serious injuries, and fatal outcomes also gradually increase. Therefore, in the injury severity analysis of run-off-road crashes, we cannot only focus on whether the driver is speeding. Instead, we need to build the injury severity model of run-off-road crashes under different speeding intervals, so as to further deeply understand the impact of speeding on injury severity outcomes.

2.2. Review on temporal stability of crash injury severity model

A large amount of research has gradually focused on the temporal stability of parameters in accident severity models, thereby developing more accurate models and proposing road safety countermeasures that are more responsive to time shifts. Mannering (2018) reported that effects of explanatory variables may be unstable over time, based on previous research in fields such as neuroscience, psychology, cognitive science, and economics. This conclusion has also been confirmed in multiple studies, so temporal stability is an important consideration in crash injury severity model.

For the temporal stability analysis of parameters, the transferability test includes encompassing global and pairwise tests, which are used to estimate parameter transfer and determine the critical factors that present differences in different periods (Washington et al., 2020). Moreover, out-of-sample prediction can also be used to evaluate temporal instability. This method uses a set of estimated parameters to develop

Table 1
A summary of important variables on the injury severity of run-off-road crashes.

Variables name	Findings
Driver characteristics	
Age	The age more than 75 years (Khan et al. 2023) and young (age < 30) and middle-aged (30 < age < 50) (Yu et al 2020b) are positively contribute to higher run-off-road crashes severity outcome.
Gender	Male drivers were likely to result in the severe or fatal injuries. (Montella et al., 2021; Yu et al., 2020b). However, Al-Bdairi and Hernandez (2020) found that female drivers were more likely to be involved in severe injuries on rural roadways.
Restraint	Non-use of seat belt increased the likelihood of fatalities or incapacitating injuries (Gong et al., 2017; Al-Bdairi and Hernandez, 2017).
Speeding	Speeding was reported to increase crash severity (Khan et al., 2023; Lee and Mannering, 2002; Al-Bdairi and Hernandez, 2017).
Fatigued driving	Fatigued driving were connected with severe and fatal crashes in run-off-road crashes (Al-Bdairi and Hernandez, 2017; Yu et al., 2020b).
Alcohol-impaired	Alcohol-impaired driving had positive effect on higher crash severity outcome (Khan et al., 2023; Lee and Mannering, 2002; Yu et al., 2020b).
Maneuver	Khan et al. (2023) found that driving straight increases the likelihood of minor or severe injuries.
Environmental characteristics	
Weather condition	Clear or cloudy condition increased the possibility of more serious injury (Lee and Mannering, 2002; Montella et al., 2021; Yu et al., 2020b).
Lighting condition	Run-off-road crash severity is more likely to be a more severe injury outcome under dark lighted conditions (Yu et al., 2020b).
Roadway attributes	
Roadway geometry	Run-off-road crashes occurred at curves were more likely to lead to serious outcome (Al-Bdairi and Hernandez, 2017; Gong et al., 2017; Yu et al., 2020b). However, straight road sections were reported to increase the likelihood of serious outcome compared with on curved road sections (Khan et al., 2023).
Speed limit	The posted speed limit of 110 km/h or more (Khan et al. 2023) and the speed limits exceeding 85 km/h (Lee and Mannering, 2002) are more likely to result in severe and fatal injuries. However, driving on highways with speed limits between 30 mph and 60 mph was found to be more likely to result in severe injuries to older drivers than on highways with speed limits above 60 mph (Gong et al., 2017).
Area	Yu et al (2020) found that urban area is more likely to result in more severe injury.
Roadway surface condition	Gong et al. (2017) found that run-off-road crashes occurred on snow/ice/wet roadway condition are more likely to result in property damage only outcome for young and middle-age drivers, but severe or fatal injuries for old drivers. However, dry roads were reported to be associated with an increase in severe and fatal crashes (Montella et al., 2021; Yu et al., 2020b).
Vehicle characteristics	
Vehicle type	Young and middle-aged drivers are more likely to be involved in severe or fatal injuries while driving a sport utility vehicle (SUV) or a van (Gong et al., 2017). Passenger car, pick-up and SUV increased the possibility of property damage only outcome (Yu et al., 2020b).
Traffic characteristics	
Traffic volume	The increase of AADT decrease the likelihood of severe crash outcome (Khan et al., 2023). Similarly, higher AADT were likely to result in fatal injuries for young drivers (Gong et al., 2017).
Temporal characteristics	
Season	Al-Bdairi and Hernandez (2017) found that run-off-road crashes involving a large truck occurred between January and April are more likely to result in no injury outcome.
Weekdays	Run-off-road crashes occurred on weekends are less likely to result in disabling injury/fatality (Lee and Mannering, 2002).
Time of day	Lee and Mannering (2002) found that day time increased the likelihood of higher injury severity. However, driving in the dark environment was reported to contribute the likelihood of non-incapacitating injuries for young drivers (Gong et al., 2017).

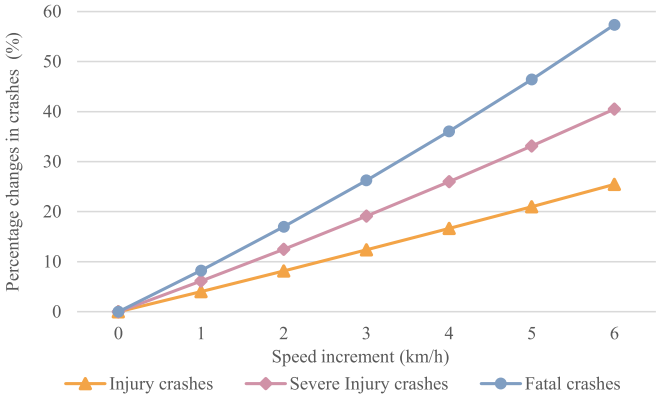


Fig. 1. Percentage changes in crashes with the speed variation (reference speed is 50 km/h based on power model proposed by Nilsson, 1981, 2004).

the prediction model in different periods, and has gradually been widely applied in recent research (Alnawmasi and Mannering, 2023; Alogaili and Mannering, 2022; Wang et al., 2024b). Meanwhile, the partially constrained method is proposed to resolve temporal instability by aggregating crashes across all periods and defining variables for each period to determine whether the parameters therein will show significant changes over time (Alnawmasi and Mannering, 2023; Wang et al., 2024; Zhang et al., 2024). In addition, the temporal stability is considered in various types of crash severity modeling, including alcohol-impaired crashes (Song et al., 2021; Yan et al., 2021a), work-zone crashes (Islam et al., 2020), run-off-road crashes in 2014–2017 (Yu et al., 2021, 2020), single-vehicle crashes (Behnood and Mannering, 2015; Islam and Mannering, 2021; Se et al., 2021; Yan et al., 2022; Yu et al., 2020b; Ding et al., 2024; Wang et al., 2023), rear-end crashes (Islam and Mannering, 2021; Wang et al., 2022c), pedestrian-vehicle crashes (Li et al., 2021; Zamani et al., 2021), motorcycle or bicycle crashes (Alnawmasi et al., 2024; Hosseini et al., 2022; Wang et al., 2022b), intersection crashes (Alnawmasi et al., 2024; Wang et al., 2021), etc.

In addition, as Mannering (2018) emphasized, temporal stability analysis is quite valuable in revealing that factors related to injury severity shift or consistency in different periods, which can analyze the shift of driver behavior, environment, and traffic pattern, thereby enhancing before-and-after safety assessments. The COVID-19 pandemic has been demonstrated to have a significant impact on drivers' speeding behavior in existing studies, but the potential association between the COVID-19 outbreak and injury outcomes in run-off-road crashes remains to be explored. Therefore, it is necessary to explore the shifts in injury outcomes of run-off-road crashes before, during and after COVID-19, which will contribute to new traffic safety strategies under major public health emergencies.

3. Data description

The data source of this study is the three-year run-off-road crashes collected from Interstate, State and U.S. freeways in Florida from

January 1st, 2019 to December 31st, 2021. Based on the three road classes and in order to make the analysis more accurate, we filtered the crash data with the speed limit of not less than 45mph and the estimated driving speed of not less than 25mph to form the dataset of this study (Kobelo et al., 2008).[1] This data records the severity of single vehicle run-off-road crashes and related demographics, vehicle, environmental, roadway and temporal information. Furthermore, the police applied a variety of methods including skid mark analysis, stopping distances, vehicle data recorders, vehicle damage assessments and time-distance analysis to estimate the vehicle's speed at the time of the collision[2] (Brach et al., 2022; Knill and Fawcett, 1981).

The crash dataset records the demographic, vehicle and road information, as well as environmental and temporal characteristics of run-off-road crashes. Moreover, the driving speed at the time that crashes occurred, and the injury severity outcomes were also estimated and identified by the police to provide a more comprehensive crash analysis. Based on the estimated speed at the time of the crash and speed limit, the speeding value (Δv) is calculated and divided into three intervals in this study: $\Delta v \leq 0$ mph, 0 mph $< \Delta v \leq 10$ mph, and $\Delta v > 10$ mph. This dataset includes a total of 34,463 single-vehicle run-off-road crashes, which contains four different driver injury severity categories: no injury, minor injury, serious injury, and fatality. Since fatality crashes account for a relatively low proportion of only 1.40 %, they are merged with serious injury crashes into a separate serious injury/fatality category. In addition, the Chi-square tests are conducted to ensure the validity and feasibility of dividing speeding values into the above three intervals in this study. As shown in the results of Table 2, it can be found that under the high confidence level (>99.99 %), the null hypothesis that the three injury severities of run-off-road crashes caused by different Δv intervals in the three periods are the same is rejected.

Table 2
Chi-square test result for the injury severity of run-off-road crashes caused by different Δv intervals.

Period	Δv intervals	No Injury	Injury	Serious injury/ Fatality	Total
Pre-COVID-19 (2019)	$\Delta v \leq 0$ mph	5995	2745	500	**9240**
	0 mph $\leq \Delta v \leq$ 10 mph	489	234	65	**788**
	$\Delta v > 10$ mph	163	134	82	**379**
	χ^2 test	**191.42 (4) [>99.99 %]**			
During-COVID-19 (2020)	$\Delta v \leq 0$ mph	7387	3031	558	**10,976**
	0 mph $\leq \Delta v \leq$ 10 mph	566	308	52	**926**
	$\Delta v > 10$ mph	222	183	92	**497**
	χ^2 test	**214.36 (4) [>99.99 %]**			
Post-COVID-19 (2021)	$\Delta v \leq 0$ mph	6661	2907	623	**10,191**
	0 mph $\leq \Delta v \leq$ 10 mph	557	295	71	**923**
	$\Delta v > 10$ mph	235	193	115	**543**
	χ^2 test	**220.71 (4) [>99.99 %]**			

Fig. 2 presents the proportional distribution of injury severity under three different speeding intervals. It is obvious that as the speeding value increases, the proportions of the two categories of injury and serious injury/fatality also gradually increase, although the frequency of crashes decreases. It shows that there is a positive correlation between speeding value and the percentage of injury, as well as the percentage of serious injury/fatality. Notably, there are 7.3 % and 14.9 % increases in the proportions of minor injury and serious injury/fatality in speeding interval of $\Delta v > 10$ mph, compared with non-speeding interval of $\Delta v \leq 0$ mph. In the meanwhile, the proportion of all injuries and fatalities (the total of the minor injury category and the serious injury/fatality category) exceeds 50 % on the condition of $\Delta v > 10$ mph. This phenomenon is consistent with the conclusion of existing studies that speeding increases the likelihood of the higher injury severity outcome of run-off-road crashes. Therefore, it is necessary to explore the relevant factors of run-off-road crash injury severity under different speeding intervals.

Furthermore, to analyze the proportion of crash injury severity from different speeding intervals and combined with different periods of the COVID-19 pandemic according to Table 2. First, the total number of run-off-road crashes that occurred in 2020 was the highest among the three periods of COVID-19. This also shows that although traffic volume decreased during the COVID-19 epidemic, the multi-vehicle interactive scenario decreased at the same time, and the percentage of single-vehicle run-off-road crashes increased. Second, on the condition of speeding interval of 0 mph $< \Delta v \leq 10$ mph, the proportion of all the injuries and fatalities have been increasing compared with pre COVID-19. Finally, on the condition of speeding interval of $\Delta v > 10$ mph, the crash frequency has also been increasing since the COVID-19 outbreak. Thus, this shows that since the COVID-19 pandemic outbreak, the injury outcome of run-off-road crashes became more serious to a certain extent, indicating the significant safety issues caused by COVID-19. Therefore, this observation suggests that more attention needs to be paid to road traffic safety since the COVID-19 outbreak, so as to further improve and develop more comprehensive strategies for road traffic safety.

Moreover, the descriptive statistics of the explanatory variables related to the run-off-road crash severity model are summarized in Appendix A, according to different speeding intervals and covering the pre, during and post COVID-19 pandemic, which includes driver, environment, vehicle, roadway, crash and temporal characteristics.

4. Methodology

Considering potential unobserved heterogeneity in explanatory variables in run-off-road crashes, this study adopts a random parameter logit model with heterogeneity in mean and variance to explore the severity of run-off-road crashes and explain unobserved heterogeneity under different condition. This method is widely applied in crash severity analysis (Hamed and Al-Eideh, 2020; Li et al., 2021; Yan et al., 2021b; Yu et al., 2020a; Zamani et al., 2021). Based on the above three categories of crash severity, the corresponding injury severity function can be defined as (Behnood and Al-Bdairi, 2020; Islam and Mannering, 2020):

$$U_{kn} = \beta_k \boldsymbol{X}_{kn} + \varepsilon_{kn} \quad (1)$$

where U_{kn} denotes the injury severity function that determines the probability of injury severity category k in crash n, $\boldsymbol{X}_{kn}$ denotes the vector of explanatory variables for run-off-road crash n associated with injury severity category k, β_k represents the vector of estimated parameters, and ε_{kn} is the disturbance term with the assumption of extreme value type I distribution.

Since the collected crash data are insufficient to fully represent the factors that affect crash injury severity, there is still unobserved het-

[1] By analyzing the data of this study, combined with actual driving conditions, and supported by (Kobelo et al., 2008), it can be found that the speed of the basic traffic flow is 40mph-45mph, and the speed limit is usually 5-7mph higher than the base free flow. Considering the need to retain as many data samples as possible, this study selected samples with speed limits not less than 45mph. At the same time, considering the traffic congestion, the driving speed of more than 25mph is also used as a condition for data selection.

[2] Taking skid marks analysis and parking distance approach as examples to specifically explain how the traveling speed is estimated: (1) Skid marks analysis uses a radar gun to measure the speed of the car at the beginning of the skid marks and a tape measure to measure the length of the skid marks, and further calculates the speed based on the mechanical formula (2) Parking distance approach is to measure the parking distance and friction resistance on site, with the reaction time, further to estimate the driving speed based on the corresponding mechanical formula.

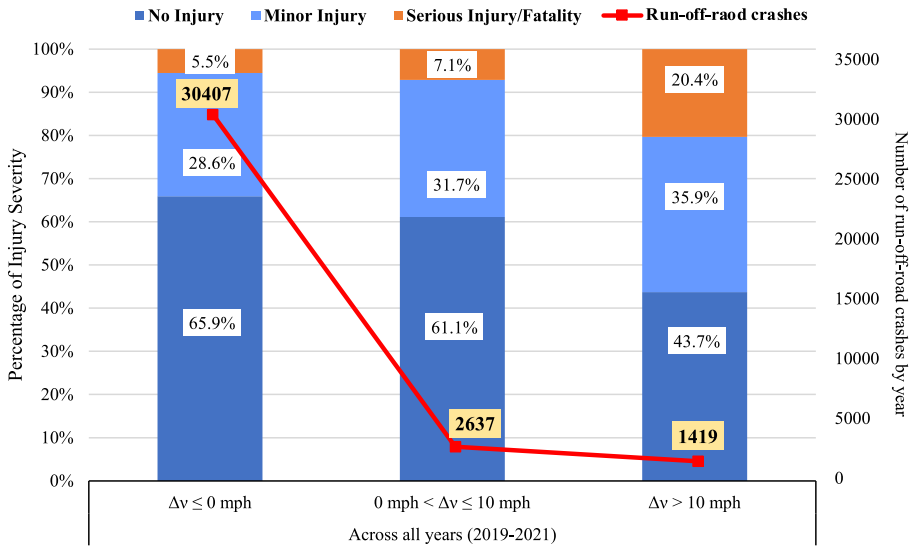


Fig. 2. Driver' injury severities of run-off-road crashes by different speeding intervals across all years.

erogeneity that will cause changes in the impact of observed variables on crash injury severity, and if heterogeneity is ignored, estimated models will be biased, leading to erroneous inferences (Mannering et al., 2016). To address the potential unobserved heterogeneity, β_{kn} is introduced to be the vector of estimated parameter that varies across observation (Al-Bdairi et al., 2020; Behnood and Mannering, 2019).

$$\beta_{kn} = \beta_k + \vartheta_{kn}\boldsymbol{Z}_{kn} + \sigma_{kn}\exp(\omega_{kn}\boldsymbol{W}_{kn})\upsilon_{kn} \tag{2}$$

where β_k represents the mean parameter estimated across all the run-off-road crashes, $\boldsymbol{Z}_{kn}$ is the vector of explanatory variables capturing heterogeneity in the mean for injury severity category k, ϑ_{kn} is the estimable parameters corresponding to $\boldsymbol{Z}_{kn}$, $\boldsymbol{W}_{kn}$ denotes the vector of explanatory variables capturing heterogeneity in the standard deviation σ_{kn}, ω_{kn} is the estimable parameters corresponding to $\boldsymbol{W}_{kn}$, and υ_{kn} is the disturbance term. With the potential unobserved heterogeneity allowed, the probability of injury severity category k to the crash n is written as (Al-Bdairi et al., 2020; Islam and Mannering, 2020):

$$P_n(k) = \int \frac{\exp(\beta_k \boldsymbol{X}_{kn})}{\sum_{\forall k}\exp(\beta_k \boldsymbol{X}_{kn})} f(\beta|\varphi)d\beta \tag{3}$$

where $f(\beta|\varphi)$ denotes the density function of random vector β, and φ is referring to the vector of parameters (e.g., mean and variance) of the density function.

The Halton sampling method is proposed to optimize the accuracy and efficiency of the estimation model (McFadden and Train, 2000). To trade off estimation accuracy and computation time, a simulated maximum likelihood approach with 1000 Halton draw is employed to estimate all the models to ensure accuracy and efficiency, after different Halton draws have been examine (Li et al., 2021; Yu et al., 2020a). The normal distribution is selected to describe the distribution form of random parameter due to its better fitting performance. Moreover, marginal effects are introduced to explore the impacts of significant variables on the different injury severity categories. This study uses random parameter logit model with heterogeneity in mean and variance to estimate the single vehicle run-off-road crashes in each speed interval during each COVID-19 period.

5. Transferability tests and out-of-sample prediction

This study applies transferability tests to statistically examine the temporal instability of run-off-road crashes in different periods of the COVID-19 epidemic. In addition, out-of-sample prediction is combined to explore the non-transferability of different Δv in the estimated model.

5.1. Transferability tests

Two groups of likelihood ratio tests are conducted to determine the temporal instability of variables in the estimated model over three periods. The first group of likelihood ratio tests evaluate transferability by comparing models in two individual periods (years), and the statistical test quantity can be defined as:

$$\chi^2_{t_1} = -2\left[LL\left(\beta_{y_1y_2}\right) - LL(\beta_{y_1})\right] \tag{4}$$

where $LL\left(\beta_{y_1y_2}\right)$ is the log-likelihood at convergence of a model containing parameters from y_2 while using data subset y_1, $LL(\beta_{y_1})$ is the log-likelihood at convergence of a model using data subset y_1. To obtain the two results of each pair comparison, the test is conducted by reversing the subsets y_1 and y_2. The degree of freedom in this test is equivalent to the number of estimated parameters in the model $\beta_{y_1y_2}$. Table C1 presents the pairwise test results between different periods for the run-off-road crashes models caused by different Δv intervals to determine whether the null hypothesis that the estimated parameters are transferable in the two years can be rejected. The results indicate that in 13 out of 18 of the tests, the null test hypothesis that the two periods are the same can be rejected with a 90 % confidence level. Notably, most of the results with confidence level of lower than 90 % exist in the speed interval of $\Delta v \leq 0$ mph. Consequently, the temporal instability for run-off-road crashes under the condition $\Delta v \leq 0$ mph is not as pronounced as it is for the other two conditions. Therefore, it can be proven that it is reasonable to estimate the model separately for the three periods pre, during, post COVID-19 epidemic to a certain extent.

Another likelihood ratio test is by examining the temporal stability between the joint model and each temporal model, and its statistical test quantity can be defined as:

$$\chi^2_{t_2} = -2\left[LL(\beta_{allyears,s}) - \sum_{2019}^{2021} LL(\beta_{y_i,s})\right] \tag{5}$$

where $LL\left(\beta_{allyears,s}\right)$ is the log-likelihood at convergence of the model estimated for each speeding group s ($\Delta v \leq 0$ mph, 0 mph $< \Delta v \leq 10$ mph, $\Delta v > 10$ mph) over all the periods (pre, during and post COVID-19), and $LL(\beta_{y_i})$ is the log-likelihood at convergence of the model estimated for each speeding group s in period y_i. The degrees of freedom in this test are

defined as the sum of the parameter number of the estimated model for each period minus the parameter number of the joint model estimated with data across all periods. The χ^2 values obtained by this test are 96.964, 51.237 and 48.718, with corresponding degrees of freedom of 50, 14 and 10 for run-off-road crashes caused by $\Delta v \leq 0$ mph, 0 mph $< \Delta v \leq 10$ mph, $\Delta v > 10$ mph, respectively. It can be seen from the results that the null hypothesis can be rejected at the 95 % confidence level, and the null hypothesis is that the model parameters of the run-off-road crashes caused by Δv values have statistically significant stability in the three periods.

Moreover, the transferability of the run-off-road crash models caused by different Δv values also needs to be tested, and its statistical test quantity is

$$\chi_s^2 = -2\left[LL(\beta_{all\Delta v,\,y}) - LL(\beta_{\Delta v1,y}) - LL(\beta_{\Delta v2,y}) - LL(\beta_{\Delta v3,y})\right] \quad (6)$$

where $LL(\beta_{all\Delta v,y})$ denotes the log-likelihood at convergence of the model estimated for each period y (pre, during and post COVID-19) over all the Δv intervals, and $LL(\beta_{\Delta v1,y})$, $LL(\beta_{\Delta v2,y})$ and $LL(\beta_{\Delta v3,y})$ are the log-likelihood at convergence of the model for $\Delta v \leq 0$ mph, 0 mph $< \Delta v \leq 10$ mph, $\Delta v > 10$ mph at corresponding period y, respectively. Likewise, the degrees of freedom equal the sum of the number of statistically significant parameters in each separate model minus the number of parameters in the joint model. The χ^2 results for pre, during and post COVID-19 in this test are 143.358, 189.273 and 220.247, with corresponding degrees of freedom of 32, 28 and 33, respectively. These results allow us to reject the null hypothesis which defines the stability of statistically significant parameters among the three distinct Δv intervals, with a confidence level exceeding 99.99 %.

5.2. Out-of-sample prediction

Out-of-sample prediction was also applied to evaluate the temporal instability of the run-off-road crashes injury severity model across different periods of COVID-19, and the implementation is using estimated parameters in one model to predict the observations from another model, which is based on the non-transferability of estimated parameters in different disaggregate data (Wang et al., 2022b; Xu et al., 2021). Out-of-sample prediction is conducted by calculating the average probability difference, which is obtained based on the following definition (Hou et al., 2022).

$$P_n(k) = \frac{1}{M}\sum_{m=1}^{M}\frac{\exp[(\beta_k + \vartheta_{kn}\boldsymbol{Z}_{kn} + \sigma_{kn}\exp(\omega_{kn}\boldsymbol{W}_{kn})\upsilon_{kn})\boldsymbol{X}_{kn}]}{\sum_{k=1}^{K}\exp[(\beta_k + \vartheta_{kn}\boldsymbol{Z}_{kn} + \sigma_{kn}\exp(\omega_{kn}\boldsymbol{W}_{kn})\upsilon_{kn})\boldsymbol{X}_{kn}]} \quad (7)$$

where M denotes the total number of draws used for the individual observation, and 500 Halton draws are adopted in the simulation process to establish the prediction, and other symbols are defined in Eqs. (1)-(3). The transferability or non– transferability is also explored from two aspects: temporal variation and different speeding intervals. First, this method is used to verify temporal instability. Specifically, for the same Δv, the run-off-road crash model in one period is proposed to predict the crash severity model in subsequent periods. Table C2 shows the mean of difference between the actual probability and the predicted probability of injury severity outcomes, where the base period is the estimated model based on a certain period, and the predicted period is the predicted subsequent period model based on the base model. Based on the prediction, the predicted probability of the predicted period can be obtained, and the probability difference can be calculated combined with the real probability value.

Clearly, significant variations in probability differences emerge when using a model from one period to predict data from another period. For example, employing model parameters from the pre COVID-19 (2019) to forecast run-off-road crashes during the COVID-19 period (2020) for $\Delta v \leq 10$ mph results in an increase in probability for no injury and minor injury by 0.0015 and 0.0032, respectively, and a decrease in probability of 0.0047 for serious injury/fatality. Otherwise, adopting during COVID-19 period (2020) to predict post COVID-19 (2021) for $\Delta v > 10$mph underestimates the probabilities of no injury and minor injury, while overestimates that of serious injury/fatality. Consequently, the marked disparities presented in the table indicate notable temporal instability through the out-of-sample prediction.

Table C3 displays the mean differences in probabilities when applying parameters from one run-off-road crash model to predict outcomes for a specific period. Significantly, the probabilities of SI outcomes are consistently overestimated when using the $\Delta v \leq 0$ mph model to predict for intervals of 0 mph $< \Delta v \leq 10$ mph and $\Delta v > 10$ mph across all three periods. Additionally, these results in Table 3 highlight the clear differences in injury severity outcomes attributable to various Δv intervals. In summary, the findings from out-of-sample predictions reinforce the noted temporal instability and issues related to non-transferability.

6. Temporal unconstrained and partially temporal constrained modeling approaches

6.1. Temporal unconstrained modeling approaches

Appendix B presents the estimated models results for single vehicle run-off-road crashes caused by different Δv intervals of $\Delta v \leq 0$ mph, 0 mph $< \Delta v \leq 10$ mph, and $\Delta v > 10$ mph based on the unconstrained random parameter logit model with heterogeneity in means. All the models are found to have significant random parameters, but the models caused by 0 mph $< \Delta v \leq 10$ mph pre and during COVID-19 are not found to be significant on heterogeneity in the mean of the random parameters. It is interesting that restraint-protected driving indicators produce the random parameters in four models caused by 0 mph $< \Delta v \leq 10$ mph pre and during COVID-19 and $\Delta v > 10$ mph pre and during COVID-19. Restraint-protected driving indicators are observed to be random parameters only in the speeding intervals pre and during COVID-19, and some variables have the positive effect on the mean of this indicator, thus increasing the probability of serious injury/fatality. This phenomenon shows that drivers may have risk compensation pre and during COVID-19, that is, drivers feel safe when they are restraint-protected driving, so they attempt to overspeed and it increases the risk instead.

The results of three models caused by 0 mph $< \Delta v \leq 10$ mph across all the years show that ρ^2 values exceeding 0.160. And all other models consistently demonstrate ρ^2 values exceeding 0.280, in which ρ^2 values of the run-off-road crashes models caused by $\Delta v \leq 0$ mph pre, during and post COVID-19 pandemic exceeding 0.310.

6.2. Partially temporal constrained modeling approaches

In addition, a partially constrained approach proposed by Alnawmasi and Mannering (2023) is to capture temporal instability and examine whether the parameters belonging to the same significant indicators produce variation across time (Wang et al., 2024). Therefore, the partially temporal constrained random parameters logit models with heterogeneity in means are estimated, and Table 3 exhibits all the results. As shown in Table 3, multiple indicators are found to produce the same parameter values across all periods, such as the traffic control sign indicator, male driver indicator, and restraint-protected driving indicator, and there are also the several indicators to produce the same parameter values in two period. By comparing the results, it is apparent that many variables which produced random parameters in the temporally unconstrained model shift to fixed parameters in the partially temporally constrained model. For instance, in the $\Delta v \leq 0$ mph model, several variables such as sunny, cloudy, new vehicle, and dry surface indicators transition to fixed parameters in the partially temporally constrained framework, whereas they were random parameters in the temporally unconstrained model.

Table 3
Model results of injury severity of single vehicle run-off-road crashes caused by three Δv intervals pre (2019), during (2020) and post (2021) COVID-19 pandemic (t-statistics in parentheses) based on partially constrained temporal random parameters approach with heterogeneity in means.*.

Variable	$\Delta v \leq 0$ mph		0 mph $< \Delta v \leq$ 10 mph		$\Delta v >$ 10 mph	
	Parameter estimate	Z value	Parameter estimate	Z value	Parameter estimate	Z value
[NI] Constant	2.602	26.45			−0.350	−3.09
[MI] Constant	2.532	23.04				
[SI] Constant			−1.477	−8.40		
Variables producing the same parameter value across all periods						
[MI] Male driver indicator (1 if male, 0 otherwise)	−0.339	−12.53				
[MI] Restraint-protected driving indicator (1 if restraint-protected driving, 0 otherwise)	−0.792	−14.25				
[MI] Front center bumper indicator (1 if vehicle most damage area is front center bumper, 0 otherwise)	0.324	12.08				
[SI] Urban areas indicator (1 if roadway is urban, 0 otherwise)	−0.325	−5.41				
[SI] Curve indicator (1 if curved alignment, 0 otherwise)	0.580	7.55				
[SI] New vehicle indicator (1 if auto age less than 10 years, 0 otherwise)	−0.264	−4.83				
[SI] Passenger car indicator (1 if passenger car, 0 otherwise)	−0.397	−6.67				
[SI] Off roadway indicator (1 if crash location is off roadway, 0 otherwise)	0.335	5.73				
[SI] Cloudy indicator (1 if cloudy, 0 otherwise)	0.417	5.68				
[SI] Alcohol-impaired driving indicator (1 if Alcohol-impaired driving, 0 otherwise)	0.470	4.77	1.248	5.59		
[MI] Drug-impaired driving indicator (1 if drug −impaired driving, 0 otherwise)	1.604	12.65			1.333	5.27
[SI] Restraint-protected driving indicator (1 if restraint-protected driving, 0 otherwise)					−1.726	−12.18
Driver Characteristics						
[NI] Male driver indicator (1 if male, 0 otherwise) [2020]			0.448	4.28		
[MI] Male driver indicator (1 if male, 0 otherwise) [2019, 2021]			−0.649	−6.41		
[NI] Driver below 18 years indicator (1 if age below 18 years, 0 otherwise) [2019, 2021]	0.252	2.68				
[MI] Driver 18–30 years indicator (1 if age between 18–30 years, 0 otherwise) [2019]	−0.132	−2.85	−0.451	−3.57		
[MI] Driver above 45 years indicator (1 if age above 45 years, 0 otherwise) [2020, 2021]	0.201	5.28				
[MI] Driver 30–45 years indicator (1 if age between 30–45 years, 0 otherwise) [2020]	0.082	1.68				
[MI] Driver below 18 years indicator (1 if age below 18 years, 0 otherwise) [2020]	−0.361	−2.58				
[SI] Driver 18–30 years indicator (1 if age between 18–30 years, 0 otherwise) [2020]	−0.6037	−7.95				
[SI] Driver 30–45 years indicator (1 if age between 30–45 years, 0 otherwise) [2020]	−0.397	−5.05				
[SI] Driver below 18 years indicator (1 if age below 18 years, 0 otherwise) [2020, 2021]	−1.260	−4.65				
[SI] Driver above 45 years indicator (1 if age above 45 years, 0 otherwise) [2020]			1.324	4.44		
[NI] Male driver indicator (1 if male, 0 otherwise) [2020, 2021]					0.314	2.44
[SI] Driver above 45 years indicator (1 if age above 45 years, 0 otherwise) [2020, 2021]					0.996	3.54
Vehicle Characteristics						
[MI] Passenger car indicator (1 if passenger car, 0 otherwise) [2020, 2021]	−0.147	−4.52				
[MI] Truck indicator (1 if truck, 0 otherwise) [2021]	−0.464	−2.97				
[MI] SUV indicator (1 if sport utility vehicle (SUV), 0 otherwise) [2019]	0.152	2.50				
[SI] SUV indicator (1 if sport utility vehicle (SUV), 0 otherwise) [2020]	−0.327	−2.75				
[SI] Truck indicator (1 if truck, 0 otherwise) [2020]	−0.897	−2.84				
[MI] New vehicle indicator (1 if auto age less than 10 years, 0 otherwise) [2021]			−0.540	−2.46		
[MI] Van indicator (1 if van, 0 otherwise) [2021]			1.294	1.72		
[SI] Passenger car indicator (1 if passenger car, 0 otherwise) [2019, 2021]			−0.724	−3.91		
Roadway Characteristics						
[NI] Dry surface indicator (1 if roadway surface is dry, 0 otherwise) [2019, 2020]	−0.404	−12.68				
[NI] Level indicator (1 if level grade, 0 otherwise) [2019, 2020]	0.144	3.33				
[NI] Two-way-divided indicator (1 if traffic way is two-way and divided, 0 otherwise) [2019]	−0.176	−3.26				
[NI] Two-way-no-divided indicator (1 if traffic way is two-way and not divided, 0 otherwise) [2019]	−0.325	−4.23				
[NI] Curb shoulder indicator (1 if shoulder is curb, 0 otherwise) [2020]	−0.148	−2.17				
[NI] One-way indicator (1 if traffic way is one-way, 0 otherwise) [2020]	0.176	1.9				
[MI] Traffic control sign indicator (1 if traffic control sign, 0 otherwise) [2020]	−0.275	−2.66				
[MI] Curve indicator (1 if curved alignment, 0 otherwise) [2020, 2021]	0.163	3.45				
[MI] Dry surface indicator (1 if roadway surface is dry, 0 otherwise) [2021]	0.337	7.72				
[MI] Paved shoulder indicator (1 if shoulder is paved, 0 otherwise) [2021]	−0.251	−5.40				
[MI] Urban areas indicator (1 if roadway is urban, 0 otherwise) [2021]	−0.163	−3.51				
[SI] Dry surface indicator (1 if roadway surface is dry, 0 otherwise) [2020, 2021]	0.849	12.00				
[SI] Two-way-no-divided indicator (1 if traffic way is two-way and not divided, 0 otherwise) [2020]	0.203	1.82				
[SI] Paved shoulder indicator (1 if shoulder is paved, 0 otherwise) [2021]	−0.200	−2.12				
[NI] Curve indicator (1 if curved alignment, 0 otherwise) [2021]			0.914	2.37	−0.510	−2.30
[SI] Curve indicator (1 if curved alignment, 0 otherwise) [2021]			2.130	4.70		
[NI] One-way indicator (1 if traffic way is one-way, 0 otherwise) [2019]					0.797	1.87
[SI] Unpaved shoulder indicator (1 if shoulder is unpaved, 0 otherwise) [2019]					−0.784	−2.10
[SI] Curve indicator (1 if curved alignment, 0 otherwise) [2019]					1.152	4.34
[SI] Traffic control sign indicator (1 if traffic control sign, 0 otherwise) [2020]					−1.332	−2.32
[SI] One-way indicator (1 if traffic way is one-way, 0 otherwise) [2020]					−2.165	−1.96
[SI] Level indicator (1 if level grade, 0 otherwise) [2021]					0.796	3.75
[SI] Lane_2 indicator (1 if crash occurred on two lanes on each side of road, 0 otherwise) [2021]					−0.952	−2.95
Environmental Characteristics						
[MI] Cloudy indicator (1 if cloudy, 0 otherwise) [2019, 2021]	0.214	4.94				
[SI] Sunny indicator (1 if sunny, 0 otherwise) [2019]	0.407	4.55				
[SI] No-lighted in dark indicator (1 if not lighted during nighttime, 0 otherwise) [2021]	0.534	4.27				
[MI] No-lighted in dark indicator (1 if not lighted during nighttime, 0 otherwise) [2020]			0.459	2.41		
[MI] Rainy indicator (1 if rainy, 0 otherwise) [2020]			−0.875	−6.15		
Crash Characteristics						

(*continued on next page*)

Table 3 (*continued*)

Variable	$\Delta v \leq 0$ mph		0 mph $< \Delta v \leq 10$ mph		$\Delta v > 10$ mph	
	Parameter estimate	Z value	Parameter estimate	Z value	Parameter estimate	Z value
[NI] Shoulder indicator (1 if crash location is on shoulder, 0 otherwise) [2019, 2020]	−0.155	−4.03				
[NI] On roadway indicator (1 if crash location is on roadway, 0 otherwise) [2020]	0.290	5.75				
[MI] Straight ahead indicator (1 if maneuver action is straight ahead, 0 otherwise) [2019]	−0.183	−3.76				
[MI] Drug-impaired driving indicator (1 if drug −impaired driving, 0 otherwise) [2019, 2021]	0.405	3.39				
[MI] On roadway indicator (1 if crash location is on roadway, 0 otherwise) [2019]	−0.265	−4.82				
[MI] Lane-changing indicator (1 if maneuver action is changing lanes, 0 otherwise) [2020, 2021]	0.173	3.43				
[MI] Front right bumper indicator (1 if vehicle most damage area is front right bumper, 0 otherwise) [2020]	−0.173	−2.24				
[MI] Distracted driving indicator (1 if distracted driving, 0 otherwise) [2021]	0.124	1.92				
[MI] Shoulder indicator (1 if crash location is on shoulder, 0 otherwise) [2021]	0.183	2.93				
[MI] Off roadway indicator (1 if crash location is off roadway, 0 otherwise) [2021]	0.238	5.03				
[SI] Front right bumper indicator (1 if vehicle most damage area is front right bumper, 0 otherwise) [2019, 2020]	−0.619	−4.91				
[SI] Lane-changing indicator (1 if maneuver action is changing lanes, 0 otherwise) [2019]	0.386	2.65				
[SI] Negotiating curve indicator (1 if maneuver action is negotiating curve, 0 otherwise) [2020, 2021]	−0.290	−2.4				
[SI] Shoulder indicator (1 if crash location is on shoulder, 0 otherwise) [2021]	0.417	3.32				
[MI] Lane-changing indicator (1 if maneuver action is changing lanes, 0 otherwise) [2020]			0.471	2.27		
[MI] Front right bumper indicator (1 if vehicle most damage area is front left bumper, 0 otherwise) [2020]			−0.826	−2.95		
[MI] Drug-impaired driving indicator (1 if drug −impaired driving, 0 otherwise) [2021]			1.249	2.03		
[MI] Straight ahead indicator (1 if maneuver action is straight ahead, 0 otherwise) [2021]			0.628	2.96		
[MI] Negotiating curve indicator (1 if maneuver action is negotiating curve, 0 otherwise) [2021]			1.419	3.15		
[SI] Off roadway indicator (1 if crash location is off roadway, 0 otherwise) [2019, 2021]			0.713	3.87		
[SI] Drug-impaired driving indicator (1 if drug −impaired driving, 0 otherwise) [2019, 2021]			1.233	3.37		
[SI] Front center bumper indicator (1 if vehicle most damage area is front center bumper, 0 otherwise) [2019]			−1.064	−3.64		
[SI] Front right bumper indicator (1 if vehicle most damage area is front right bumper, 0 otherwise) [2019]			−3.181	−3.06		
[SI] Shoulder indicator (1 if crash location is on shoulder, 0 otherwise) [2020]			1.040	3.46		
[SI] Restraint-protected driving indicator (1 if restraint-protected driving, 0 otherwise) [2020, 2021]			−1.652	−8.55		
[NI] Front left bumper indicator (1 if vehicle most damage area is front left bumper, 0 otherwise) [2020]					0.892	2.59
[NI] Restraint-protected driving indicator (1 if restraint-protected driving, 0 otherwise) [2021]					0.443	2.96
[NI] On roadway indicator (1 if crash location is on roadway, 0 otherwise) [2021]					0.354	1.73
[MI] Straight ahead indicator (1 if maneuver action is straight ahead, 0 otherwise) [2019]					−0.711	−4.07
[MI] Lane-changing indicator (1 if maneuver action is changing lanes, 0 otherwise) [2020]					0.693	2.52
[MI] Negotiating curve indicator (1 if maneuver action is negotiating curve, 0 otherwise) [2021]					−0.529	−1.94
[SI] Alcohol-impaired driving indicator (1 if Alcohol-impaired driving, 0 otherwise) [2020]					0.845	2.78
Temporal Characteristics						
[NI] Hurricane indicator (1 if crash occurred in hurricane season (June to November), 0 otherwise) [2021]	0.103	2.44				
[SI] Weekend indicator (1 if crash occurred on weekend, 0 otherwise) [2021]	0.296	2.99				
[MI] Day indicator (1 if crash occurred during the day, 0 otherwise) [2020]					−0.698	−3.72
[SI] Weekend indicator (1 if crash occurred on weekend, 0 otherwise) [2019]					−0.783	−2.78
Random parameters						
[SI] Driver 18–30 years indicator (1 if age between 18–30 years, 0 otherwise) [2021]	−2.094	−2.99				
Standard deviation	***1.918***	***3.42***				
[SI] Driver 30–45 years indicator (1 if age between 30–45 years, 0 otherwise) [2021]	−0.980	−2.07				
Standard deviation	***1.400***	***2.75***				
[MI] Two-way-divided indicator (1 if traffic way is two-way and divided, 0 otherwise) [2021]			−1.283	−2.47		
Standard deviation			***2.011***	***1.95***		
[SI] Paved shoulder indicator (1 if shoulder is paved, 0 otherwise) [2021]					−1.439	−2.14
Standard deviation					1.544	2.09
Heterogeneity in the means of random parameters						
[SI] Driver 18–30 years indicator (1 if age between 18–30 years, 0 otherwise) [2021]: Lighted in dark indicator (1 if not lighted during nighttime, 0 otherwise) [2021]	0.360	1.74				
[MI] Two-way-divided indicator (1 if traffic way is two-way and divided, 0 otherwise) [2021]: Weekend indicator (1 if crash occurred on weekend, 0 otherwise) [2021]			0.567	1.83		
[SI] Paved shoulder indicator (1 if shoulder is paved, 0 otherwise) [2021]: Off roadway indicator (1 if crash location is off roadway, 0 otherwise) [2021]					1.459	2.64
[SI] Paved shoulder indicator (1 if shoulder is paved, 0 otherwise) [2021]: Lane-changing indicator (1 if maneuver action is changing lanes, 0 otherwise) [2021]					−1.534	−2.20
Model statistics						
Number of observations (N)	30,407		2637		1419	
Log-likelihood at zero	−33405.504		−2897.041		−1558.931	
Log-likelihood at convergence	−23019.971		−2083.437		−1331.797	
$\rho^2 = 1 - LL(\beta)/LL(0)$	0.31		0.28		0.15	

*Parameter defined for: [NI] No Injury; [MI] Minor Injury; [SI] Serious Injury/Fatality.

Moreover, for variables producing the same parameter value across all periods in the partially temporal constrained model, it is found that the restraint-protected driving indicator is effective in all intervals for the injury severity of the run-off-crashes, so drivers should be actively encouraged to apply these safety protection measures. It is interesting to find that drug-impaired driving only has no effect in the 0 mph $< \Delta v \leq$ 10 mph during COVID-19, indicating that the consequences of drug-impaired driving during the COVID-19 epidemic may be no speeding or excessive speeding. This also illustrates the dangers of drug-impaired driving, so the corresponding drug-impaired driving laws should be enforced more strictly. Similarly, male driver has no effect in $\Delta v > 10$ mph during COVID-19, indicating that if the driver exceeds the speed limit by 10 or more, there may be no correlation between the injury severity of run-off-road crashes and gender during the COVID-19 epidemic. In addition, other variables producing the same parameter value across all periods have an impact in individual overspeed interval model, and their effects are consistent with those in the temporal unconstrained model. And in the following analysis, the impact of each variable on the injury severity of run-off-road crashes will be elaborated through the marginal effect of the temporal unconstrained model.

Overall, all the model results indicate that a range of relatively stable and unstable indicators influence the injury severity of run-off-road crashes. In the meanwhile, the partially temporal constrained can also verify the temporal stability of these indicators, thereby providing more effective suggestions for improving traffic safety. Statistically significant factors can be grouped into driver characteristics, vehicle, roadway, environmental, crash and temporal characteristics, and corresponding discussion on the result will be provided in detail. For a further discussion on the temporal instability of the injury determinants over different time periods, Tables B4-B6 show the marginal effects for all variables together with the no injury, minor injury and serious injury.

7. Discussion and interpretation

7.1. Heterogeneity in means and variances of random parameters

A total of 16, 3, 3 random parameters are captured in $\Delta v \leq 0$ mph, 0 $< \Delta v \leq$ 10mph, and $\Delta v > 10$ mph run-off-road crashes models, respectively. In addition, there is 2, 1, 1 random parameters are observed in partially temporal constrained model. This is because in a partially temporal constrained model, the increased number in variables and parameters may cause changes in the effects of the parameters. Table B1 shows the results in $\Delta v \leq 0$ mph interval across pre, during and post COVID-19. For the pre COVID-19 period, the driver 18–30 years indicator, new vehicle indicator, sunny indicator, and cloudy indicator are identified to be the random parameters. The mean of sunny indicator is significantly increased by the variables reflecting crashes occurred on weekend and increasing the possibility of serious injury/fatality, and distracted driving rises the mean of driver 18–30 years indicator and increases the possibility of serious injury/fatality. For the during COVID-19 period, dry surface indicator, new vehicle indicator and front right bumper indicator, passenger car indicator, truck indicator, and driver 30–45 years indicator produce random parameters with heterogeneity in means. Drivers who are distracted increase the mean of passenger car indicator making serious injuries/fatality more probable. However, drivers who are distracted driving reduces the mean of the new vehicle indicator, decreasing the possibility of serious injury/fatality. This shows that even if the driver is distracted driving, the driver keeps within the speed limit and does not cause speeding. Therefore, the possibility of running off the roadway is reduced, thereby decreasing the probability of serious crashes. Moreover, driving in hurricane seasons rises the mean of new vehicle indicator, increasing the possibility of serious injury/ fatality, and driving on two lanes on each side of road rises the mean of truck indicator, increasing the possibility of serious injury/fatality. For the post COVID-19 period, off roadway indicator, paved shoulder indicator, new vehicle indicator, passenger car indicator, driver 18–30 years indicator, driver 30–45 years indicator are observed to be the random parameters. Driving under the lighted in dark condition increases the mean of driver 18–30 years indicator, resulting in higher possibility of serious injury/fatality. Driving on the road which has traffic control sign rises the mean of new vehicle indicator and increases the possibility of serious injury/fatality. However, driving on the road which has traffic control sign reduces the mean of driver 30–45 years indicator and decreases the possibility of serious injury/fatality.

Similarly, Table B2 shows the model results in $0 < \Delta v \leq$ 10mph interval across pre, during and post COVID-19. For the pre COVID-19 period, restraint-protected driving indicator is found to be a random parameter, the mean of which is significantly increased by the variables reflecting the vehicle type is other vehicle, increasing the possibility of serious injury/fatality. Similarly, restraint-protected driving indicator produce a random parameter for the during COVID-19. For the post COVID-19 period, two-way-divided indicator produces random parameters with heterogeneity in means and variance. Driving in weekend and the variable reflecting the vehicle's most damage area is front center bumper simultaneously increase the mean of two-way-divided indicator, resulting in higher possibility of serious injury/fatality.

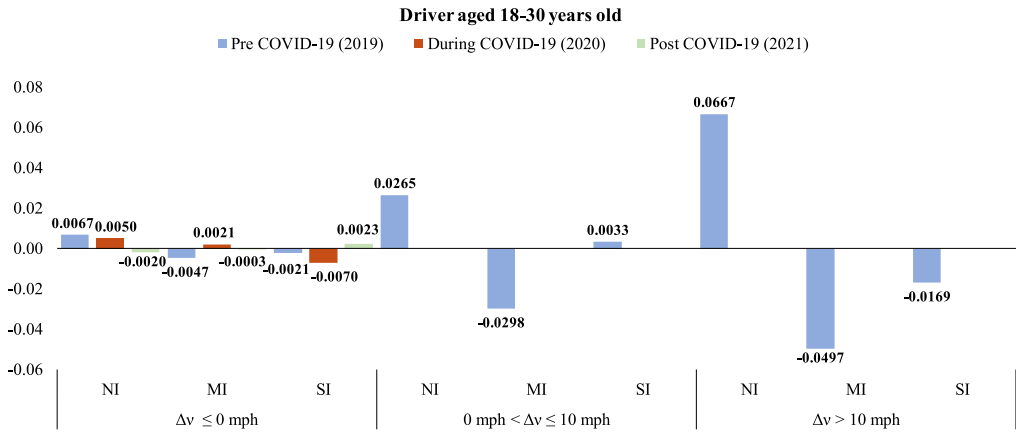
Furthermore, Table B3 shows the model results in $\Delta v >$ 10mph interval across pre, during and post COVID-19. For the both pre and during COVID-19 period, restraint-protected driving indicators are identified to be the random parameters. Moreover, for the pre COVID-19 period, both the driving under the sunny weather and driving on the road which has traffic control sign increase the mean of restraint-protected driving indicator, resulting in the higher possibility of serious injury/fatality. In addition, driving in urban area reduce the mean of restraint-protected driving indicator and decreases the possibility of serious injury/fatality. For the post COVID-19 period, paved shoulder indicator is observed to be a random parameter, the mean of which is significantly increased by the variables reflecting the location of the first harmful event being off-roadway, increasing the possibility of serious injury/fatality. Moreover, the maneuver action being lane-changing reduces the mean of paved shoulder indicator and makes serious injuries/fatality less probable.

7.2. Driver characteristics

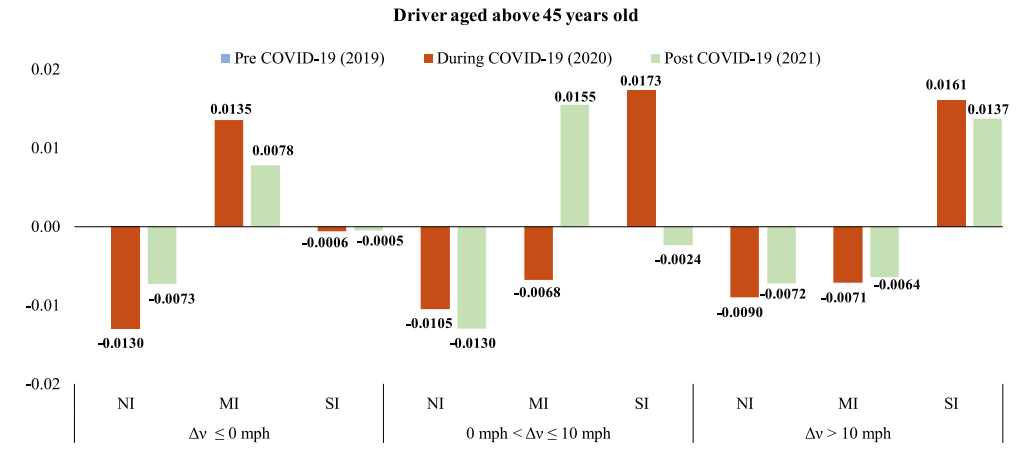
As discussed in Section 2, age has been considered to be one of the significant variables that significantly affects the injury severity outcomes in several previous studies. For the driver aged below 18 years old, this variable is associated with the increased possibility of no injury, and decreased possibilities of minor injury and serious injury/fatality in the estimated models for the $\Delta v \leq 0$ mph interval during and post COVID-19.

For the driver aged 18–30 years old, it has the significant effect on the injury severity of run-off-road crashes for the $\Delta v \leq 0$ mph across all the years, $0 < \Delta v \leq 10$ mph, and $\Delta v > 10$ mph intervals pre COVID-19, as shown in Fig. 3(a). This variable has the consistent effect that it is positively linked with the possibility of no injury, and negatively linked with the possibilities of minor injury and serious injury/fatality in the models estimated for $\Delta v \leq 0$ mph and $\Delta v > 10$ mph intervals pre COVID-19. For the model estimated for $\Delta v \leq 0$ mph post COVID-19, it is positively associated with the possibilities of no injury and serious injury/fatality, and negatively associated with the possibility of minor injury. And its effect on the model estimated for $\Delta v \leq 0$ mph during COVID-19 is totally converse with the model estimated for $\Delta v \leq 0$ mph post COVID-19. In addition, this variable increases the likelihoods of the no injury and serious injury/fatality, and decreases the likelihood of minor injury in the model estimated for $0 < \Delta v \leq 10$ mph pre COVID-19. The effect on these models further demonstrating the non-transferability. Moreover, it is found that the driver aged 18–30 years old has stronger connection with the situation of $\Delta v > 10$ mph.

In addition, the driver aged 30–45 years old has the significant effect on the injury severity of run-off-road crashes only for the $\Delta v \leq 0$ mph



(a) The driver aged 18-30 years old



(b) The driver aged above 45 years old

Fig. 3. The marginal effects of age indicator based on temporal unconstrained approach corresponding to all the injury severity outcomes: NI (No Injury); MI (Minor Injury); SI (Serious Injury/Fatality).

across all the years. For the model estimated for $\Delta v \leq 0$ mph pre COVID-19, it decreases the likelihood of serious injury/fatality, and increases the likelihoods of minor injury and no injury, and the model estimated for $\Delta v \leq 0$ mph post COVID-19 presents the totally converse effect. Moreover, the driver aged 30–45 years old decreases the likelihoods of no injury and serious injury/fatality, and increases the likelihood of minor injury in the estimated model for $\Delta v \leq 0$ mph during COVID-19.

As shown in Fig. 3(b), the driver aged above 45 years old has the significant effect on the injury severity of run-off-road crashes only for the all the Δv intervals during and post COVID-19. This variable has the same effect that it is positively linked with the possibility of minor injury, and negatively linked with the possibilities of no injury and serious injury/fatality for $\Delta v \leq 0$ mph during and post COVID-19, and $0 < \Delta v \leq 10$ mph post COVID-19. Interestingly, this variable is positively linked with the possibility of serious injury/fatality, and negatively linked with the possibilities of no injury and minor injury in the estimated models for $0 < \Delta v \leq 10$ mph during COVID-19 and $\Delta v > 10$ mph during and post COVID-19. Furthermore, it is found that the driver aged above 45 years old has the consistently negative effect on no injury. This finding might be explained by the diminished perception and reaction capabilities, as well as the reduced physiological robustness, of older drivers (Marmeleira et al., 2009). Otherwise, the older drivers are always with low physical fitness compared to younger drivers (Chen et al. 2022).

Turning to the effects of gender, male drivers significantly influence on different injury severity outcomes in all models, except for one model caused by $\Delta v > 10$ mph pre COVID-19. The male drivers are negatively associated with minor injury outcome in run-off-road crashes in the above models. In the meanwhile, Fig. 4 exhibits the marginal effects of this factor for all the injury severity outcomes in eight models. As demonstrated in Fig. 4, the tendencies are consistent and stable for both the $\Delta v \leq 0$ mph across all the periods and $0 < \Delta v \leq 10$ mph pre and post COVID-19, with the increased probabilities of no injury and serious injury/fatality, and decreased probability of minor injury. This tendency also can be demonstrated with the partially temporal constrained approach shown in the Table 3, and the male driver parameters involved in minor category can be unified to the same value in all periods respectively for $\Delta v \leq 0$ mph, so as to verify partially temporal stability. In addition, in the models estimated for the $0 < \Delta v \leq 10$ mph during COVID-19, and $\Delta v > 10$ mph during and post COVID-19, male drivers are consistently associated with increased possibility of no injury outcome, and decreased possibilities of minor injury and serious injury/fatality outcomes. This is consistent with the research of Al-Bdairi and Hernandez (2020), in which the female drivers were found to be more vulnerable to severe injuries in run-off-road crashes.

7.3. Vehicle characteristics

Vehicle types including passenger cars, SUVs, vans, trucks influence resulting in injury crash severity. The vehicle being passenger car is

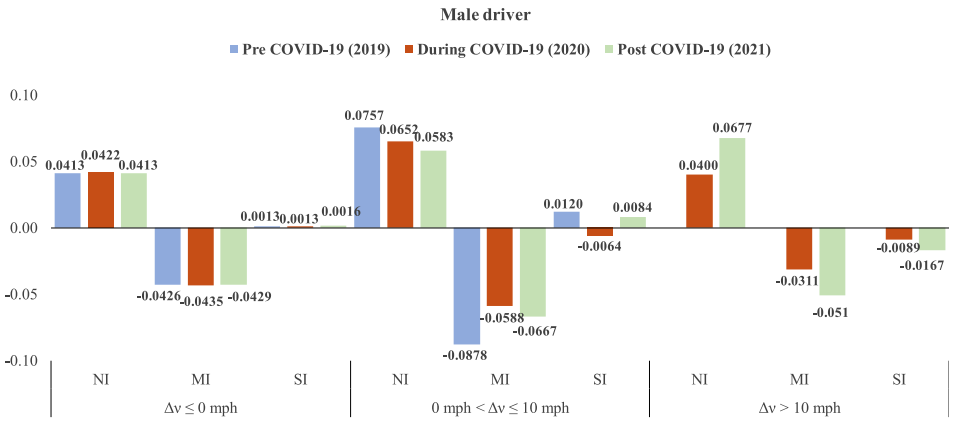


Fig. 4. The marginal effects of gender indicator based on temporal unconstrained approach corresponding to all the injury severity outcomes: NI (No Injury); MI (Minor Injury); SI (Serious Injury/Fatality).

positively related to the probabilities of no injury and minor injury, and the negatively related to the probability of serious injury/fatality for $\Delta v \leq 0$ mph pre COVID-19 and $0 < \Delta v \leq 10$ mph pre and post COVID-19, as shown in Fig. 5. Moreover, passenger car in the model estimated for $\Delta v \leq 0$ mph during COVID-19 is positively related to the probability of no injury and serious injury/fatality, and the negatively related to the probability of minor injury. In the meanwhile, this variable is positively associated with the possibility of no injury, and negatively associated with the possibilities of minor injury and serious injury/fatality in the model estimated for $\Delta v \leq 0$ mph post COVID-19. In the above all the models, the passenger car increasing the possibility of no injury is consistent with the founding of Yu et al. (2020b).

In addition, trucks significantly influence the degree of injury in the models estimated for $\Delta v \leq 0$ mph during and post COVID-19 with increased probability of no injury outcome, and trucks do not show stable effects on the probabilities of minor injuries and serious injury/fatality for the above models. In the meanwhile, SUVs also have the similar effects with decreased probability of serious injury/fatality in the estimated models for $\Delta v \leq 0$ mph across all the periods. For the estimated model for pre COVID-19, this variable is negatively associated with the possibility of no injury, and positively associated with minor injury, with the converse effect in the model estimated for post COVID-19. In addition, in the model estimated for during COVID-19, this variable is associated with the possibilities of no injury and minor injury. For the run-off-road crashes occurring during COVID-19 with $\Delta v > 10$ mph, vans can increase the likelihood of minor injury by 0.0040 and decrease the likelihoods of no injury and serious injury/fatality by 0.0034 and 0.0006, respectively. However, Gong and Fan (2017) found that young and middle-aged drivers are more likely to be involved in severe or fatal injuries while driving a sport utility vehicle (SUV) or a van. This explanation might the significant increase in the deployment of specialized vehicles, including those allocated for rescue operations, disinfection tasks, command centers, and vaccine distribution throughout the COVID-19 pandemic (Grimm, 2021). Van drivers, particularly those operating for commercial purposes, may demonstrate enhanced cautious driving behaviors owing to heightened awareness of safety protocols and the possibility of extended emergency response times.

The vehicle using less than 10 years significantly influence on different injury severity outcomes in the models caused by $\Delta v \leq 0$ mph across all the periods, and $0 < \Delta v \leq 10$ mph post COVID-19, as depicted in Fig. 6. These marginal effects show that the vehicle using less than 10 years increases the possibility of no injury, and decreases the possibilities of minor injury and serious injury/fatality in the models estimated for $\Delta v \leq 0$ mph during COVID-19 and $0 < \Delta v \leq 10$ mph post COVID-19. Interestingly, this variable has the totally converse effect in the model estimated for $\Delta v \leq 0$ mph pre COVID-19. In addition, in the model estimated for $\Delta v \leq 0$ mph post COVID-19, this variable is associated with the increased likelihoods of no injury and minor injury, and the decreased likelihood of serious injury/fatality.

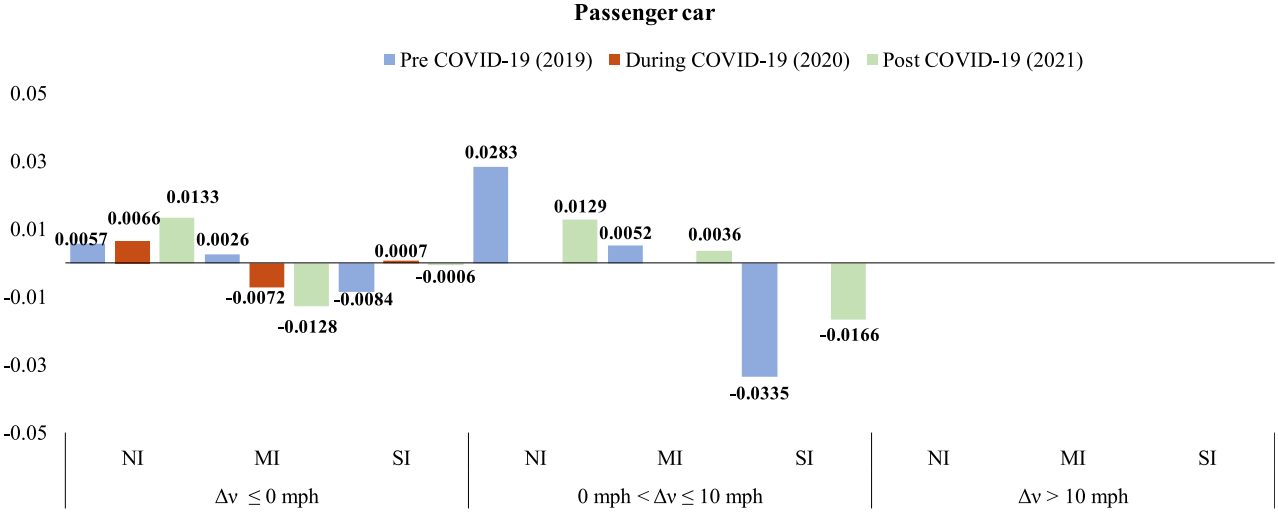


Fig. 5. The marginal effects of passenger car indicator based on temporal unconstrained approach corresponding to all the injury severity outcomes: NI (No Injury); MI (Minor Injury); SI (Serious Injury/Fatality).

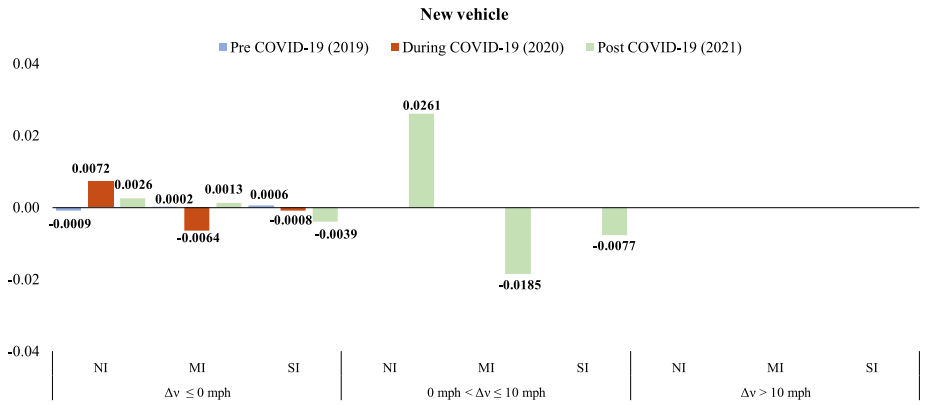


Fig. 6. The marginal effects of new vehicle indicator based on temporal unconstrained approach corresponding to all the injury severity outcomes: NI (No Injury); MI (Minor Injury); SI (Serious Injury/Fatality).

7.4. Roadway characteristics

Curve segments are found to decrease the likelihood of no injury of all the models except $0 < \Delta v \leq 10$ mph pre and during COVID-19 and $\Delta v > 10$ mph during COVID-19. The curve segment is positively associated the possibility of with serious injury/fatality, and negatively associated with the possibilities of no injury and minor injury in the models estimated for $\Delta v \leq 0$ mph and $\Delta v > 10$ mph pre COVID-19, as depicted in Fig. 7. In the meanwhile, in the estimated model for $\Delta v \leq 0$ mph during and post COVID-19 and $\Delta v > 10$ mph post COVID-19, the curve segment is negatively associated with the possibility of no injury, and positively associated with the possibilities of minor injury and serious injury/fatality. In addition, this variable increases the possibilities of no injury and serious injury/fatality, and decreases the possibility of minor injury in the estimated model for $0 < \Delta v \leq 10$ mph post COVID-19. Overall, the curve segment is positively associated with the increased likelihood of serious injury/fatality, which is consistent with the research of Al-Bdairi and Hernandez (2017); Gong et al. (2017); Yu et al (2020b). In the meanwhile, it is found that the curve segment has stronger connection with the situation of over speeding.

Similarly, traffic control sign is found to have significant effects on all the injury outcomes in the estimated models for $\Delta v \leq 0$ mph and $0 < \Delta v \leq 10$ mph during COVID-19. This variable is positively linked with the likelihoods of no injury and serious injury/fatality outcomes, and negatively linked with the likelihood of minor injury in the model estimated for $\Delta v \leq 0$ mph during COVID-19. And in the estimated model for $0 < \Delta v \leq 10$ mph during COVID-19, this variable increases the possibilities of no injury and minor injury outcomes, and decreases the possibility of serious injury/fatality.

Furthermore, urban areas only have significant effect in the estimated models for $\Delta v \leq 0$ mph across all the periods, and this variable is positively associated with the likelihood of no injury for the three models, but not the stable effect on the minor injury and serious injury/fatality. In the model estimated for during COVID-19, this variable is negatively linked with the likelihood of minor injury, and positively linked with the likelihood of serious injury/fatality, which is consistent with the finding of Yu et al (2020) that urban area is more likely to result in more severe injury. However, in the models estimated for pre and post COVID-19, this variable is negatively linked with the likelihood of serious injury/fatality. The reason might be urban areas have better traffic signs, road surfaces and lighting conditions, which may reduce the risk of run-off-road crashes if the drivers are not over speeding.

Level grade is found to decease the likelihoods of minor injury and serious injury/fatality, and increase the likelihood of no injury in the estimated models for $\Delta v \leq 0$ mph pre and during COVID-19, as depicted in Fig. 8. Moreover, this variable is positively linked with the likelihoods of no injury and minor injury, and negatively likelihood of serious injury/fatality in the estimated model for $0 < \Delta v \leq 10$ mph during COVID-19, with the totally converse effect in the estimated model for $\Delta v > 10$ mph post COVID-19.

Dry surface has the consistent effect in the models caused by $\Delta v \leq 0$ mph across all the periods, which is positively associated with the possibilities of the minor injury and serious injury/fatality, and negatively associated with the possibility of the no injury, as shown in Fig. 9.

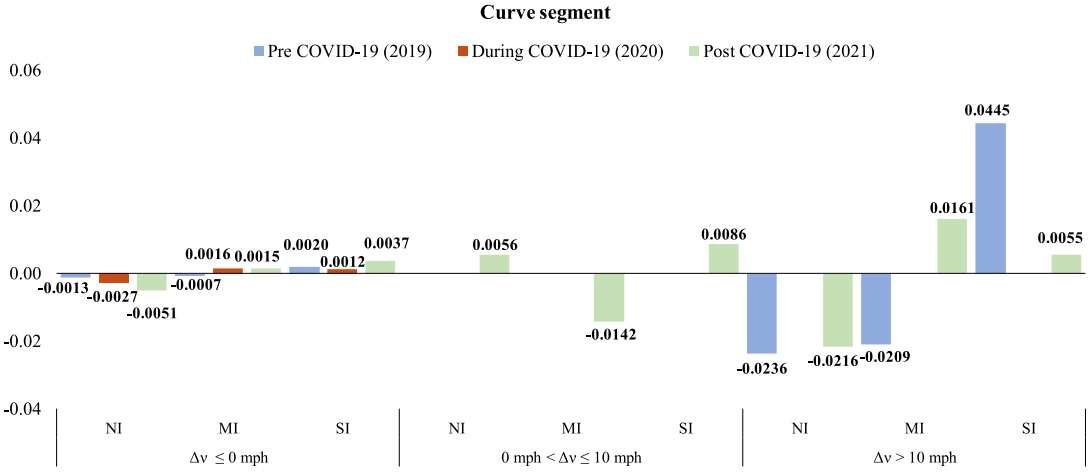


Fig. 7. The marginal effects of curve segment indicator based on temporal unconstrained approach corresponding to all the injury severity outcomes: NI (No Injury); MI (Minor Injury); SI (Serious Injury/Fatality).

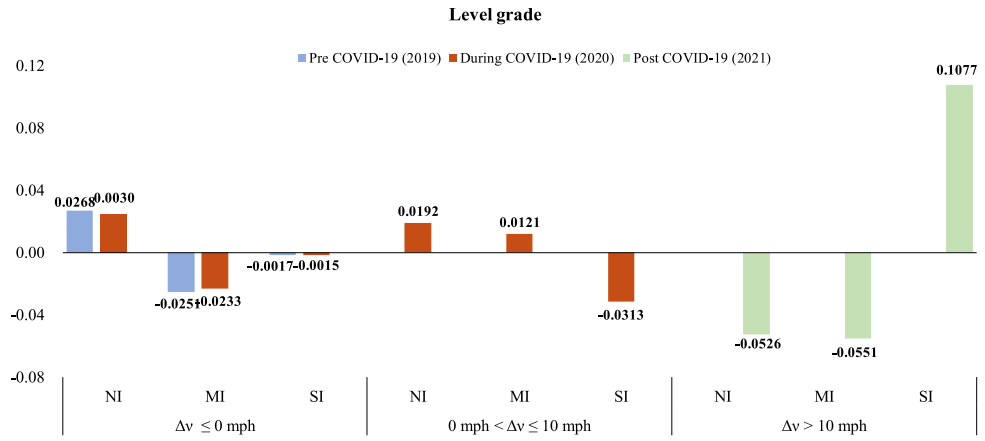


Fig. 8. The marginal effects of level grade indicator based on temporal unconstrained approach corresponding to all the injury severity outcomes: NI (No Injury); MI (Minor Injury); SI (Serious Injury/Fatality).

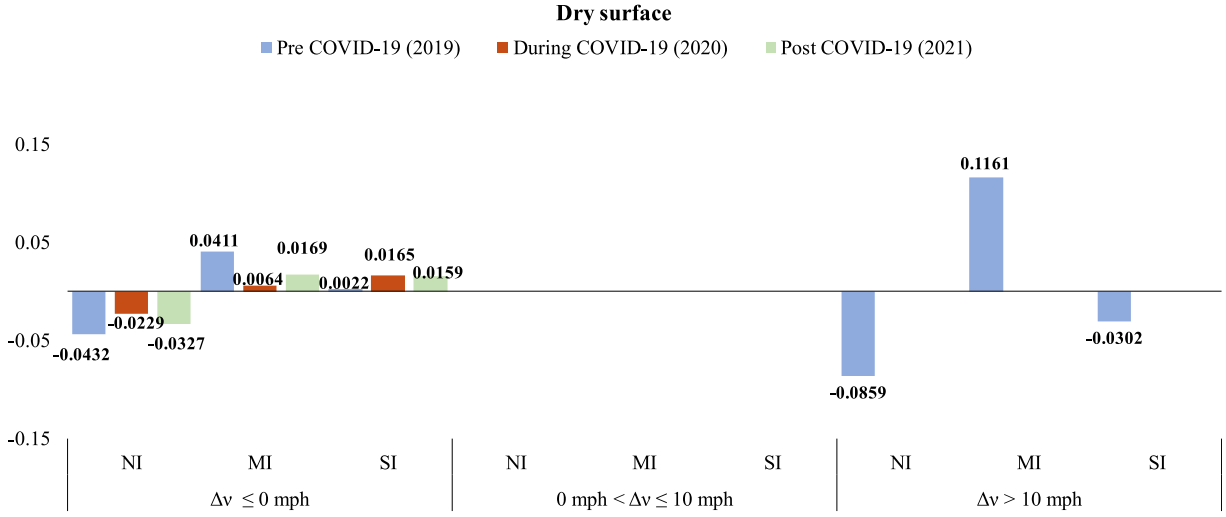


Fig. 9. The marginal effects of dry surface indicator based on temporal unconstrained approach corresponding to all the injury severity outcomes: NI (No Injury); MI (Minor Injury); SI (Serious Injury/Fatality).

This finding is consistent with the results in Montella et al. (2021); Yu et al., (2020b) that dry surface is associated with the increased possibility of serious injury/fatality. However, this variable decreases the possibility of no injury, and increases the possibilities of minor injury and serious injury/fatality in the estimated model for $\Delta v > 10$ mph pre COVID-19. The reason might be that the driver is speeding, and dry roads can reduce the driver's braking distance, thereby decreasing the possibility of serious injury/fatality.

When traffic way is two-way-divided, this variable increases the possibilities of minor injury and serious injury/fatality, and decreases the possibility of no injury. In the meanwhile, this variable increases the possibility of no injury by 0.0067, and decreases the possibility of minor injury by 0.0067 and has no effect on the serious injury/fatality. In addition, when traffic way is two-way-no-divided, this variable is positively associated with the likelihoods of minor injury and serious injury/fatality in the estimated model for $\Delta v \leq 0$ mph pre COVID-19. And this variable is positively associated with the likelihood of serious injury/fatality, and negatively associated with the likelihoods of no injury and minor injury in the estimated models for $\Delta v \leq 0$ mph during COVID-19. Moreover, when traffic way is one-way, this variable is negatively associated with the possibilities of minor injury and serious injury/fatality, and positively associated with the possibility of no injury in the estimated models for $\Delta v \leq 0$ mph during COVID-19 and $\Delta v > 10$ mph pre COVID-19. And this variable is negatively associated with the possibility of serious injury/fatality, and positively associated with the possibilities of no injury and minor injury in the estimated model for $\Delta v > 10$ mph during COVID-19.

Moreover, in the estimated models for $\Delta v \leq 0$ mph and $\Delta v > 10$ mph post COVID-19, the run-off-road crashes occurred on two lanes on each side of road is positively linked with the likelihood of no injury and negatively linked with the likelihood of serious injury/fatality, but decreases the likelihood of minor injury for $\Delta v \leq 0$ mph, and increases the likelihood of minor injury for $\Delta v > 10$ mph.

Furthermore, curb shoulder increases the likelihoods of minor injury and serious injury/fatality, and decreases the likelihood of no injury in the estimated model for $\Delta v \leq 0$ mph during COVID-19. Moreover, paved shoulder is positively associated with the likelihood of no injury, and negatively associated with the likelihoods of minor injury and serious injury/fatality in the estimated model for $\Delta v \leq 0$ mph post COVID-19. And this variable is positively associated with the likelihood of serious injury/fatality, and negatively associated with the likelihoods of no injury and minor injury in the estimated model for $\Delta v > 10$ mph post COVID-19. In addition, unpaved shoulder is positively associated with the likelihoods of no injury and minor injury, and negatively associated with the likelihood of serious injury/fatality in the estimated model for $\Delta v > 10$ mph pre COVID-19.

7.5. Environmental characteristics

Sunny weather is positively associated with the possibility of serious injury/fatality, negatively associated with the possibilities of no injury and minor injury in the estimated models for $\Delta v \leq 0$ mph and $0 < \Delta v \leq 10$ mph pre COVID-19. Furthermore, cloudy weather is positively associated with the likelihood of serious injury/fatality, and negatively associated with the likelihoods of no injury and minor injury in the estimated models for $\Delta v \leq 0$ mph during COVID-19 and $0 < \Delta v \leq 10$ mph pre COVID-19, as depicted in Fig. 10. Additionally, cloudy weather is positively associated with the likelihoods of minor injury and serious injury/fatality, and negatively associated with the likelihood of no injury in the estimated models for $\Delta v \leq 0$ mph pre and post COVID-19. These results are consistent with the related research that clear or cloudy condition increased the possibility of more serious injury (Lee and Mannering, 2002; Montella et al., 2021; Yu et al., 2020b).

In addition, rainy weather is positively associated with the likelihoods of no injury and serious injury/fatality, and negatively associated with the likelihood of minor injury in the estimated models for $\Delta v \leq 0$ mph and $\Delta v > 10$ mph during COVID-19.

Turning to the lighting condition, no-light condition during nighttime is found to increase the possibility of serious injury/fatality and decrease the possibilities of no injury and minor injury in the estimated models for $\Delta v \leq 0$ mph post COVID-19 and $0 < \Delta v \leq 10$ mph pre COVID-19. In the meanwhile, this variable is found to increase the possibility of minor injury and decrease the possibilities of no injury and serious injury/fatality in the estimated model for $0 < \Delta v \leq 10$ mph during COVID-19, illustrating the temporal instability among models. Moreover, light condition during nighttime is positively associated with minor injury in the models for $\Delta v > 10$ mph pre and post COVID-19. In the meanwhile, this variable is negatively linked with the likelihood of no injury and positively linked with the likelihood of serious injury/fatality in the models for pre COVID-19, and it has the converse effect in the model for post COVID-19. Additionally, daylight condition is positively linked with the possibility of serious injury/fatality, and negatively linked with the possibilities of no injury and minor injury for $0 < \Delta v \leq 10$ mph pre COVID-19, which is consistent with the research of Yu et al. (2020b). Furthermore, other light condition is positively linked with the possibility of no injury, and negatively linked with the possibilities of minor injury and serious injury/fatality for $\Delta v > 10$ mph post COVID-19.

7.6. Crash characteristics

Regarding crash-related attributes, restraint-protected driving has significant influence on the injury severity of run-off-road crashes in all the models, and this variable has the consistently positive effect on the no injury outcome. As shown in Fig. 11, this variable has the consistent effect on the three injury severity outcomes in the estimated models for $\Delta v \leq 0$ mph across all the periods and $0 < \Delta v \leq 10$ mph pre COVID-19, and it is positively associated with likelihoods of the no injury and serious injury/fatality, and negatively associated with likelihood of minor injury. In addition, this variable is positively associated with likelihoods of the no injury and minor injury, and negatively associated with likelihood of serious injury/fatality in the estimated models for $0 < \Delta v \leq 10$ mph during and post COVID-19 and $\Delta v > 10$ mph pre and during COVID-19. Moreover, in the estimated model for $\Delta v > 10$ mph post COVID-19, this variable is positively linked with the likelihood of no injury, negatively linked with the likelihoods of minor injury and serious injury. The effect of restraint-protected driving indicators is consistent with the conclusions of Gong et al. (2017); Al-Bdairi and Hernandez (2017).

Table 3 also demonstrates the same effect, so restraint-protected driving indicators involved in minor injury category produce the same parameter for $\Delta v \leq 0$ mph across all the periods. Moreover, restraint-protected driving indicators involved serious injury/fatality category in the estimated models for $\Delta v > 10$ mph across all the periods produce the same parameters.

Drug-impaired driving has the significant influence on the injury severity of run-off-road crashes in all the models except for $0 < \Delta v \leq 10$ mph during COVID-19. Drug-impaired driving consistently increases the likelihood of serious injury/fatality, and decreases the likelihoods of no injury and minor injury in above models except for $\Delta v \leq 0$ mph pre COVID-19 and $0 < \Delta v \leq 10$ mph post COVID-19, as shown in Fig. 12. Additionally, in the estimated models for $\Delta v \leq 0$ mph pre COVID-19 and $0 < \Delta v \leq 10$ mph post COVID-19, this variable decreases the likelihood of no injury, and increases the likelihoods of minor injury and serious injury/fatality. Therefore, partially constrained approach also verifies that this variable produces the same parameter and presents the same tendency for $\Delta v \leq 0$ mph and $\Delta v > 10$ mph intervals across all the periods. Furthermore, it is found that drug-impaired driving has the stronger connection with $\Delta v > 10$ mph situation.

Alcohol-impaired driving has the significant influence on the injury severity of run-off-road crashes in all the models except for $\Delta v > 10$ mph pre and post COVID-19. It consistently increases the likelihood of serious injury/fatality, and decreases the likelihoods of no injury and minor injury in the above models, as shown in Fig. 13. Similar results can be found in Khan et al. (2023); Lee and Mannering, (2002); Yu et al. (2020). Moreover, alcohol-impaired driving is found to have more significant effect on the all the injury outcomes of run-off-road crashes under the circumstance of over speeding.

Furthermore, distracted driving is found to increase the possibility of minor injury by 0.0032, and decrease the possibilities of no injury and serious injury/fatality by 0.0031 and 0.0001, respectively, in the estimated model for $\Delta v \leq 0$ mph post COVID-19.

Turning to the driver's maneuver, lane-changing, negotiating curve,

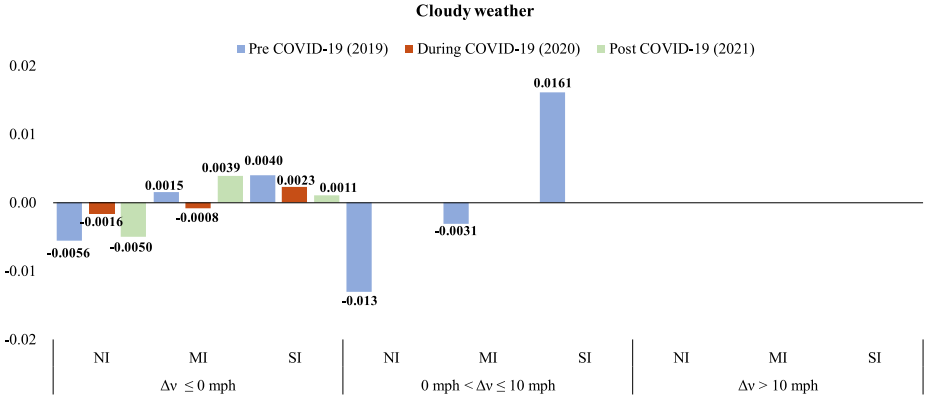


Fig. 10. The marginal effects of cloudy weather indicator based on temporal unconstrained approach corresponding to all the injury severity outcomes: NI (No Injury); MI (Minor Injury); SI (Serious Injury/Fatality).

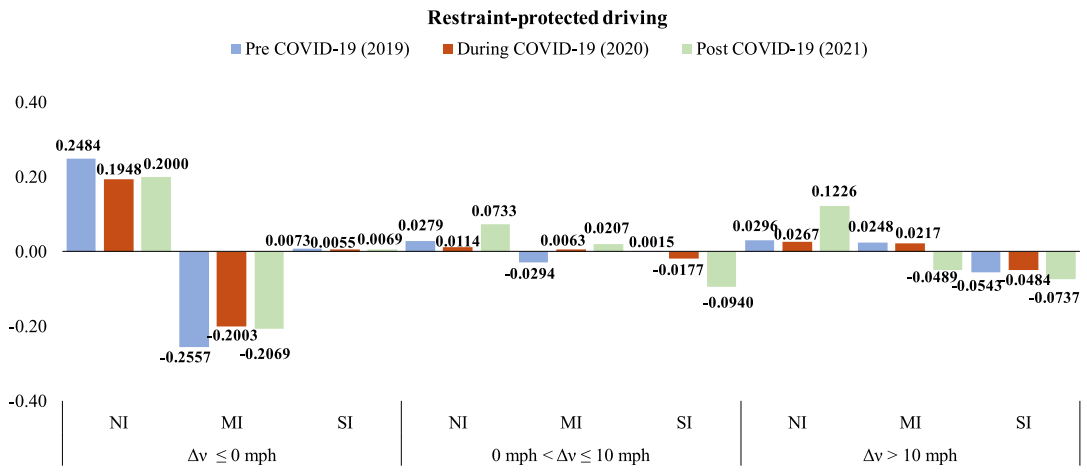


Fig. 11. The marginal effects of restraint-protected driving indicator based on temporal unconstrained approach corresponding to all the injury severity outcomes: NI (No Injury); MI (Minor Injury); SI (Serious Injury/Fatality).

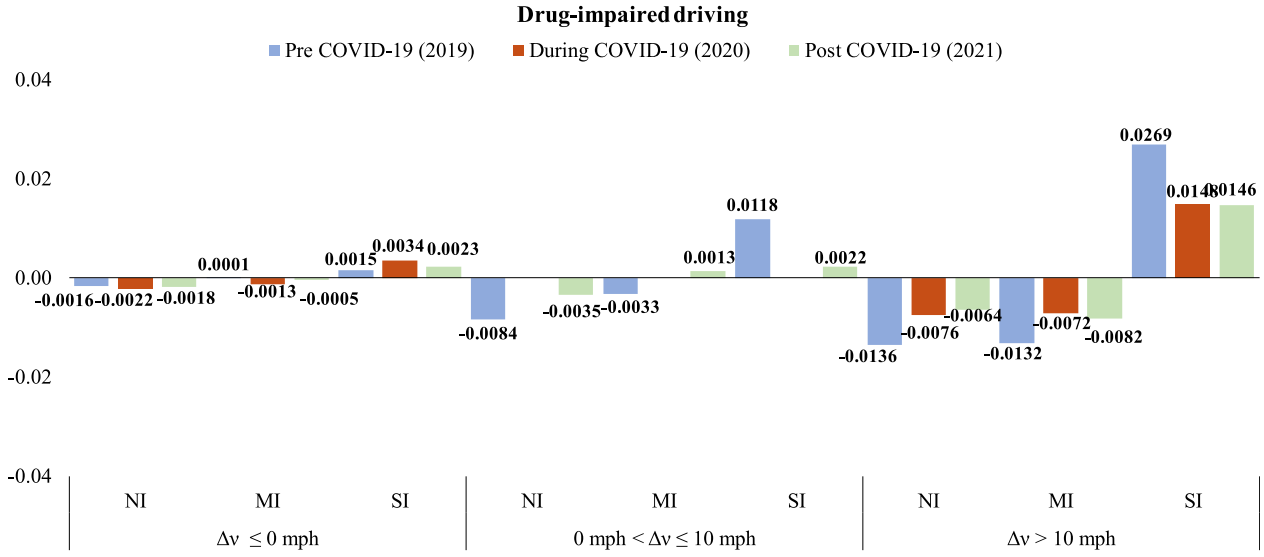


Fig. 12. The marginal effects of drug-impaired driving indicator based on temporal unconstrained approach corresponding to all the injury severity outcomes: NI (No Injury); MI (Minor Injury); SI (Serious Injury/Fatality).

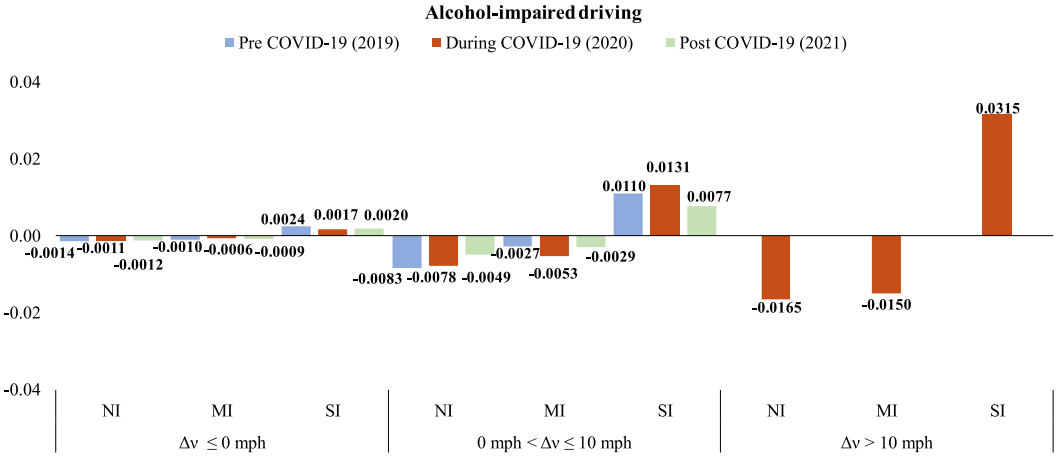


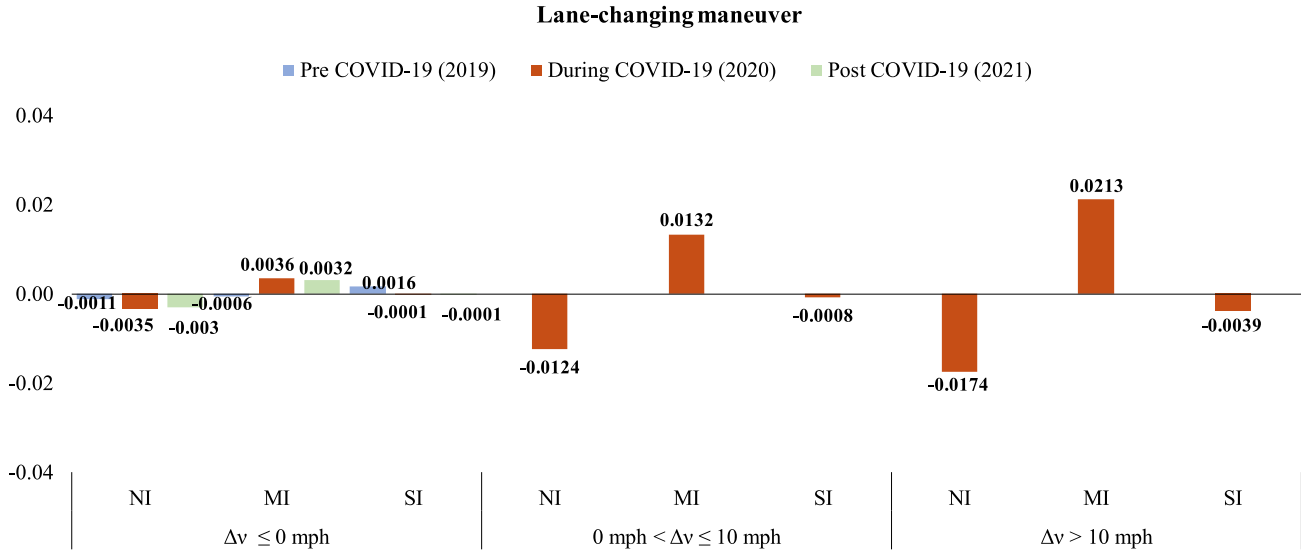
Fig. 13. The marginal effects of alcohol-impaired driving indicator based on temporal unconstrained approach corresponding to all the injury severity outcomes: NI (No Injury); MI (Minor Injury); SI (Serious Injury/Fatality).

and straight ahead have the various influence on the injury severity of run-off-road crashes. As shown in Fig. 16 (a), Lane-changing maneuver has the significant influence on the injury severity of run-off-road crashes in all the models except for $0 < \Delta v \leq 10$ mph and $\Delta v > 10$ mph and $0 < \Delta v \leq 10$ mph pre and post COVID-19. Lane-changing maneuver is positively associated with the possibility of minor injury, and negatively associated with the possibilities of no injury and serious injury/fatality in the above estimated models except for $\Delta v \leq 0$ mph pre COVID-19. In addition, in the estimated models for $\Delta v \leq 0$ mph pre COVID-19, this variable is positively linked with the likelihood of serious injury/fatality, and negatively linked with the likelihoods of no injury and minor injury. As shown in Fig. 14(a), it is found that lane-changing maneuver have stronger connection with the injury severity of run-off-crashes under the over speeding situation.

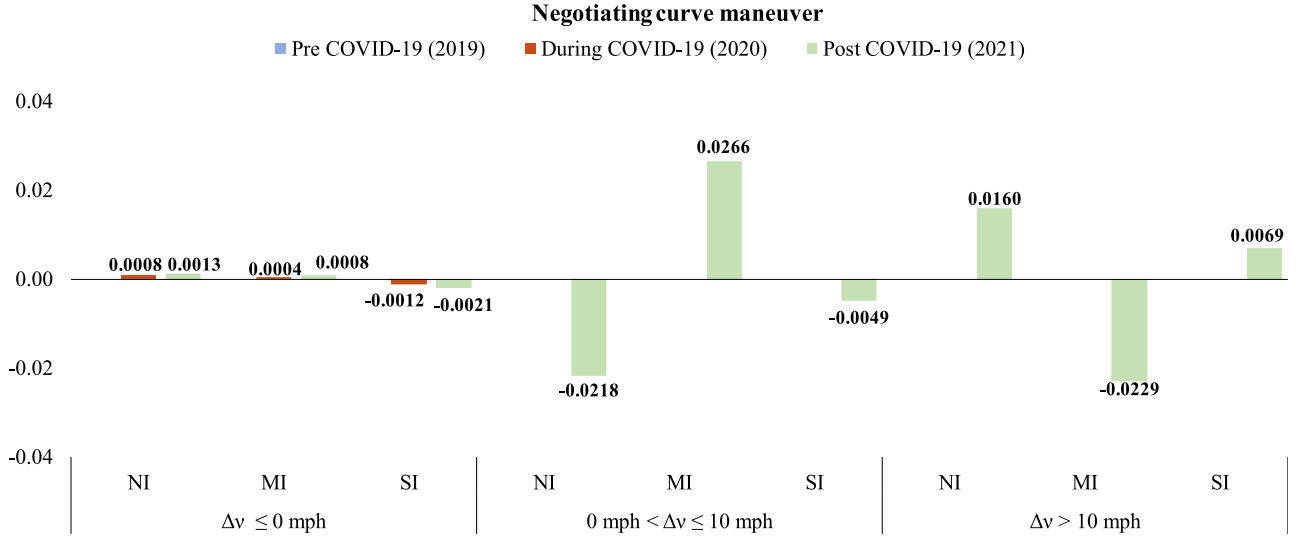
Negotiating curve maneuver has the totally inconsistent in the estimated models for $\Delta v \leq 0$ mph during and post COVID-19, and it increases the possibilities of no injury and minor injury, and decreases the possibility of serious injury/fatality, as shown in Fig. 14(b). In the estimated model for 0 mph $< \Delta v \leq 10$ mph post COVID-19, this variable increases the possibility of minor injury and decreases the possibilities of no injury and serious injury/fatality, and it has the totally conversely effect in the estimated model for $\Delta v > 10$ mph post COVID-19.

Moreover, straight ahead maneuver is positively associated with the likelihood of minor injury, and negatively associated with the likelihoods of on injury and serious injury in the estimated models for $\Delta v \leq 0$ mph and $\Delta v > 10$ mph pre COVID-19, which is consistent the finding of Khan et al. (2023). However, this variable has the totally converse effect in the estimated model for 0 mph $< \Delta v \leq 10$ mph post COVID-19.

From the aspect of the vehicle most damage area, the front center bumper has stable effect on the injury severity of run-off-road crashes for



(a) Lane-changing maneuver



(b) Negotiating curve maneuver

Fig. 14. The marginal effects of driver's maneuver indicator based on temporal unconstrained approach corresponding to all the injury severity outcomes: NI (No Injury); MI (Minor Injury); SI (Serious Injury/Fatality).

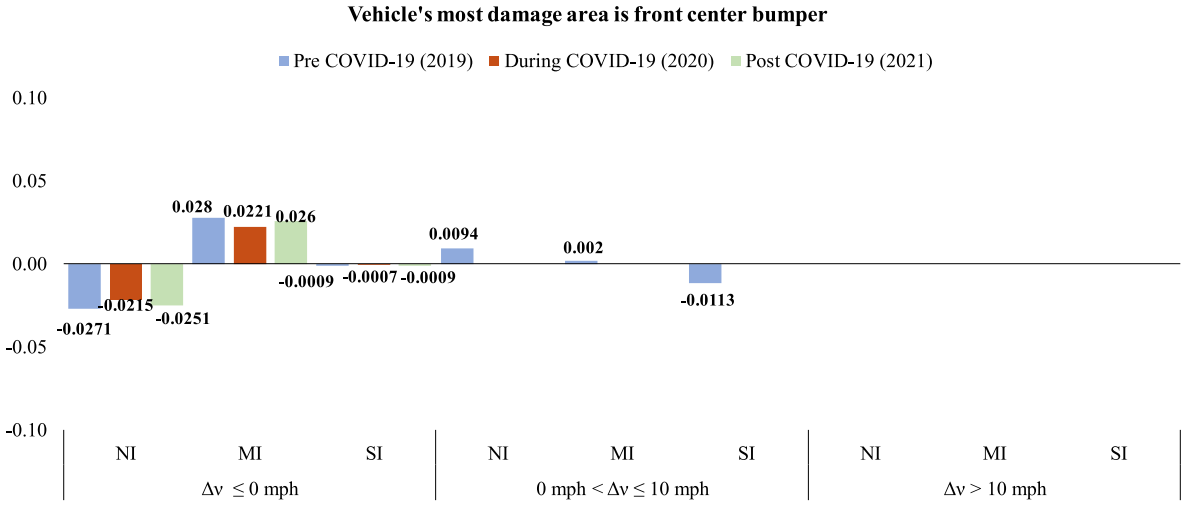
$\Delta v \leq 0$ mph across all the periods, and it is positively associated with the possibility of minor injury, and negatively associated with the possibilities of no injury and serious injury/fatality in the estimated models for $\Delta v \leq 0$ mph across all the periods, as depicted in Fig. 15 (a). In the estimated model for 0 mph $< \Delta v \leq 10$ mph pre COVID-19, this variable is positively associated with the possibilities of no injury and minor injury, and negatively associated with the possibility of serious injury/fatality. Overall, the front center bumper is consistently associated with the decreased likelihood of minor injury.

Front right bumper is positively associated with the likelihoods of no injury and minor injury, and negatively associated with the likelihood of serious injury in the estimated models for $\Delta v \leq 0$ mph and 0 mph $< \Delta v \leq 10$ mph pre COVID-19, as shown in Fig. 15(b). Moreover, this variable increases the possibility of no injury and decreases the possibility of minor injury in the estimated models for $\Delta v \leq 0$ mph and 0 mph $< \Delta v \leq 10$ mph during COVID-19, but decreases the possibility of serious injury/fatality for $\Delta v \leq 0$ mph and increases the possibility of serious injury/fatality for 0 mph $< \Delta v \leq 10$ mph.

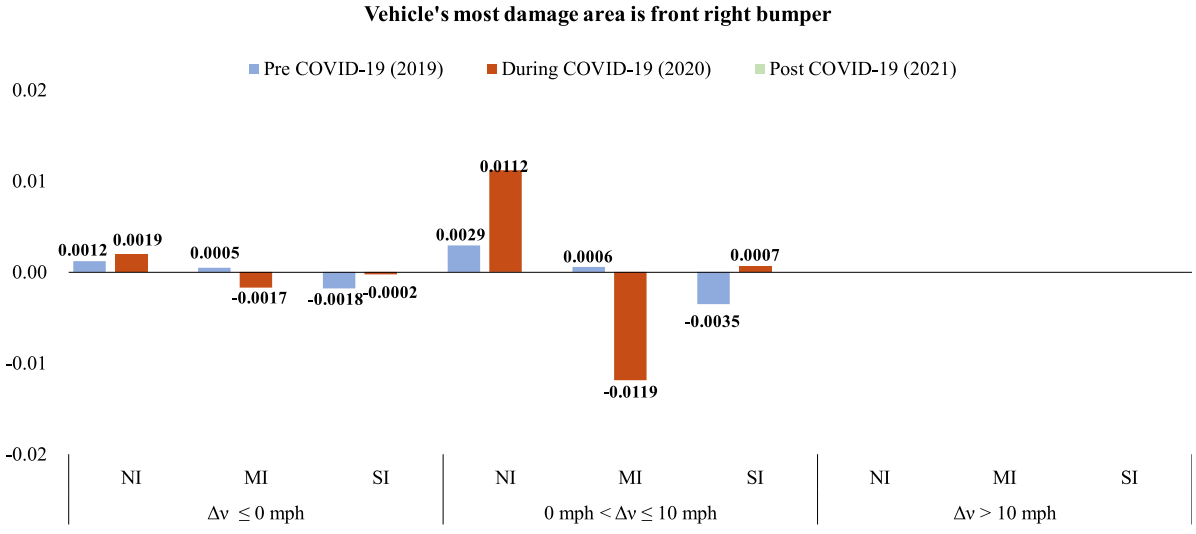
In addition, vehicle's most damage area being front left bumper also influences the injury severity of run-off-road crashes. This variable is negatively associated with the possibilities of minor injury and serious injury/fatality, and positively associated with the possibility of no injury in the estimated models for $\Delta v > 10$ mph during COVID-19.

Turning to the location of the first harmful event, the location being off-roadway is positively associated with the possibility of serious injury/fatality, and negatively associated with the possibilities of no injury and minor injury in the estimated models for $\Delta v \leq 0$ mph pre and during COVID-19, and 0 mph $< \Delta v \leq 10$ mph pre and post COVID-19, as shown in Fig. 16(a). In the estimated model for $\Delta v \leq 0$ mph post COVID-19, this variable is positively associated with the possibilities of minor injury and serious injury/fatality, and negatively associated with the possibility of no injury. Moreover, this variable is positively associated with the possibility of minor injury, and negatively associated with the possibilities of no injury and serious injury/fatality in the estimated model for $\Delta v > 10$ mph during COVID-19. Overall, the location being off-roadway is found to decrease the possibility of no injury in all the models.

As shown in Fig. 16(b), in the estimated models for $\Delta v \leq 0$ mph

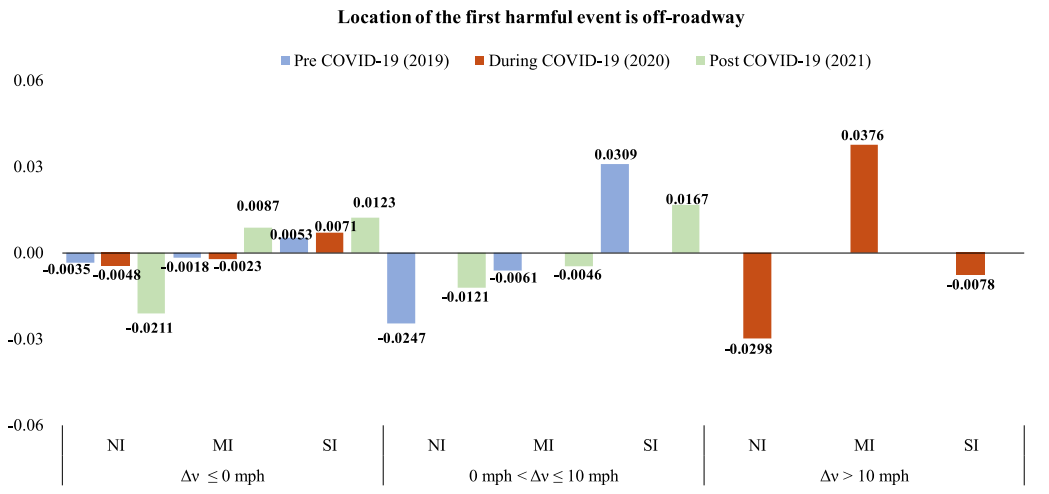


(a) Vehicle's most damage area is front center bumper

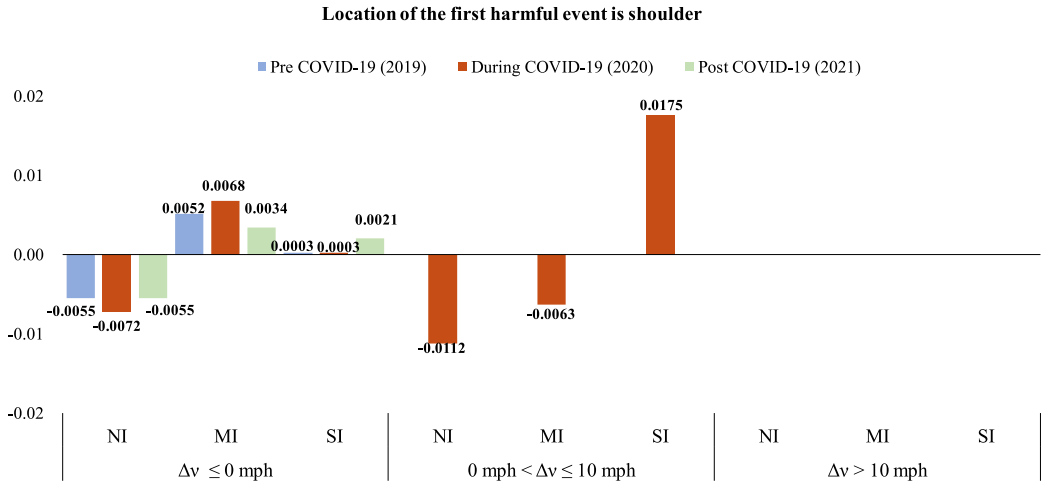


(b) Vehicle's most damage area is front right bumper

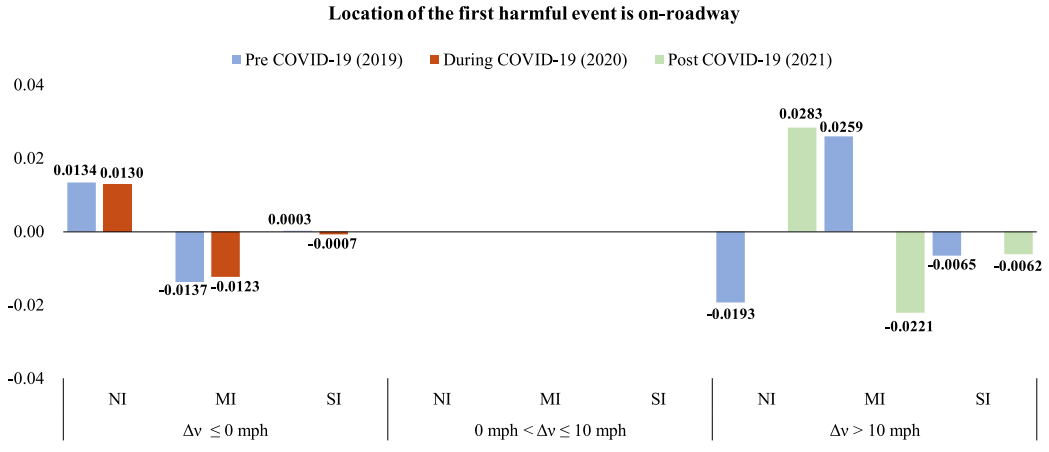
Fig. 15. The marginal effects of most damage area indicator based on temporal unconstrained approach corresponding to all the injury severity outcomes: NI (No Injury); MI (Minor Injury); SI (Serious Injury/Fatality).



(a) Location of the first harmful event is off-roadway



(b) Location of the first harmful event is shoulder



(c) Location of the first harmful event is on-roadway

Fig. 16. The marginal effects of location of the first harmful event based on temporal unconstrained approach corresponding to all the injury severity outcomes: NI (No Injury); MI (Minor Injury); SI (Serious Injury/Fatality).

across all the periods, the location being shoulder is positively associated with the possibilities of minor injury and serious injury/fatality, and negatively associated with the possibility of no injury. In the meanwhile, in the estimated model for 0 mph $< \Delta v \leq$ 10 mph during COVID-19, this variable is positively associated with the possibility of serious injury/fatality, and negatively associated with the possibilities of no injury and minor injury.

Moreover, the location being on-roadway also have corresponding effect on the injury severity of run-off-road crashes. In the estimated models for $\Delta v \leq 0$ mph during COVID-19 and $\Delta v >$ 10 mph post COVID-19, this variable is associated with the increased likelihood of no injury, and the decreased likelihoods of minor injury and serious injury/fatality, as shown in Fig. 16(c). Moreover, in the model for $\Delta v \leq 0$ mph pre COVID-19, this variable is associated with the decreased likelihood of minor injury, and associated with the increased likelihoods of no injury and serious injury/fatality. However, the effect in the estimated model for $\Delta v >$ 10 mph pre COVID-19 is totally converse. It is evident that this variable has the stronger connection with the injury severity of run-off-road crashes for $\Delta v >$ 10 mph situation.

7.7. Temporal characteristics

Weekend is found to increase the likelihood of serious injury/fatality and decrease the likelihoods of no injury and minor injury in the estimated model for $\Delta v \leq 0$ mph post COVID-19. However, this variable has the totally converse effect in the estimated model for $\Delta v >$ 10 mph pre COVID-19.

Additionally, the hurricane season, spanning from June to November, is positively associated with the possibility of no injury, and negatively associated with the possibility of serious injury/fatality in the estimated models for $\Delta v \leq 0$ mph post COVID-19 and 0 mph $< \Delta v \leq$ 10 mph during COVID-19, but decreases the possibility of minor injury for $\Delta v \leq 0$ mph, and increases the possibility of minor injury for 0 mph $< \Delta v \leq$ 10 mph.

Furthermore, driving during day is found to increase the likelihoods of no injury and serious injury/fatality, and decrease the likelihood of minor injury in the estimated models for $\Delta v \leq 0$ mph and $\Delta v >$ 10 mph during COVID-19.

8. Conclusions

To examine the temporal instability and non-transferability of factors influencing single-vehicle run-off-road crashes across different Δv intervals, single-vehicle run-off-road crashes that occurred on Interstate, State and U.S. freeways in Florida from 2019 to 2021 are classified by pre-, during-, and post-COVID-19 pandemic. To explore the difference in temporal instability and non-transferability issues, both temporal unconstrained and partially temporal constrained random parameter logit models are utilized. Considering three injury severity outcomes: no injury, minor injury and serious injury/fatality, various variables in terms of driver, vehicle, roadway, environmental, crash, and temporal attributes are estimated.

Robust outcomes from likelihood ratio tests and out-of-sample predictions affirm the issues of temporal instability and non-transferability, particularly for run-off-road crashes induced by over speeding behaviors ($v >$ 0 mph). The estimation results indicate that a range of relatively stable and unstable indicators influence the injury severity of run-off-road crashes.

Comparing the outcomes from both the partially constrained temporal model and the unconstrained temporal model reveals a distinctive shift. It is apparent that many variables which produced random parameters in the temporally unconstrained model shift to fixed parameters in the partially temporally constrained model. For instance, in the $\Delta v \leq 0$ mph model, several variables such as sunny, cloudy, new vehicle, and dry surface indicators transition to fixed parameters in the partially temporally constrained framework, whereas they were random parameters in the temporally unconstrained model.

Otherwise, calculation of marginal effects sheds light on issues of temporal instability and non-transferability, revealing that certain differences in the effects of contributing factors on the injury severity outcomes with distinct periods and speed intervals. For instance, negotiating curve maneuver makes inconsistent effect in the minor injury and serious injury/fatality for $\Delta v \leq 0$ mph, $0 < \Delta v \leq$ 10 mph, and $\Delta v >$ 10 mph intervals post COVID-19. Other variables such as restraint-protected driving also produced distinct effects in the injury severity levels.

In partially constrained temporal random parameter logit models, several indicators consistently yield identical parameter values across all periods. These include the new vehicle indicator, the male driver indicator, and the restraint-protected driving indicator. Additionally, some indicators show consistent parameter values in two specific periods. Drawing from these observations, long-term recommendations can be formulated. First, efforts to alcohol-impaired and driving drug-impaired driving, and encouraging the use of restraints should be intensified through enhanced publicity and stricter law enforcement, aiming to cultivate safe driving habits. Second, strategically placed signs at curves could serve as reminders for drivers to exercise caution. Lastly, regular vehicle maintenance reminders could ensure that vehicles remain in optimal condition, thereby mitigating risk.

However, the current study has certain limitations. For example, data on braking and lateral offset trajectory prior to running off the road were not collected. Future research could gain from capturing specific driving behaviors in advance, which would aid in comprehending the risk mechanisms of crashes in terms of evasion and risk-compensation behaviors.

CRediT authorship contribution statement

Zhe Wang: Writing – original draft, Validation, Software, Data curation. **Chenzhu Wang:** Writing – review & editing, Writing – original draft, Formal analysis. **Mohamed Abdel-Aty:** Writing – review & editing, Resources, Project administration. **Lei Han:** Data curation. **Helai Huang:** Writing – review & editing, Validation. **Jinjun Tang:** Writing – review & editing, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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The first author conducted this research during her visit to the UCF SST lab.

Appendix A

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Table A1
Descriptive statistics (Std. Dev. in parenthesis) of significant variables for injury severity models of ROR crashes by different intervals of Δv pre, during and post COVID-19 pandemic.

Variable	$\Delta v \leq 0$ mph			0 mph $< \Delta v \leq$ 10 mph			$\Delta v >$ 10 mph		
	Pre-COVID-19 (2019)	During-COVID-19 (2020)	Post-COVID-19 (2021)	Pre-COVID-19 (2019)	During-COVID-19 (2020)	Post-COVID-19 (2021)	Pre-COVID-19 (2019)	During-COVID-19 (2020)	Post-COVID-19 (2021)
The proportion of No Injury	0.649	0.621	0.430	0.673	0.611	0.447	0.654	0.603	0.433
The proportion of Minor Injury	0.297	0.297	0.354	0.276	0.333	0.368	0.285	0.320	0.355
The proportion of Serious Injury/Fatality	0.054	0.082	0.216	0.051	0.056	0.185	0.061	0.077	0.212
Driver Characteristics									
Male driver indicator (1 if male, 0 otherwise)	0.647 (0.478)	0.660 (0.474)	0.655 (0.475)	0.687 (0.464)	0.686 (0.464)	0.686 (0.464)	0.776 (0.418)	0.755 (0.431)	0.744 (0.437)
Driver below 18 years indicator (1 if age below 18 years, 0 otherwise)	0.030 (0.171)	0.029 (0.168)	0.030 (0.170)	0.036 (0.185)	0.042 (0.201)	0.040 (0.196)	0.058 (0.234)	0.074 (0.263)	0.046 (0.210)
Driver 18–30 years indicator (1 if age between 18–30 years, 0 otherwise)	0.432 (0.495)	0.435 (0.496)	0.424 (0.494)	0.530 (0.499)	0.528 (0.499)	0.501 (0.500)	0.575 (0.495)	0.571 (0.495)	0.575 (0.495)
Driver 30–45 years indicator (1 if age between 30–45 years, 0 otherwise)	0.281 (0.450)	0.294 (0.456)	0.301 (0.459)	0.277 (0.448)	0.271 (0.445)	0.285 (0.452)	0.237 (0.426)	0.258 (0.438)	0.271 (0.445)
Driver above 45 years indicator (1 if age above 45 years, 0 otherwise)	0.256 (0.437)	0.242 (0.428)	0.245 (0.430)	0.157 (0.364)	0.159 (0.366)	0.174 (0.380)	0.129 (0.336)	0.097 (0.296)	0.109 (0.311)
Vehicle Characteristics									
Passenger car indicator (1 if passenger car, 0 otherwise)	0.630 (0.483)	0.629 (0.483)	0.623 (0.485)	0.690 (0.463)	0.678 (0.467)	0.674 (0.469)	0.704 (0.457)	0.734 (0.442)	0.735 (0.442)
SUV indicator (1 if sport utility vehicle (SUV), 0 otherwise)	0.167 (0.373)	0.169 (0.374)	0.175 (0.380)	0.142 (0.349)	0.161 (0.368)	0.169 (0.375)	0.121 (0.327)	0.121 (0.326)	0.120 (0.325)
Van indicator (1 if van, 0 otherwise)	0.024 (0.153)	0.028 (0.165)	0.027 (0.163)	0.022 (0.145)	0.018 (0.134)	0.022 (0.146)	0.016 (0.125)	0.016 (0.126)	0.017 (0.128)
Bus indicator (1 if bus, 0 otherwise)	0.000 (0.021)	0.000 (0.021)	0.001 (0.026)	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)
Truck indicator (1 if truck, 0 otherwise)	0.031 (0.172)	0.029 (0.166)	0.026 (0.159)	0.009 (0.094)	0.010 (0.098)	0.012 (0.109)	0.013 (0.114)	0.000 (0.000)	0.011 (0.105)
Other vehicle indicator (1 if other types of vehicles, 0 otherwise)	0.149 (0.356)	0.145 (0.352)	0.148 (0.355)	0.137 (0.344)	0.133 (0.340)	0.124 (0.329)	0.145 (0.353)	0.129 (0.335)	0.118 (0.323)
New vehicle indicator (1 if auto age less than 10 years, 0 otherwise)	0.488 (0.500)	0.535 (0.499)	0.533 (0.499)	0.476 (0.500)	0.523 (0.500)	0.517 (0.500)	0.520 (0.500)	0.523 (0.500)	0.527 (0.500)
Roadway Characteristics									
Level indicator (1 if level grade, 0 otherwise)	0.887 (0.316)	0.895 (0.306)	0.897 (0.304)	0.886 (0.318)	0.853 (0.354)	0.853 (0.355)	0.873 (0.333)	0.885 (0.319)	0.849 (0.358)
Curve indicator (1 if curved alignment, 0 otherwise)	0.132 (0.338)	0.127 (0.333)	0.127 (0.334)	0.162 (0.369)	0.195 (0.397)	0.192 (0.394)	0.274 (0.447)	0.227 (0.420)	0.278 (0.448)
Lane_2 indicator (1 if crash occurred on two lanes on each side of road, 0 otherwise)	0.192 (0.394)	0.177 (0.382)	0.202 (0.402)	0.216 (0.412)	0.170 (0.375)	0.199 (0.400)	0.274 (0.447)	0.231 (0.422)	0.252 (0.435)
Urban areas indicator (1 if roadway is urban, 0 otherwise)	0.387 (0.487)	0.404 (0.491)	0.376 (0.484)	0.425 (0.495)	0.484 (0.500)	0.464 (0.499)	0.427 (0.495)	0.481 (0.500)	0.471 (0.500)
Dry surface indicator (1 if roadway surface is dry, 0 otherwise)	0.553 (0.497)	0.491 (0.500)	0.594 (0.491)	0.523 (0.500)	0.502 (0.500)	0.628 (0.483)	0.755 (0.431)	0.710 (0.454)	0.775 (0.418)
Paved shoulder indicator (1 if shoulder is paved, 0 otherwise)	0.756 (0.430)	0.766 (0.423)	0.751 (0.432)	0.732 (0.443)	0.754 (0.431)	0.715 (0.452)	0.628 (0.484)	0.662 (0.474)	0.595 (0.491)
Unpaved shoulder indicator (1 if shoulder is unpaved, 0 otherwise)	0.137 (0.343)	0.131 (0.337)	0.132 (0.338)	0.155 (0.362)	0.134 (0.341)	0.157 (0.364)	0.201 (0.401)	0.145 (0.352)	0.188 (0.391)
Curb shoulder indicator (1 if shoulder is curb, 0 otherwise)	0.108 (0.310)	0.103 (0.304)	0.117 (0.322)	0.113 (0.317)	0.112 (0.316)	0.128 (0.334)	0.172 (0.377)	0.193 (0.395)	0.217 (0.413)
One-way indicator (1 if traffic way is one-way, 0 otherwise)	0.064 (0.244)	0.058 (0.233)	0.061 (0.240)	0.065 (0.246)	0.065 (0.246)	0.054 (0.226)	0.069 (0.253)	0.060 (0.238)	0.085 (0.279)
Two-way-divided indicator (1 if traffic way is two-way and divided, 0 otherwise)	0.803 (0.398)	0.819 (0.385)	0.801 (0.399)	0.788 (0.409)	0.828 (0.377)	0.807 (0.395)	0.707 (0.456)	0.765 (0.425)	0.746 (0.436)
Two-way-no-divided indicator (1 if traffic way is two-way and not divided, 0 otherwise)	0.133 (0.339)	0.123 (0.328)	0.137 (0.344)	0.147 (0.355)	0.107 (0.309)	0.138 (0.345)	0.222 (0.416)	0.175 (0.380)	0.169 (0.375)
Traffic control sign indicator (1 if traffic control sign, 0 otherwise)	0.064 (0.245)	0.050 (0.219)	0.060 (0.237)	0.062 (0.242)	0.048 (0.213)	0.067 (0.250)	0.121 (0.327)	0.093 (0.290)	
Environmental Characteristics									
Sunny indicator (1 if sunny, 0 otherwise)	0.487 (0.500)	0.436 (0.496)	0.528 (0.499)	0.462 (0.499)	0.460 (0.499)	0.569 (0.496)	0.683 (0.466)	0.636 (0.482)	0.715 (0.452)
Cloudy indicator (1 if cloudy, 0 otherwise)	0.167 (0.373)	0.154 (0.361)	0.155 (0.362)	0.188 (0.391)	0.151 (0.358)	0.154 (0.361)	0.166 (0.373)	0.177 (0.382)	0.140 (0.347)
Rainy indicator (1 if rainy, 0 otherwise)	0.338 (0.473)	0.402 (0.490)	0.305 (0.460)	0.340 (0.474)	0.380 (0.486)	0.264 (0.441)	0.140 (0.347)	0.181 (0.385)	0.134 (0.341)
Other weather indicator (1 if other weather conditions, 0 otherwise)	0.009 (0.092)	0.008 (0.088)	0.012 (0.111)	0.010 (0.100)	0.009 (0.093)	0.013 (0.113)	0.011 (0.102)	0.006 (0.078)	0.011 (0.105)
Daylight indicator (1 if daylight, 0 otherwise)	0.534 (0.499)	0.542 (0.498)	0.500 (0.500)	0.459 (0.499)	0.475 (0.500)	0.431 (0.496)	0.367 (0.483)	0.362 (0.481)	0.326 (0.469)
Lighted in dark indicator (1 if lighted during nighttime, 0 otherwise)	0.270 (0.444)	0.262 (0.440)	0.284 (0.451)	0.299 (0.458)	0.313 (0.464)	0.330 (0.471)	0.406 (0.492)	0.412 (0.493)	0.427 (0.495)

(*continued on next page*)

Table A1 (*continued*)

Variable	$\Delta v \leq 0$ mph			0 mph $< \Delta v \leq$ 10 mph			$\Delta v >$ 10 mph		
	Pre-COVID-19 (2019)	During-COVID-19 (2020)	Post-COVID-19 (2021)	Pre-COVID-19 (2019)	During-COVID-19 (2020)	Post-COVID-19 (2021)	Pre-COVID-19 (2019)	During-COVID-19 (2020)	Post-COVID-19 (2021)
No-lighted in dark indicator (1 if not lighted during nighttime, 0 otherwise)	0.135 (0.341)	0.127 (0.333)	0.149 (0.356)	0.174 (0.379)	0.147 (0.354)	0.170 (0.376)	0.158 (0.366)	0.169 (0.375)	0.195 (0.397)
Other light condition indicator (1 if other light condition, 0 otherwise)	0.061 (0.239)	0.069 (0.254)	0.067 (0.249)	0.067 (0.251)	0.065 (0.246)	0.068 (0.252)	0.069 (0.253)	0.056 (0.231)	0.052 (0.221)
Crash Characteristics									
Straight ahead indicator (1 if maneuver action is straight ahead, 0 otherwise)	0.738 (0.440)	0.736 (0.441)	0.713 (0.453)	0.728 (0.445)	0.695 (0.460)	0.705 (0.456)	0.602 (0.490)	0.612 (0.488)	0.586 (0.493)
Lane-changing indicator (1 if maneuver action is changing lanes, 0 otherwise)	0.092 (0.290)	0.095 (0.293)	0.107 (0.309)	0.102 (0.302)	0.117 (0.321)	0.103 (0.304)	0.119 (0.324)	0.131 (0.338)	0.140 (0.347)
Negotiating curve indicator (1 if maneuver action is negotiating curve, 0 otherwise)	0.091 (0.287)	0.084 (0.277)	0.093 (0.290)	0.093 (0.290)	0.103 (0.304)	0.104 (0.305)	0.179 (0.384)	0.157 (0.364)	0.184 (0.388)
Distracted driving indicator (1 if distracted driving, 0 otherwise)	0.127 (0.333)	0.121 (0.326)	0.131 (0.338)	0.135 (0.341)	0.135 (0.342)	0.129 (0.335)	0.145 (0.353)	0.159 (0.366)	0.151 (0.358)
Alcohol-impaired driving indicator (1 if Alcohol-impaired driving, 0 otherwise)	0.050 (0.217)	0.042 (0.201)	0.054 (0.225)	0.086 (0.281)	0.070 (0.256)	0.086 (0.280)	0.198 (0.399)	0.177 (0.382)	0.153 (0.360)
Drug-impaired driving indicator (1 if drug −impaired driving, 0 otherwise)	0.017 (0.129)	0.016 (0.125)	0.021 (0.145)	0.044 (0.206)	0.019 (0.138)	0.029 (0.169)	0.069 (0.253)	0.093 (0.290)	0.087 (0.281)
Restraint-protected driving indicator (1 if restraint-protected driving, 0 otherwise)	0.950 (0.219)	0.952 (0.213)	0.944 (0.231)	0.918 (0.275)	0.909 (0.287)	0.912 (0.283)	0.741 (0.438)	0.777 (0.417)	0.753 (0.432)
Front center bumper indicator (1 if vehicle most damage area is front center bumper, 0 otherwise)	0.374 (0.484)	0.369 (0.482)	0.367 (0.482)	0.368 (0.483)	0.377 (0.485)	0.359 (0.480)	0.388 (0.488)	0.388 (0.488)	0.374 (0.484)
Front left bumper indicator (1 if vehicle most damage area is front left bumper, 0 otherwise)	0.111 (0.314)	0.117 (0.321)	0.114 (0.318)	0.114 (0.318)	0.111 (0.315)	0.098 (0.297)	0.100 (0.301)	0.082 (0.275)	0.096 (0.295)
Front right bumper indicator (1 if vehicle most damage area is front right bumper, 0 otherwise)	0.100 (0.301)	0.098 (0.297)	0.104 (0.305)	0.109 (0.312)	0.090 (0.286)	0.093 (0.291)	0.071 (0.258)	0.060 (0.238)	0.081 (0.273)
Off roadway indicator (1 if crash location is off roadway, 0 otherwise)	0.409 (0.492)	0.433 (0.496)	0.444 (0.497)	0.439 (0.497)	0.404 (0.491)	0.395 (0.489)	0.451 (0.498)	0.439 (0.497)	0.449 (0.498)
On roadway indicator * (1 if crash location is on roadway, 0 otherwise)	0.267 (0.442)	0.257 (0.437)	0.262 (0.440)	0.222 (0.416)	0.240 (0.427)	0.268 (0.443)	0.261 (0.440)	0.225 (0.418)	0.260 (0.439)
Shoulder indicator (1 if crash location is on shoulder, 0 otherwise)	0.219 (0.414)	0.204 (0.403)	0.194 (0.396)	0.225 (0.418)	0.205 (0.404)	0.207 (0.405)	0.201 (0.401)	0.225 (0.418)	0.203 (0.402)
Median indicator (1 if crash location is on median, 0 otherwise)	0.105 (0.307)	0.106 (0.308)	0.099 (0.299)	0.114 (0.318)	0.151 (0.358)	0.130 (0.336)	0.087 (0.282)	0.111 (0.314)	0.088 (0.284)
Temporal Characteristics									
Hurricane indicator (1 if crash occurred in hurricane season (June to November), 0 otherwise)	0.552 (0.497)	0.619 (0.486)	0.569 (0.495)	0.549 (0.498)	0.602 (0.490)	0.570 (0.495)	0.520 (0.500)	0.592 (0.492)	0.530 (0.500)
Weekend indicator (1 if crash occurred on weekend, 0 otherwise)	0.351 (0.477)	0.354 (0.478)	0.330 (0.470)	0.386 (0.487)	0.401 (0.490)	0.364 (0.481)	0.422 (0.495)	0.421 (0.494)	0.411 (0.492)
Day indicator (1 if crash occurred during the day, 0 otherwise)	0.540 (0.498)	0.541 (0.498)	0.502 (0.500)	0.471 (0.499)	0.481 (0.500)	0.420 (0.494)	0.361 (0.481)	0.360 (0.481)	0.317 (0.466)

Appendix B

Table B1
Model results of injury severity of single vehicle run-off-road crashes caused by $\Delta v \leq 0$ mph pre, during and post COVID-19 pandemic (t-statistics in parentheses) based on the unconstrained random parameter logit models with heterogeneity in means *.

Variable	$\Delta v \leq 0$ mph					
	Pre COVID-19 (2019)		During COVID-19 (2020)		Post COVID-19 (2021)	
	Parameter estimate	Z value	Parameter estimate	Z value	Parameter estimate	Z value
[NI] Constant	2.546	8.99	2.889	8.48	4.305	6.59
[MI] Constant	3.072	10.4	3.424	9.20	4.627	6.59
Driver Characteristics						
[NI] Driver below 18 years indicator (1 if age below 18 years, 0 otherwise)	0.236	1.68			0.297	2.15
[MI] Male driver indicator (1 if male, 0 otherwise)	−0.353	−7.19	−0.365	−7.87	−0.361	−7.44
[MI] Driver 18–30 years indicator (1 if age between 18–30 years, 0 otherwise)	−0.129	−2.64				
[SI] Driver 30–45 years indicator (1 if age between 30–45 years, 0 otherwise)	−0.668	−2.52				
[MI] Driver below 18 years indicator (1 if age below 18 years, 0 otherwise)			−0.392	−2.74		
[MI] Driver 30–45 years indicator (1 if age between 30–45 years, 0 otherwise)			0.109	2.04		

(*continued on next page*)

Table B1 (*continued*)

Variable	$\Delta v \leq 0$ mph					
	Pre COVID-19 (2019)		During COVID-19 (2020)		Post COVID-19 (2021)	
	Parameter estimate	Z value	Parameter estimate	Z value	Parameter estimate	Z value
[MI] Driver above 45 years indicator (1 if age above 45 years, 0 otherwise)			0.281	4.89	0.163	2.99
[SI] Driver below 18 years indicator (1 if age below 18 years, 0 otherwise)			−4.324	−2.99	−1.698	−2.24
[SI] Driver 18–30 years indicator (1 if age between 18–30 years, 0 otherwise)			−1.095	−4.09		
Vehicle Characteristics						
[MI] SUV indicator (1 if sport utility vehicle (SUV), 0 otherwise)	0.155	2.47				
[SI] Passenger car indicator (1 if passenger car, 0 otherwise)	−0.885	−3.78				
[MI] Passenger car indicator (1 if passenger car, 0 otherwise)			−0.127	−2.66	−0.225	−3.57
[MI] New vehicle indicator (1 if auto age less than 10 years, 0 otherwise)			−0.0139	−3.08		
[SI] SUV indicator (1 if sport utility vehicle (SUV), 0 otherwise)			−0.822	−2.62		
[NI] SUV indicator (1 if sport utility vehicle (SUV), 0 otherwise)					0.153	1.99
[MI] Truck indicator (1 if truck, 0 otherwise)					−0.530	−3.23
Roadway Characteristics						
[NI] Two-way-divided indicator (1 if traffic way is two-way and divided, 0 otherwise)	−0.201	−2.01				
[NI] Two-way-no-divided indicator (1 if traffic way is two-way and not divided, 0 otherwise)	−0.315	−2.69				
[NI] Level indicator (1 if level grade, 0 otherwise)	0.150	2.02	0.143	1.95		
[NI] Dry surface indicator (1 if roadway surface is dry, 0 otherwise)	−0.373	−7.62	−0.247	−3.32		
[SI] Curve indicator (1 if curved alignment, 0 otherwise)	0.663	2.30	0.907	2.8	2.097	4.94
[SI] Urban areas indicator (1 if roadway is urban, 0 otherwise)	−0.981	−3.79	−0.565	−2.37	−0.635	−2.48
[NI] Curb shoulder indicator (1 if shoulder is curb, 0 otherwise)			−0.122	−1.68		
[NI] One-way indicator (1 if traffic way is one-way, 0 otherwise)			0.181	1.84		
[MI] Traffic control sign indicator (1 if traffic control sign, 0 otherwise)			−0.314	−2.96		
[MI] Curve indicator (1 if curved alignment, 0 otherwise)			0.156	2.25	0.236	3.39
[SI] Two-way-no-divided indicator (1 if traffic way is two-way and not divided, 0 otherwise)			0.992	2.86		
[NI] Lane_2 indicator (1 if crash occurred on two lanes on each side of road, 0 otherwise)					0.148	2.5
[MI] Dry surface indicator (1 if roadway surface is dry, 0 otherwise)					0.386	7.78
[MI] Paved shoulder indicator (1 if shoulder is paved, 0 otherwise)					−0.238	−4.47
[MI] Urban areas indicator (1 if roadway is urban, 0 otherwise)					−0.161	−3.31
[SI] Dry surface indicator (1 if roadway surface is dry, 0 otherwise)					2.235	5.57
Environmental Characteristics						
[MI] Cloudy indicator (1 if cloudy, 0 otherwise)	0.173	2.75			0.279	4.46
[MI] Rainy indicator (1 if rainy, 0 otherwise)			−0.236	−3.05		
[SI] Cloudy indicator (1 if cloudy, 0 otherwise)			0.677	2.58	0.704	2.44
[SI] No-lighted in dark indicator (1 if not lighted during nighttime, 0 otherwise)					0.862	2.76
Crash Characteristics						
[NI] Shoulder indicator (1 if crash location is on shoulder, 0 otherwise)	−0.118	−2.00	−0.170	−3.03		
[MI] Restraint-protected driving indicator (1 if restraint-protected driving, 0 otherwise)	−1.386	−11.35	−1.127	−10.13	−1.164	−10.01
[MI] Straight ahead indicator (1 if maneuver action is straight ahead, 0 otherwise)	−0.184	−3.44				
[MI] Front center bumper indicator (1 if vehicle most damage area is front center bumper, 0 otherwise)	0.357	7.39	0.295	6.31	0.344	7.34
[MI] Drug-impaired driving indicator (1 if drug −impaired driving, 0 otherwise)	0.591	3.09			0.349	2.08
[MI] On roadway indicator (1 if crash location is on roadway, 0 otherwise)	−0.288	−4.94				
[SI] Off roadway indicator (1 if crash location is off roadway, 0 otherwise)	0.583	2.6	0.757	3.14		
[SI] Alcohol-impaired driving indicator (1 if Alcohol-impaired driving, 0 otherwise)	1.485	3.38	1.347	2.79	1.073	2.23
[SI] Drug-impaired driving indicator (1 if drug −impaired driving, 0 otherwise)	4.648	4.95	4.853	5.43	4.253	5.16
[SI] Front right bumper indicator (1 if vehicle most damage area is front right bumper, 0 otherwise)	−1.526	−2.89				
[SI] Lane-changing indicator (1 if maneuver action is changing lanes, 0 otherwise)	0.765	2.26				
[NI] On roadway indicator (1 if crash location is on roadway, 0 otherwise)			0.287	5.26		
[MI] Lane-changing indicator (1 if maneuver action is changing lanes, 0 otherwise)			0.187	2.54	0.146	2.02
[MI] Front right bumper indicator (1 if vehicle most damage area is front right bumper, 0 otherwise)			−0.208	−2.59		
[SI] Negotiating curve indicator (1 if maneuver action is negotiating curve, 0 otherwise)			−0.951	−2.05	−1.114	−2.37
[MI] Distracted driving indicator (1 if distracted driving, 0 otherwise)					0.121	1.83
[MI] Shoulder indicator (1 if crash location is on shoulder, 0 otherwise)					0.223	3.39
[MI] Off roadway indicator (1 if crash location is off roadway, 0 otherwise)					0.297	5.56
[SI] Shoulder indicator (1 if crash location is on shoulder, 0 otherwise)					0.898	3.20
Temporal Characteristics						
[NI] Hurricane indicator (1 if crash occurred in hurricane season (June to November), 0 otherwise)					0.102	2.19
[SI] Weekend indicator (1 if crash occurred on weekend, 0 otherwise)					0.624	2.39
[MI] Day indicator (1 if crash occurred during the day, 0 otherwise)			−0.075	−1.67		
Random parameters						
[SI] Sunny indicator (1 if sunny, 0 otherwise)	−7.814	−3.37				
Standard deviation	***7.703***	***4.52***				
[SI] Cloudy indicator (1 if cloudy, 0 otherwise)	−6.030	−2.14				
Standard deviation	***6.627***	***3.21***				
[SI] Driver 18–30 years indicator (1 if age between 18–30 years, 0 otherwise)	−2.066	−2.83			−4.787	−3.84
Standard deviation	***1.645***	***2.32***			***4.300***	***4.13***
[SI] New vehicle indicator (1 if auto age less than 10 years, 0 otherwise)	−1.726	−2.48	−1.555	−2.6	−1.242	−2.09
Standard deviation	***2.277***	***3.86***	***1.500***	***2.42***	***1.532***	***1.67***
[SI] Dry surface indicator (1 if roadway surface is dry, 0 otherwise)			−4.965	−2.82		
Standard deviation			***7.052***	***4.53***		
[SI] Front right bumper indicator (1 if vehicle most damage area is front right bumper, 0 otherwise)			−2.661	−1.77		
Standard deviation			***2.702***	***2.1***		
[SI] Passenger car indicator (1 if passenger car, 0 otherwise)			−2.649	−3.51	−1.813	−2.86

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Table B1 (*continued*)

Variable	Δν ≤ 0 mph					
	Pre COVID-19 (2019)		During COVID-19 (2020)		Post COVID-19 (2021)	
	Parameter estimate	Z value	Parameter estimate	Z value	Parameter estimate	Z value
Standard deviation			***2.902***	***5.05***	***2.527***	***3.27***
[SI] Truck indicator (1 if truck, 0 otherwise)			−6.286	−2.05		
Standard deviation			***3.125***	***1.98***		
[SI] Driver 30–45 years indicator (1 if age between 30–45 years, 0 otherwise)			−1.591	−2.27	−2.558	−2.98
Standard deviation			***2.157***	***3.27***	***3.484***	***3.86***
[SI] Off roadway indicator (1 if crash location is off roadway, 0 otherwise)					−3.648	−2.48
Standard deviation					***6.318***	***4.28***
[SI] Paved shoulder indicator (1 if shoulder is paved, 0 otherwise)					−1.419	−2.38
Standard deviation					***2.173***	***2.85***
Heterogeneity in the means of random parameters						
[SI] Sunny indicator (1 if sunny, 0 otherwise): Weekend indicator (1 if crash occurred on weekend, 0 otherwise)	1.214	2.12				
[SI] Driver 18–30 years indicator (1 if age between 18–30 years, 0 otherwise): Distracted driving indicator (1 if distracted driving, 0 otherwise)	1.579	2.84				
[SI] New vehicle indicator (1 if auto age less than 10 years, 0 otherwise): Hurricane indicator (1 if crash occurred in hurricane season (June to November), 0 otherwise)			0.795	1.77		
[SI] New vehicle indicator (1 if auto age less than 10 years, 0 otherwise): Distracted driving indicator (1 if distracted driving, 0 otherwise)			−1.232	−1.84		
[SI] Passenger car indicator (1 if passenger car, 0 otherwise): Distracted driving indicator (1 if distracted driving, 0 otherwise)			1.162	1.94		
[SI] Truck indicator (1 if truck, 0 otherwise): Lane_2 indicator (1 if crash occurred on two lanes on each side of road, 0 otherwise)			3.566	1.69		
[SI] Driver 30–45 years indicator (1 if age between 30–45 years, 0 otherwise): Lane_2 indicator (1 if crash occurred on two lanes on each side of road, 0 otherwise)			−1.070	−1.68		
[SI] New vehicle indicator (1 if auto age less than 10 years, 0 otherwise): Traffic control sign indicator (1 if traffic control sign, 0 otherwise)					2.083	2.64
[SI] Driver 18–30 years indicator (1 if age between 18–30 years, 0 otherwise): Lighted in dark indicator (1 if lighted during nighttime, 0 otherwise)					1.479	2.22
[SI] Driver 30–45 years indicator (1 if age between 30–45 years, 0 otherwise): Traffic control sign indicator (1 if traffic control sign, 0 otherwise)					−2.232	−1.84
Model statistics						
Number of observations (N)	9240		10,976		10,191	
Log-likelihood at zero	−10151.178		−12058.368		−11195.958	
Log-likelihood at convergence	−7041.461		−8058.333		−7765.842	
$\rho^2 = 1 - LL(\beta)/LL(0)$	0.31		0.33		0.31	

*Parameter defined for: [NI] No (Considering the length of the manuscript, the model estimated for $\Delta\nu \leq 0$ mph pre COVID-19 is taken as an example: the χ^2 values obtained by likelihood ratio test are 86.243 and 14.476, with corresponding degrees of freedom of 2 and 2 for traditional logit model VS random parameter logit model with heterogeneity in means and variance, and random parameter logit model VS random parameter logit model with heterogeneity in means and variance, respectively. This means that the simplified model hypothesis can be rejected with 99% confidence and the random parameter logit model with heterogeneity in means and variance model fits the data significantly better than the simplified model. For the remaining models, the conclusions are consistent, indicating that more complex models produce more accurate results.) Injury; [MI] Minor Injury; [SI] Serious Injury/Fatality.

Table B2
Model results of injury severity of single vehicle run-off-road crashes caused by 0 mph $< \Delta\nu \leq$ 10 mph pre, during and post COVID-19 pandemic (t-statistics in parentheses) based on the unconstrained random parameter logit models with heterogeneity in means.*

Variable	0 mph < Δν ≤ 10 mph					
	Pre COVID-19 (2019)		During COVID-19 (2020)		Post COVID-19 (2021)	
	Parameter estimate	Z value	Parameter estimate	Z value	Parameter estimate	Z value
[NI] Constant	−1.322	−2.19				
[SI] Constant	−4.440	−5.67				
Driver Characteristics						
[MI] Driver 18–30 years indicator (1 if age between 18–30 years, 0 otherwise)	−0.635	−1.74				
[MI] Male driver indicator (1 if male, 0 otherwise)	−1.391	−2.43			−0.871	−3.51
[NI] Male driver indicator (1 if male, 0 otherwise)			0.452	4.17		
[SI] Driver above 45 years indicator (1 if age above 45 years, 0 otherwise)			1.918	3.13		
[MI] Driver above 45 years indicator (1 if age above 45 years, 0 otherwise)					0.707	2.14
Vehicle Characteristics						
[SI] Passenger car indicator (1 if passenger car, 0 otherwise)	−0.958	−3.27			−0.560	−2.07
[MI] Van indicator (1 if van, 0 otherwise)					1.530	1.74
[MI] New vehicle indicator (1 if auto age less than 10 years, 0 otherwise)					−0.712	−2.85
[SI] New vehicle indicator (1 if auto age less than 10 years, 0 otherwise)					−0.939	−3.1

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Table B2 (*continued*)

Variable	0 mph < Δν ≤ 10 mph					
	Pre COVID-19 (2019)		During COVID-19 (2020)		Post COVID-19 (2021)	
	Parameter estimate	Z value	Parameter estimate	Z value	Parameter estimate	Z value
Roadway Characteristics						
[SI] Level indicator (1 if level grade, 0 otherwise)			−1.247	−2.81		
[NI] Curve indicator (1 if curved alignment, 0 otherwise)					1.151	2.69
[SI] Curve indicator (1 if curved alignment, 0 otherwise)					1.863	3.78
Environmental Characteristics						
[SI] Daylight indicator (1 if daylight, 0 otherwise)	0.700	1.91				
[SI] No-lighted in dark indicator (1 if not lighted during nighttime, 0 otherwise)	1.059	2.62				
[SI] Sunny indicator (1 if sunny, 0 otherwise)	1.065	2.66				
[SI] Cloudy indicator (1 if cloudy, 0 otherwise)	1.047	2.25				
[MI] No-lighted in dark indicator (1 if not lighted during nighttime, 0 otherwise)			0.474	2.46		
[MI] Rainy indicator (1 if rainy, 0 otherwise)			−0.896	−6.23		
Crash Characteristics						
[SI] Alcohol-impaired driving indicator (1 if Alcohol-impaired driving, 0 otherwise)	0.975	2.35	2.178	3.33	0.776	1.80
[SI] Drug-impaired driving indicator (1 if drug −impaired driving, 0 otherwise)	1.641	3.25			1.822	2.58
[SI] Front center bumper indicator (1 if vehicle most damage area is front center bumper, 0 otherwise)	−0.635	−1.94				
[SI] Front right bumper indicator (1 if vehicle most damage area is front right bumper, 0 otherwise)	−3.000	−2.8				
[SI] Off roadway indicator (1 if crash location is off roadway, 0 otherwise)	0.803	2.71			0.563	2.18
[MI] Front right bumper indicator (1 if vehicle most damage area is front left bumper, 0 otherwise)			−0.824	−2.92		
[MI] Lane-changing indicator (1 if maneuver action is changing lanes, 0 otherwise)			0.489	2.33		
[SI] Shoulder indicator (1 if crash location is on shoulder, 0 otherwise)			1.766	2.59		
[MI] Drug-impaired driving indicator (1 if drug −impaired driving, 0 otherwise)					1.567	2.17
[MI] Straight ahead indicator (1 if maneuver action is straight ahead, 0 otherwise)					0.751	2.89
[MI] Negotiating curve indicator (1 if maneuver action is negotiating curve, 0 otherwise)					1.743	3.36
[SI] Restraint-protected driving indicator (1 if restraint-protected driving, 0 otherwise)					−2.349	−8.93
Temporal Characteristics						
[SI] Hurricane indicator (1 if crash occurred in hurricane season (June to November), 0 otherwise)			1.766	2.59		
Random parameters						
[MI] Restraint-protected driving indicator (1 if restraint-protected driving, 0 otherwise)	−2.461	−1.99				
Standard deviation	***3.606***	***1.77***				
[SI] Restraint-protected driving indicator (1 if restraint-protected driving, 0 otherwise)			−5.076	−2.24		
Standard deviation			***2.955***	***1.91***		
[MI] Two-way-divided indicator (1 if traffic way is two-way and divided, 0 otherwise)					−2.004	−2.76
Standard deviation					***3.113***	***2.65***
Heterogeneity in the means of random parameters						
[MI] Restraint-protected driving indicator (1 if restraint-protected driving, 0 otherwise): Other vehicle indicator (1 if other types of vehicles, 0 otherwise)	2.013	1.98				
[MI] Two-way-divided indicator (1 if traffic way is two-way and divided, 0 otherwise): Weekend indicator (1 if crash occurred on weekend, 0 otherwise)					0.697	1.71
[MI] Two-way-divided indicator (1 if traffic way is two-way and divided, 0 otherwise): Front center bumper indicator (1 if vehicle most damage area is front center bumper, 0 otherwise)					0.686	1.65
Model statistics						
Number of observations (N)	788		926		923	
Log-likelihood at zero	−865.706		−1017.315		−1014.019	
Log-likelihood at convergence	−624.451		−697.616		−715.820	
$\rho^2 = 1 - LL(\beta)/LL(0)$	0.28		0.31		0.29	

*Parameter defined for: [NI] No Injury; [MI] Minor Injury; [SI] Serious Injury/Fatality.

Table B3
Model results of injury severity of single vehicle run-off-road crashes caused by $\Delta\nu > 10$ mph pre, during and post COVID-19 pandemic (t-statistics in parentheses) based on the unconstrained random parameter logit models with heterogeneity in means *.

Variable	Δν > 10 mph					
	Pre COVID-19 (2019)		During COVID-19 (2020)		Post COVID-19 (2021)	
	Parameter estimate	Z value	Parameter estimate	Z value	Parameter estimate	Z value
[NI] Constant	−0.622	−1.76			−1.182	−3.54
[MI] Constant	−0.959	−2.31				
Driver Characteristics						
[NI] Driver 18–30 years indicator (1 if age between 18–30 years, 0 otherwise)	0.539	2.26				
[NI] Male driver indicator (1 if male, 0 otherwise)			0.241	1.66	0.438	2.00
[SI] Driver above 45 years indicator (1 if age above 45 years, 0 otherwise)			1.611	2.52	0.948	2.18
Roadway Characteristics						
[N] One-way indicator (1 if traffic way is one-way, 0 otherwise)	0.825	1.76				
[MI] Dry surface indicator (1 if roadway surface is dry, 0 otherwise)	0.734	2.63				
[SI] Curve indicator (1 if curved alignment, 0 otherwise)	1.303	2.94				

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Table B3 (*continued*)

Variable	Δν > 10 mph					
	Pre COVID-19 (2019)		During COVID-19 (2020)		Post COVID-19 (2021)	
	Parameter estimate	Z value	Parameter estimate	Z value	Parameter estimate	Z value
[SI] Unpaved shoulder indicator (1 if shoulder is unpaved, 0 otherwise)	−1.483	−2.7				
[SI] One-way indicator (1 if traffic way is one-way, 0 otherwise)			−2.477	−2.03		
[SI] Traffic control sign indicator (1 if traffic control sign, 0 otherwise)			−1.563	−2.11		
[NI] Curve indicator (1 if curved alignment, 0 otherwise)					−0.397	−1.66
[SI] Level indicator (1 if level grade, 0 otherwise)					1.159	3.43
[SI] Lane_2 indicator (1 if crash occurred on two lanes on each side of road, 0 otherwise)					−1.229	−3.31
Environmental Characteristics						
[NI] Lighted in dark indicator (1 if lighted during nighttime, 0 otherwise)	−0.537	−2.23				
[NI] Other light condition indicator (1 if other light condition, 0 otherwise)					0.946	2.07
[SI] Lighted in dark indicator (1 if lighted during nighttime, 0 otherwise)					−0.859	−2.65
Crash Characteristics						
[MI] Straight ahead indicator (1 if maneuver action is straight ahead, 0 otherwise)	−0.611	−2.54				
[MI] On roadway indicator (1 if crash location is on roadway, 0 otherwise)	0.455	1.76				
[SI] Drug-impaired driving indicator (1 if drug −impaired driving, 0 otherwise)	2.810	3.19	1.151	2.18	1.201	2.55
[NI] Front left bumper indicator (1 if vehicle most damage area is front left bumper, 0 otherwise)			0.824	2.31		
[MI] Lane-changing indicator (1 if maneuver action is changing lanes, 0 otherwise)			0.728	2.47		
[MI] Off roadway indicator (1 if crash location is off roadway, 0 otherwise)			0.394	2.16		
[SI] Alcohol-impaired driving indicator (1 if Alcohol-impaired driving, 0 otherwise)			1.597	2.69		
[NI] Restraint-protected driving indicator (1 if restraint-protected driving, 0 otherwise)					1.033	3.72
[NI] On roadway indicator (1 if crash location is on roadway, 0 otherwise)					0.512	2.35
[MI] Negotiating curve indicator (1 if maneuver action is negotiating curve, 0 otherwise)					−0.660	−2.35
[SI] Restraint-protected driving indicator (1 if restraint-protected driving, 0 otherwise)					−1.839	−5.04
Temporal Characteristics						
[SI] Weekend indicator (1 if crash occurred on weekend, 0 otherwise)	−1.163	−2.79				
[MI] Day indicator (1 if crash occurred during the day, 0 otherwise)			−0.616	−3.16		
Random parameters						
[SI] Restraint-protected driving indicator (1 if restraint-protected driving, 0 otherwise)	−3.344	−2.66				
Standard deviation	***2.076***	***1.74***				
[SI] Restraint-protected driving indicator (1 if restraint-protected driving, 0 otherwise)			−3.078	−2.43		
Standard deviation			***2.282***	***1.84***		
[SI] Paved shoulder indicator (1 if shoulder is paved, 0 otherwise)					−1.769	−2.12
Standard deviation					***2.090***	***2.400***
Heterogeneity in the means of random parameters						
[SI] Restraint-protected driving indicator (1 if restraint-protected driving, 0 otherwise): Sunny indicator (1 if sunny, 0 otherwise)	1.220	1.72				
[SI] Restraint-protected driving indicator (1 if restraint-protected driving, 0 otherwise): Traffic control sign indicator (1 if traffic control sign, 0 otherwise)	1.518	1.72				
[SI] Restraint-protected driving indicator (1 if restraint-protected driving, 0 otherwise): Urban areas indicator (1 if roadway is urban, 0 otherwise)	−1.375	−1.89				
[SI] Paved shoulder indicator (1 if shoulder is paved, 0 otherwise): Off roadway indicator (1 if crash location is off roadway, 0 otherwise)					1.688	2.49
[SI] Paved shoulder indicator (1 if shoulder is paved, 0 otherwise): Lane-changing indicator (1 if maneuver action is changing lanes, 0 otherwise)					−1.880	−2.21
Model statistics						
Number of observations (N)	379		497		543	
Log-likelihood at zero	−416.374		−546.010		−596.546	
Log-likelihood at convergence	−345.147		−455.546		−498.632	
$\rho^2 = 1 - LL(\beta)/LL(0)$	0.17		0.17		0.16	

*Parameter defined for: [NI] No Injury; [MI] Minor Injury; [SI] Serious Injury/Fatality.

Table B4

The marginal effects of determinants in injury severity of single vehicle run-off-road crashes caused by $\Delta\nu \leq 0$ mph pre, during and post COVID-19 pandemic based on the unconstrained models*.

Variable	Δν ≤ 0 mph								
	Pre COVID-19 (2019)			During COVID-19 (2020)			Post COVID-19 (2021)		
	NI	MI	SI	NI	MI	SI	NI	MI	SI
Driver Characteristics									
Driver below 18 years indicator (1 if age below 18 years, 0 otherwise)	0.0014	−0.0013	−0.0001	0.0012	−0.0009	−0.0004	0.0011	−0.0007	−0.0005
Driver above 45 years indicator (1 if age above 45 years, 0 otherwise)				−0.0130	0.0135	−0.0006	−0.0073	0.0078	−0.0005
Male driver indicator (1 if male, 0 otherwise)	0.0413	−0.0426	0.0013	0.0422	−0.0435	0.0013	0.0413	−0.0429	0.0016
Driver 18–30 years indicator (1 if age between 18–30 years, 0 otherwise)	0.0067	−0.0047	−0.0021	0.0050	0.0021	−0.0070	−0.0020	−0.0003	0.0023
Driver 30–45 years indicator (1 if age between 30–45 years, 0 otherwise)	0.0023	0.0012	−0.0035	−0.0031	0.0032	−0.0001	−0.0024	−0.0005	0.0029
Vehicle Characteristics									

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Table B4 (*continued*)

Variable	Δv ≤ 0 mph								
	Pre COVID-19 (2019)			During COVID-19 (2020)			Post COVID-19 (2021)		
	NI	MI	SI	NI	MI	SI	NI	MI	SI
Passenger car indicator (1 if passenger car, 0 otherwise)	0.0057	0.0026	−0.0084	0.0066	−0.0072	0.0007	0.0133	−0.0128	−0.0006
SUV indicator (1 if sport utility vehicle (SUV), 0 otherwise)	−0.0051	0.0053	−0.0002	0.0017	0.0009	−0.0026	0.0054	−0.0049	−0.0005
Truck indicator (1 if truck, 0 otherwise)				0.0002	0.0001	−0.0003	0.0020	−0.0022	0.0001
New vehicle indicator (1 if auto age less than 10 years, 0 otherwise)	−0.0009	0.0002	0.0006	0.0072	−0.0064	−0.0008	0.0026	0.0013	−0.0039
Roadway Characteristics									
Two-way-divided indicator (1 if traffic way is two-way and divided, 0 otherwise)	−0.0324	0.0304	0.0020						
Two-way-no-divided indicator (1 if traffic way is two-way and not divided, 0 otherwise)	−0.0089	0.0083	0.0006	−0.0021	−0.0011	0.0031			
Level indicator (1 if level grade, 0 otherwise)	0.0268	−0.0251	−0.0017	0.0249	−0.0233	−0.0015			
Dry surface indicator (1 if roadway surface is dry, 0 otherwise)	−0.0432	0.0411	0.0022	−0.0229	0.0064	0.0165	−0.0327	0.0169	0.0159
Curve indicator (1 if curved alignment, 0 otherwise)	−0.0013	−0.0007	0.0020	−0.0027	0.0016	0.0012	−0.0051	0.0015	0.0037
Urban areas indicator (1 if roadway is urban, 0 otherwise)	0.0035	0.0017	−0.0052	0.0027	−0.0028	0.0001	0.0068	−0.0049	−0.0019
Curb shoulder indicator (1 if shoulder is curb, 0 otherwise)				−0.0026	0.0024	0.0001			
One-way indicator (1 if traffic way is one-way, 0 otherwise)				0.0020	−0.0019	−0.0001			
Traffic control sign indicator (1 if traffic control sign, 0 otherwise)				0.0027	−0.0028	0.0001			
Paved shoulder indicator (1 if shoulder is paved, 0 otherwise							0.0167	−0.0162	−0.0005
Lane_2 indicator (1 if crash occurred on two lanes on each side of road, 0 otherwise)							0.0060	−0.0055	−0.0005
Environmental Characteristics									
Sunny indicator (1 if sunny, 0 otherwise)	−0.0159	−0.0083	0.0242						
Cloudy indicator (1 if cloudy, 0 otherwise)	−0.0056	0.0015	0.0040	−0.0016	−0.0008	0.0023	−0.0050	0.0039	0.0011
Rainy indicator (1 if rainy, 0 otherwise)				0.0159	−0.0163	0.0004			
No-lighted in dark indicator (1 if not lighted during nighttime, 0 otherwise)							−0.0020	−0.0011	0.0032
Crash Characteristics									
Shoulder indicator (1 if crash location is on shoulder, 0 otherwise)	−0.0055	0.0052	0.0003	−0.0072	0.0068	0.0003	−0.0055	0.0034	0.0021
Straight ahead indicator (1 if maneuver action is straight ahead, 0 otherwise)	0.0253	−0.0261	0.0008						
Restraint-protected driving indicator (1 if restraint-protected driving, 0 otherwise)	0.2484	−0.2557	0.0073	0.1948	−0.2003	0.0055	0.2000	−0.2069	0.0069
Front center bumper indicator (1 if vehicle most damage area is front center bumper, 0 otherwise)	−0.0271	0.0280	−0.0009	−0.0215	0.0221	−0.0007	−0.0251	0.0260	−0.0009
Front right bumper indicator (1 if vehicle most damage area is front right bumper, 0 otherwise)	0.0012	0.0005	−0.0018	0.0019	−0.0017	−0.0002			
Drug-impaired driving indicator (1 if drug −impaired driving, 0 otherwise)	−0.0016	0.0001	0.0015	−0.0022	−0.0013	0.0034	−0.0018	−0.0005	0.0023
Negotiating curve indicator (1 if maneuver action is negotiating curve, 0 otherwise)				0.0008	0.0004	−0.0012	0.0013	0.0008	−0.0021
On roadway indicator (1 if crash location is on roadway, 0 otherwise)	0.0134	−0.0137	0.0003	0.0130	−0.0123	−0.0007			
Lane-changing indicator (1 if maneuver action is changing lanes, 0 otherwise)	−0.0011	−0.0006	0.0016	−0.0035	0.0036	−0.0001	−0.0030	0.0032	−0.0001
Off roadway indicator (1 if crash location is off roadway, 0 otherwise)	−0.0035	−0.0018	0.0053	−0.0048	−0.0023	0.0071	−0.0211	0.0087	0.0123
Alcohol-impaired driving indicator (1 if Alcohol-impaired driving, 0 otherwise)	−0.0014	−0.0010	0.0024	−0.0011	−0.0006	0.0017	−0.0012	−0.0009	0.0020
Distracted driving indicator (1 if distracted driving, 0 otherwise)							−0.0031	0.0032	−0.0001
Temporal Characteristics									
Hurricane indicator (1 if crash occurred in hurricane season (June to November), 0 otherwise)							0.0111	−0.0104	−0.0007
Weekend indicator (1 if crash occurred on weekend, 0 otherwise)							−0.0029	−0.0016	0.0045
Day indicator (1 if crash occurred during the day, 0 otherwise)				0.0074	−0.0076	0.0002			

*Parameter defined for: [NI] No Injury; [MI] Minor Injury; [SI] Serious Injury/Fatality.

Table B5

The marginal effects of determinants in injury severity of single vehicle run-off-road crashes caused by 0 mph < Δv ≤ 10 mph pre, during and post COVID-19 pandemic based on the unconstrained models*.

Variable	0 mph < Δv ≤ 10 mph								
	Pre COVID-19 (2019)			During COVID-19 (2020)			Post COVID-19 (2021)		
	NI	MI	SI	NI	MI	SI	NI	MI	SI
Driver Characteristics									
Male driver indicator (1 if male, 0 otherwise)	0.0757	−0.0878	0.0120	0.0652	−0.0588	−0.0064	0.0583	−0.0667	0.0084
Driver 18–30 years indicator (1 if age between 18–30 years, 0 otherwise)	0.0265	−0.0298	0.0033						
Driver above 45 years indicator (1 if age above 45 years, 0 otherwise)				−0.0105	−0.0068	0.0173	−0.0130	0.0155	−0.0024
Vehicle Characteristics									

(*continued on next page*)

Table B5 (*continued*)

Variable	0 mph < Δν ≤ 10 mph								
	Pre COVID-19 (2019)			During COVID-19 (2020)			Post COVID-19 (2021)		
	NI	MI	SI	NI	MI	SI	NI	MI	SI
Passenger car indicator (1 if passenger car, 0 otherwise)	0.0283	0.0052	−0.0335				0.0129	0.0036	−0.0166
Van indicator (1 if van, 0 otherwise)							−0.0034	0.0040	−0.0006
New vehicle indicator (1 if auto age less than 10 years, 0 otherwise)							0.0261	−0.0185	−0.0077
Roadway Characteristics									
Level indicator (1 if level grade, 0 otherwise)				0.0192	0.0121	−0.0313			
Curve indicator (1 if curved alignment, 0 otherwise)							0.0056	−0.0142	0.0086
Two-way-divided indicator (1 if traffic way is two-way and divided, 0 otherwise)							0.0067	−0.0067	0.0000
Environmental Characteristics									
Daylight indicator (1 if daylight, 0 otherwise)	−0.0174	−0.0040	0.0214						
No-lighted in dark indicator (1 if not lighted during nighttime, 0 otherwise)	−0.0140	−0.0039	0.0180	−0.0147	0.0158	−0.0012			
Sunny indicator (1 if sunny, 0 otherwise)	−0.0317	−0.0082	0.0399						
Cloudy indicator (1 if cloudy, 0 otherwise)	−0.0130	−0.0031	0.0161						
Rainy indicator (1 if rainy, 0 otherwise)				0.0570	−0.0591	0.0021			
Crash Characteristics									
Alcohol-impaired driving indicator (1 if Alcohol-impaired driving, 0 otherwise)	−0.0083	−0.0027	0.0110	−0.0078	−0.0053	0.0131	−0.0049	−0.0029	0.0077
Drug-impaired driving indicator (1 if drug −impaired driving, 0 otherwise)	−0.0084	−0.0033	0.0118				−0.0035	0.0013	0.0022
Front center bumper indicator (1 if vehicle most damage area is front center bumper, 0 otherwise)	0.0094	0.0020	−0.0113						
Front right bumper indicator (1 if vehicle most damage area is front right bumper, 0 otherwise)	0.0029	0.0006	−0.0035	0.0112	−0.0119	0.0007			
Off roadway indicator (1 if crash location is off roadway, 0 otherwise)	−0.0247	−0.0061	0.0309				−0.0121	−0.0046	0.0167
Lane-changing indicator (1 if maneuver action is changing lanes, 0 otherwise)				−0.0124	0.0132	−0.0008			
Shoulder indicator (1 if crash location is on shoulder, 0 otherwise)				−0.0112	−0.0063	0.0175			
Straight ahead indicator (1 if maneuver action is straight ahead, 0 otherwise)							−0.0552	0.0618	−0.0066
Negotiating curve indicator (1 if maneuver action is negotiating curve, 0 otherwise)							−0.0218	0.0266	−0.0049
Restraint-protected driving indicator (1 if restraint-protected driving, 0 otherwise)	0.0279	−0.0294	0.0015	0.0114	0.0063	−0.0177	0.0733	0.0207	−0.0940
Temporal Characteristics									
Hurricane indicator (1 if crash occurred in hurricane season (June to November), 0 otherwise)				0.0090	0.0050	−0.0140			

*Parameter defined for: [NI] No Injury; [MI] Minor Injury; [SI] Serious Injury/Fatality.

Table B6
The marginal effects of determinants in injury severity of single vehicle run-off-road crashes caused by $\Delta\nu > 10$ mph pre, during and post COVID-19 pandemic*.

Variable	Δν > 10 mph								
	Pre COVID-19 (2019)			During COVID-19 (2020)			Post COVID-19 (2021)		
	NI	MI	SI	NI	MI	SI	NI	MI	SI
Driver Characteristics									
Driver 18–30 years indicator (1 if age between 18–30 years, 0 otherwise)	0.0667	−0.0497	−0.0169						
Male driver indicator (1 if male, 0 otherwise)				0.0400	−0.0311	−0.0089	0.0677	−0.0510	−0.0167
Driver above 45 years indicator (1 if age above 45 years, 0 otherwise)				−0.0090	−0.0071	0.0161	−0.0072	−0.0064	0.0137
Roadway Characteristics									
One-way indicator (1 if traffic way is one-way, 0 otherwise)	0.0114	−0.0070	−0.0044	0.0022	0.0020	−0.0042			
Dry surface indicator (1 if roadway surface is dry, 0 otherwise)	−0.0859	0.1161	−0.0302						
Curve indicator (1 if curved alignment, 0 otherwise)	−0.0236	−0.0209	0.0445				−0.0216	0.0161	0.0055
Unpaved shoulder indicator (1 if shoulder is unpaved, 0 otherwise)	0.0126	0.0114	−0.0240						
Traffic control sign indicator (1 if traffic control sign, 0 otherwise)				0.0046	0.0037	−0.0084			
Level indicator (1 if level grade, 0 otherwise)							−0.0526	−0.0551	0.1077
Lane_2 indicator (1 if crash occurred on two lanes on each side of road, 0 otherwise)							0.0129	0.0165	−0.0295
Paved shoulder indicator (1 if shoulder is paved, 0 otherwise)							−0.0097	−0.0030	0.0127
Environmental Characteristics									
Lighted in dark indicator (1 if lighted during nighttime, 0 otherwise)	−0.0438	0.0330	0.0108				0.0163	0.0182	−0.0345
Other light condition indicator (1 if other light condition, 0 otherwise)							0.0091	−0.0062	−0.0029
Crash Characteristics									

(*continued on next page*)

Table B6 (*continued*)

Variable	Δν > 10 mph								
	Pre COVID-19 (2019)			During COVID-19 (2020)			Post COVID-19 (2021)		
	NI	MI	SI	NI	MI	SI	NI	MI	SI
Straight ahead indicator (1 if maneuver action is straight ahead, 0 otherwise)	0.0595	−0.0746	0.0152						
On roadway indicator (1 if crash location is on roadway, 0 otherwise)	−0.0193	0.0259	−0.0065				0.0283	−0.0221	−0.0062
Drug-impaired driving indicator (1 if drug −impaired driving, 0 otherwise)	−0.0136	−0.0132	0.0269	−0.0076	−0.0072	0.0148	−0.0064	−0.0082	0.0146
Front left bumper indicator (1 if vehicle most damage area is front left bumper, 0 otherwise)				0.0143	−0.0110	−0.0033			
Lane-changing indicator (1 if maneuver action is changing lanes, 0 otherwise)				−0.0174	0.0213	−0.0039			
Off roadway indicator (1 if crash location is off roadway, 0 otherwise)				−0.0298	0.0376	−0.0078			
Alcohol-impaired driving indicator (1 if Alcohol-impaired driving, 0 otherwise)				−0.0165	−0.0150	0.0315			
Restraint-protected driving indicator (1 if restraint-protected driving, 0 otherwise)	0.0296	0.0248	−0.0543	0.0267	0.0217	−0.0484	0.1226	−0.0489	−0.0737
Negotiating curve indicator (1 if maneuver action is negotiating curve, 0 otherwise)							0.0160	−0.0229	0.0069
Temporal Characteristics									
Weekend indicator (1 if crash occurred on weekend, 0 otherwise)	0.0199	0.0172	−0.0371						
Day indicator (1 if crash occurred during the day, 0 otherwise)				0.0363	−0.0437	0.0074			

*Parameter defined for: [NI] No Injury; [MI] Minor Injury; [SI] Serious Injury/Fatality.

Appendix C

Table C1
Likelihood ratio test results of run-off-road models caused by different intervals of Δν between different periods.

Subset	y_1	y_2		
		Pre COVID-19 (2019)	During COVID-19 (2020)	Post COVID-19 (2021)
$\Delta\nu \leq 0$ mph	Pre COVID-19 (2019)	–	10.026 (63) [00.00 %]	52.053 (57) [33.91 %]
	During COVID-19 (2020)	126.463 (42) [>99.99 %]	–	69.126 (57) [86.98 %]
	Post COVID-19 (2021)	136.931(42) [>99.99 %]	68.637 (63) [69.62 %]	–
0 mph $< \Delta\nu \leq$ 10 mph	Pre COVID-19 (2019)	–	52.095 (12) [>99.99 %]	17.531 (19) [44.61 %]
	During COVID-19 (2020)	139.590 (17) [>99.99 %]	–	45.716 (19) [99.95 %]
	Post COVID-19 (2021)	88.946 (17) [>99.99 %]	71.830 (12) [>99.99 %]	–
$\Delta\nu >$ 10 mph	Pre COVID-19 (2019)	–	61.513 (12) [>99.99 %]	50.897 (17) [>99.99 %]
	During COVID-19 (2020)	35.504 (17) [99.47 %]	–	44.468 (17) [90.45 %]
	Post COVID-19 (2021)	71.142(17) [>99.99 %]	63.046 (12) [>99.99 %]	–

Table C2
Means of difference in probabilities concerning temporal instability for run-off-road crashes.

Sub-group	Predict period	Base period					
		Pre COVID-19 (2019)			During COVID-19 (2020)		
		NI	MI	SI	NI	MI	SI
$\Delta\nu \leq 0$ mph	During COVID-19 (2020)	0.0015	0.0032	−0.0047	–		
	Post COVID-19 (2021)	0.0009	0.0024	0.0015	−0.0012	−0.0019	0.0031
0 mph $< \Delta\nu \leq$ 10 mph	During COVID-19 (2020)	0.0033	−0.0052	0.0019	–		
	Post COVID-19 (2021)	0.0015	−0.0038	0.0023	−0.0014	0.0022	−0.0008
$\Delta\nu >$ 10 mph	During COVID-19 (2020)	0.0023	−0.0013	−0.0010	–		
	Post COVID-19 (2021)	0.0012	−0.0023	0.0011	−0.0015	−0.0024	0.0039

Note: NI, MI and SI denotes the no injury, minor injury and serious injury/fatality, respectively.

Table C3
Means of difference in probabilities adopting one run-off-road crash model to predict another data.

Base model	Predict data	Pre COVID-19 (2019)			During COVID-19 (2020)			Post COVID-19 (2021)		
		NI	MI	SI	NI	MI	SI	NI	MI	SI
$\Delta v \leq 0$ mph	0 mph $< \Delta v \leq 10$ mph	−0.0023	−0.0012	0.0035	0.0011	−0.0042	0.0031	−0.0021	−0.0109	0.0088
	$\Delta v > 10$ mph	−0.0121	−0.0067	0.0188	−0.0076	−0.0021	0.0097	−0.0091	−0.0054	0.0145
0 mph $< \Delta v \leq 10$ mph	$\Delta v \leq 0$ mph	0.0013	0.0008	−0.0021	−0.0011	0.0040	−0.0029	0.0013	0.0032	−0.0045
	$\Delta v > 10$ mph	−0.0082	−0.0041	0.0123	−0.0072	−0.0021	0.0093	−0.0076	−0.0019	0.0095
$\Delta v > 10$ mph	$\Delta v \leq 0$ mph	0.0121	0.0071	−0.0192	0.0065	0.0142	−0.0207	0.0082	0.0107	−0.0189
	0 mph $< \Delta v \leq 10$ mph	0.0109	0.0034	−0.0143	0.0082	0.0041	−0.0123	0.0072	0.0051	−0.0123

Note: NI, MI and SI denotes the no injury, minor injury and serious injury/fatality, respectively.

Data availability

The authors do not have permission to share data.

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