Accident Analysis and Prevention 208 (2024) 107800

Contents lists available at ScienceDirect

Accident Analysis and Prevention

journal homepage: www.elsevier.com/locate/aap

Effects of helmet usage on moped riders' injury severity in moped-vehicle crashes: Insights from partially temporal constrained random parameters bivariate probit models

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ARTICLE INFO

Keywords:
Moped crashes
Helmet usage
Injury severity outcome
Crash involvement ratio
Partially temporal constrained model
Joint bivariate probit model

ABSTRACT

Mopeds are small and move unpredictably, making them difficult for other drivers to perceive. This lack of visibility, coupled with the minimal protection that mopeds provide, can lead to serious crashes, particularly when the rider is not wearing a helmet. This paper explores the association between helmet usage and injury severity among moped riders involved in collisions with other vehicles. A series of joint bivariate probit models are employed, with injury severity and helmet usage serving as dependent variables. Data on two-vehicle moped crashes in Florida from 2019 to 2021 are collected and categorized into three periods: before, during, and after the COVID-19 pandemic. Crash involvement ratios are calculated to examine the safety risk elements of moped riders in various categories, while significant temporal shifts are also explored. The correlated joint random parameters bivariate probit models with heterogeneity in means demonstrate their superiority in capturing interactive unobserved heterogeneity, revealing how various variables significantly affect injury outcomes and helmet usage. Temporal instability related to the COVID-19 pandemic is validated through likelihood ratio tests, out-of-sample predictions, and calculations of marginal effects. Additionally, several parameters are noted to remain temporally stable across multiple periods, prompting the development of a partially temporally constrained modeling approach to provide insights from a long-term perspective. Specifically, it is found that male moped riders are less likely to wear helmets and are negatively associated with injury/fatality rates. Moped riders on two-lane roads are also less likely to wear helmets. Furthermore, moped riders face a lower risk of injury or fatality during daylight conditions, while angle crashes consistently lead to a higher risk of injuries and fatalities across the three periods. These findings provide valuable insights into helmet usage and injury severity among moped riders and offer guidance for developing countermeasures to protect them.

1. Introduction

The usage of powered two-wheelers, encompassing motorcycles, mopeds, and larger scooters, has seen a significant rise over the past decade in numerous developed nations (Atalar and Thomas, 2019). Powered two-wheelers appeal to road users for several reasons, including their reduced operational costs and the ease with which they can navigate through congested traffic (Adam and Susan, 2018). Users of powered two-wheelers frequently confront roadway infrastructure not tailored primarily to their needs in terms of travel speed and facilities (such as designated on-road lanes), posing an increased risk of collisions, injuries, or fatalities (Seymour, 2018). Previous studies have highlighted the distinct vulnerability of powered two-wheeler riders, who face fatality rates more than 20 times higher than those of car occupants per unit of distance traveled (Blackman and Haworth, 2013).

Among various powered two-wheelers, moped[1] is increasingly becoming a popular choice as a cost-effective travelling mean in most American areas like Florida. However, moped experience

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[1] The term "moped" originates from the fusion of "motor" and "pedal", defining it as a vehicle equipped with no more than three wheels, featuring pedals for human-powered propulsion. Mopeds, designed with seats or saddles, incorporate a motor that limits the vehicle's maximum speed to 30 mph. In cases where an internal combustion engine is utilized, its displacement is restricted to no more than 50 cc (CC). While ownership titles are not mandated, registration of mopeds is required for those intending to operate them on state roadways.

https://doi.org/10.1016/j.aap.2024.107800
Received 10 June 2024; Received in revised form 23 September 2024; Accepted 24 September 2024
Available online 1 October 2024

disproportionate fatality and injury rates compared with other road users. The rising national trend in moped fatalities is concerning, with moped-related deaths increasing by approximately 2 %, despite an overall 6 % decrease in motorcyclist fatalities in 2013 (USDOT, 2016). According to the Michigan Traffic Crash Facts (MTCF),[2] moped crashes in Michigan increased to 357 in 2020 and 382 in 2021, compared to 254 in 2019 (Zhang et al., 2024a). Due to their small size and poor performance, moped riders often collide with other vehicles like motorcyclists at intersections or are struck by other vehicles in congested conditions (Shinar, 2017; Wegman et al., 2012). Moreover, riders aged 16 and older are not mandated to wear helmets when operating a moped with speeds lower than 30 mph in Florida (Florida Statutes, 2023). In contrast, motorcyclists aged 21 and above may only forgo helmet use if they possess at least $10,000 in medical insurance coverage specifically for injuries sustained in a crash (FLHSMV, 2024). This distinction reflects differing risk profiles and legal considerations for mopeds versus motorcycles, particularly in terms of vehicle power, speed, and associated safety concerns. Given this, the prevention and mitigation of moped crashes colliding with other vehicles have become one of the top priorities for road safety policymakers.

For moped crashes, helmet usage has been found to be a key factor influencing the injury severity of moped riders (Blackman and Haworth, 2013; Moskal et al., 2012). However, helmet wearing remains a pressing issue in the U.S., with the usage of DOT-compliant motorcycle helmets standing at 66.5 % nationwide in 2022 (NCSA, 2023). Specifically, Galanis et al. (2016) noted that helmet usage among female moped riders was significantly higher than among males (15.2 % vs. 9.8 %), whereas among motorcyclists, the rates were comparable (45.3 % for females vs. 50.7 % for males). In Florida, helmet usage is not mandated for moped riders, except for those under the age of 16 (Florida Statutes, 2023). Universal helmet laws have proven highly effective in increasing helmet use among riders and subsequently reducing fatalities and injuries (Peng et al., 2017). However, many states have either repealed or relaxed these universal helmet laws (Patel et al., 2019), which has led to increased injury severity among trauma patients who were not wearing helmets. While extensive research has demonstrated that helmets significantly lower the risk of head and fatal injuries (Rice et al., 2016; Wang et al., 2024a), it remains critical to explore the specific relationship between helmet use and injury severity in moped crashes to fully understand the public health implications.

Meanwhile, traffic mobility has undergone substantial alterations to cause temporal instability and heterogeneity in the wake of the COVID-19 pandemic (Lee et al., 2023; Koloushani et al., 2021). For instance, due to government-enforced measures (e.g., social distancing and travel restrictions) in the pandemic, public transport use declined, whereas walking and bicycling slightly increased (Abdullah et al., 2022). Dingil and Esztergar-Kiss (2021) stated that participants perceive active modes, motorcycles, and personal cars as the least risky urban transportation options during the pandemic. Harrington and Hadjiconstantinou (2022) conducted an online survey to query individuals' transport choices in the UK. They discovered that 81.9 % of car commuters are likely to continue traveling by car once restrictions are lifted, while 3.6 % and 6.5 % are considering switching to walking and cycling, respectively. In USA, despite an 11.0 % reduction in vehicle miles traveled, the mortality rate in 2020 increased by 23.4 % to 1.37 fatalities per million vehicle miles traveled from 2019 (NHTSA, 2019; NHTSA, 2020). Katrakazas et al. (2020) collected data from a smartphone application in Greece and the Kingdom of Saudi Arabia to analyze the impact of COVID-19 on driving behaviors and safety indicators. Their findings indicate that while traffic volume decreased significantly, dangerous driving behaviors, including speeding, harsh acceleration and braking, and phone use, increased markedly following the outbreak of COVID-19. Lee et al. (2023) observed that the total number of crashes decreased by 14 % following the outbreak. The most notable reductions occurred during peak hours (22 %), while no significant changes were observed in fatal crashes in Florida.

While there is extensive research on the general impact of helmet usage in motorcycle crashes, there is limited research specifically focused on moped crashes. As moped riders take different behavior, helmet usage rates, and injury outcomes compared to motorcyclists (Blackman and Haworth, 2013). This gap in the literature leaves an incomplete understanding of how helmet usage affects injury severity specifically for moped riders. In addition, most of the research efforts addressed solely on injury severity outcomes treating riders' helmet usage as just one explanatory variable, without simultaneously analyzing the critical contributors while considering the association among helmet use and injury severity. Moreover, the COVID-19 pandemic has caused significant changes in transportation mode, traffic patterns, road usage, and potentially in crash dynamics, while the specific temporal shifts in moped crashes remain underexplored. The pandemic may have altered risk factors, exposure rates, or rider behavior, but these changes have not been fully quantified or understood.

To capture the temporal instability and heterogeneity (Mannering et al., 2016; Mannering, 2018), a growing body of methodological approaches have been developed in injury severity analysis such as latent class (Chang et al., 2019; Chang et al., 2021), nested logit model (Savolainen and Mannering, 2007), random parameters ordered logit (Cunto and Ferreira, 2017), Bayesian simultaneous random parameters model (Chang et al., 2022b), and random parameters logit models (Xin et al., 2017). Among these univariate models mentioned above, one single dependent variable approach may overlook potential relationships between dependent variables by focusing on one variable independently (Jacoby, 1997). In contrast, a bivariate model captures the interrelations between two variables, enhancing predictive accuracy by leveraging shared information (Harrell, 2015). Additionally, this approach reduces biases that might result from omitting key variables. In the current study, a joint random parameters bivariate probit model is utilized to explore the effects of helmet usage on injury outcomes in moped-vehicle crashes by adopting both injury severity and helmet usage of moped riders as dependent variables. By utilizing a partially temporal constrained structure, temporal shifts would be also captured.

While there is extensive research on the general impact of helmet usage in motorcycle crashes, studies specifically focused on moped crashes remain limited. Moped riders exhibit different behaviors, helmet usage rates, and injury outcomes compared to motorcyclists (Blackman and Haworth, 2013). This gap in the literature results in an incomplete understanding of how helmet usage influences injury severity among moped riders. Additionally, most research has focused solely on injury severity outcomes, treating helmet usage as just one explanatory variable, without concurrently analyzing other critical factors while considering the relationship between helmet use and injury severity. Furthermore, the COVID-19 pandemic has significantly altered transport modes, traffic patterns, road usage, and potentially crash dynamics, yet the specific temporal shifts in moped crashes remain underexplored. The pandemic may have changed risk factors, exposure rates, or rider behaviors, but these changes have not been fully quantified or understood.

To bridge the existing knowledge gaps, this study aims to accomplish the following objectives: (a) investigate the impact of helmet usage on the severity of injuries sustained in moped crashes, (b) assess the effectiveness of partially temporally constrained modeling approaches, and (c) determine the temporal shifts including the effects of the COVID-19 pandemic on moped crashes. Additionally, this study helps to develop long-term strategies for mitigating the outcomes of moped crashes.

Fig. 1 shows flowchart of the current study, which begins by reviewing previous research findings on moped crashes, as well as

[2] Notably, during the summer months (June, July, and August) of 2020, there were significantly more moped crashes (2 1 2) than during the same period in 2019, prior to the pandemic (1 4 5).

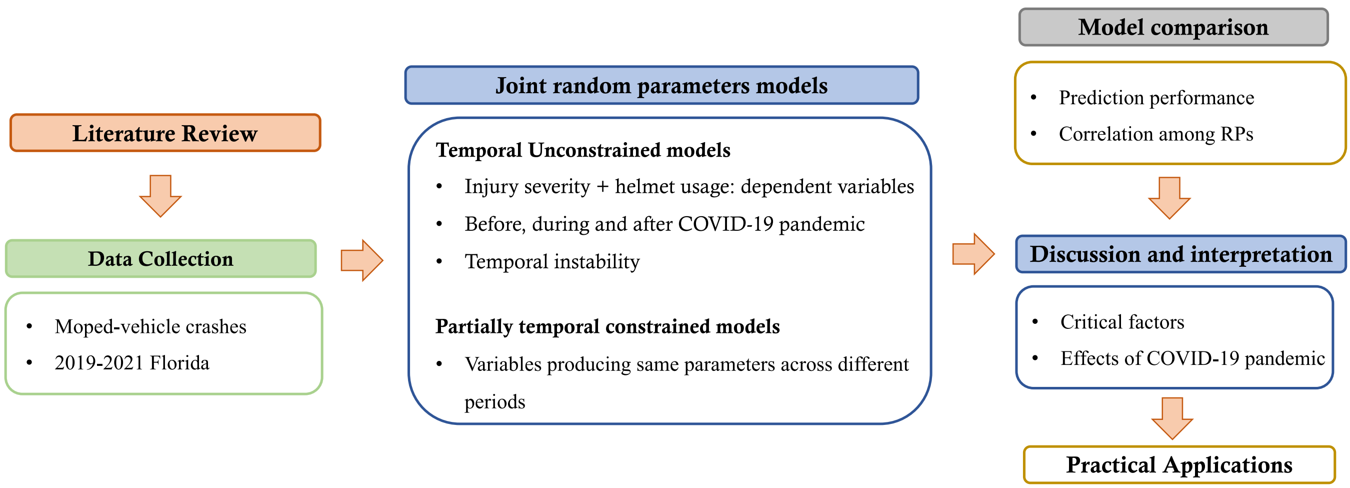


Fig. 1. Research tasks of the study.

temporal instability and related methods. Subsequently, the dataset and crash involvement ratio are presented, followed by an explanation of the methodological approaches. The model estimation is described, and the partially temporally constrained modeling approach is discussed. Following this, the results are analyzed and interpreted. Finally, conclusions are drawn regarding the findings and their implications, with suggestions for future research.

Table 1
A summary of findings regarding risk of moped crashes.

Existing research (Crash type or pattern)	Modeling method [a]	Data	Observation number	Findings
Moskal et al. (2012) (Moped and motorcycle crashes)	Case-control study	France 1996–2005	3,024	For both moped and motorcycle riders, factors such as being male, not wearing a helmet, exceeding the legal alcohol limit, and traveling for leisure purposes increased the risk of accident involvement. Carrying a passenger increased the risk of being responsible for the crashes among moped riders, but it had a protective effect against this risk for motorcycle riders.
Blackman and Haworth (2013) (Moped, scooter and motorcycle crashes)	Ordered probit regression model	QueenslandJuly 2003- June 2008	8,608	Moped crashes indicated a stronger downward trend, while moped and scooter crashes showed lower severity outcomes compared to motorcycle crashes.
White et al. (2013) (Moped/scooter and motorcycle crashes)	Comparison analysis	Queensland 2006–2010	206 moped/scooter and 2667 motorcycle riders	Mopeds/scooter riders and motorcycle riders may exhibit different injury patterns, but their overall injury severity tends to be very similar.
Moller and Haustein (2016) (Young moped riders)	Chi-square tests	Danish 2007	128	Riding speed was identified as a contributing factor in 45 % of the accidents, making it the most frequently cited factor attributed to moped riders, followed by attention errors (42 %), using a tuned-up moped (29 %), and position on the road (14 %).
Glaser et al. (2017) (Vehicle-moped conflict)	Kinematic triggers and manual video reduction	Shanghai, China	119 moped-car conflicts	Most of the vehicle-moped conflicts occurred on secondary main roads and branch roads. Car drivers primarily responded to these conflicts with hard braking rather than hard steering.
Ceunynck et al., (2018)(Urban moped crashes)	Compare analysis	Belgium2013	167 severe injury crashes	The average age of the involved moped riders is 33, with three-quarters being men. Human factors are the predominant contributors to moped crashes. Infrastructure and environmental factors play a moderate role, while vehicle-related factors have only a minor impact.
Zhang et al. (2018)(Electronic bike and moped)	Cross-sectional study	Southern China 2014–2015	3,200 riders	Traffic injuries of electric bike/moped-related crashes were significantly associated with several factors: the category of electric bike, self-reported confusion, history of crashes, running red lights, carrying children or adults while riding, riding in the motor lane, and riding in the wrong direction.
Johnson et al. (2019) (Emergency department moped-related injuries)	Binary regression analysis	U.S. 2002–2014	108,229	Summer months and weekdays were the most common times for moped crashes. Among the injured riders, three-fourths were male, two-thirds were aged 23–59 years, and 77 % were Caucasian.
Davidse et al. (2019)(Urban light moped riders)	Chi-square tests	Danish 2015–2016	349	Moving the light moped riders to the carriageway is only advisable on 30 km/h roads.
Beeharry et al. (2021) (Moped and Motorcycle crashes)	Stepwise method	Mauritius 2014–2016	4,826	For mopeds, horizontal curves from the 'Road Alignment' factor were found to be the most hazardous road configuration.
Kent et al. (2022)(Motorcycle, moped and bicycle riders)	Logistic regression	Las Vegas, Nevada 2013–2017	2,115 injuries	Compared to motorcyclists, head and neck injuries were significantly more common and helmet use was substantially lower among bicyclists and moped riders.
Zhang et al. (2024a)(Moped)	Multinomial logit model	Michigan 2017–2021	1,657	79 % of injuries sustained by moped riders in crashes were minor. The injured riders tended to be younger, male, and not wearing helmets.

2. Literature review

2.1. Literature review on risk of moped crashes and methodological approaches

Recently, the moped crashes have been analyzed in many research efforts, as shown in Table 1. Contributing factors including attributes of riders, vehicles, roadway and environment were observed to affect the injury or risk of moped crashes. For instance, male riders without helmets are found to increase the crash risk (Moskal et al., 2012). Moreover, head and neck injuries were observed more common in moped riders compared with motorcyclists (34.6 % vs 22.7 %) (Kent et al., 2022). Overall, usage of helmet was observed to be a critical factor affecting the injury outcomes or risk of moped riders in recent studies.

In the context of moped safety, methodological approaches such as case-control studies, binary regression analysis, comparative analysis, ordered probit models, and multinomial logit models have been widely utilized. To address unobserved heterogeneity (Mannering et al., 2016), more advanced approaches have been developed for crash outcome analysis, including ordered logit models (Yasmin et al., 2014), latent class models (Chang et al., 2019), Bayesian random parameters models (Ali et al., 2022), and random parameters logit models (Ren and Xu, 2023). Among these methods, random parameters approaches have been widely recognized in recent studies for their superior accuracy and effectiveness in capturing heterogeneity.

To date, several research efforts have focused on exploring the associations among two dependent variables in one model. For instance, Chakraborty et al. (2021) explored the correlation in seatbelt use and various demographic, vehicle, and site-specific factors in traffic crashes. Song et al. (2023) proposed a random parameter bivariate probit model with heterogeneity in means for truck-car crashes. Moreover, Wang et al. (2021) employed random parameters bivariate probit models to investigate the injury severity experienced by motorcycle riders and pillion passengers. Wang et al. (2024b) investigated the impact of speed difference on the injury severity of both drivers involved in two-vehicle rear-end crashes using correlated joint random parameters bivariate probit models. The analysis revealed cross-equation correlation coefficients exceeding 0.55, underscoring the presence of unobserved factors that jointly influence the injury severity outcomes of both drivers in a rear-end collision. Therefore, this bivariate model framework offers more comprehensive estimation results by capturing the potential interconnections between the two dependent variables, rather than evaluating them separately.

To the best of the authors' knowledge, few studies have examined the critical variables influencing moped riders' injury severity outcomes while considering the relationship between helmet use and injury severity as an intrinsic connection within one model. Therefore, a comprehensive analysis should be undertaken to investigate the severity of injuries resulting from moped crashes by examining this relationship, to enhance our understanding of the safety features and risk compensation related to helmet usage.

2.2. Literature review regarding the temporal instability

Temporal instability is a critical issue in safety analysis (Mannering, 2018), which could generate from changes in driving patterns, driving mode and safety attitude, and other time-varying elements such as macroeconomic conditions. A growing body of research has focused on such issue to achieve more precise estimation results (Stavrinos et al., 2020; Islam et al., 2023; Lee et al., 2023; Wang et al., 2024b). For instance, peak-hour crashes decreased significantly by 22 % during the COVID-19 pandemic, while fatal crashes remained unchanged (Lee et al., 2023).

Numerous potential temporal changes can affect the risk of moped crashes over the years, including factors such as public perception of moped usage, the demographic profile of moped users (Axsen and Sovacool, 2019), innovations in moped design (Haworth, 2012), improvements in road infrastructure (Bartkowiak et al., 2021), and economic conditions. Moreover, there was a notable rise in risky driving behaviors such as speeding, aggressive driving, and driving under the influence of drugs following the outbreak of COVID-19 in Florida (Lee et al., 2023).

Given the significant impact of risky behaviors during the COVID-19 pandemic, the potential correlations between the outbreak and the injury outcomes of moped crashes remains uncertain. Therefore, it is crucial to better understand the relationship between helmet usage and the severity of injuries from moped crashes, particularly in the context of COVID-19.

Recently, studies have employed period-separate model structures based on various time dimensions, such as by years by years (Alnawmasi and Mannering, 2019, time of day (Alogaili and Mannering, 2022), time of week (Zhang et al., 2024b). In addition to these complex structures, partially temporally constrained modeling approaches have been introduced to acquire long-term insights for safety measurements (Alnawmasi and Mannering, 2023). Similarly, Wang et al. (2024b) also developed such approaches based on bivariate methods to explore the temporal shifting variables and develop new strategies. Following this partially temporally constrained method, the current study is conducted to fill the knowledge gap in understanding the temporal shifts in the variables influencing moped crashes and to provide specific recommendations.

3. Data

3.1. Data description

A total of 4,738 moped related crashes occurred across 2019–2021 in Florida based on Signal Four Analytics (S4A), with the percentage of crash types and crash numbers shown in Fig. 2. Signal Four Analytics (S4A) is a statewide interactive, web-based geospatial crash analytical tool, developed by and hosted at University of Florida, Geoplan Center (Signal Four Analytics, 2014). The Florida Department of Transportation's Traffic Records program area provides funding for the addition of crash, citation, roadway, and Emergency Medical Service (EMS) data into this electronic record management systems, the development of comprehensive highway safety information systems and the automation of analytical processes. Programs receiving grant funding in this priority area are focused on the improvement of collection and analysis of traffic data such as: Crash Data, Roadway Data, Driver Data, Vehicle Data, Citation/Adjudication Data and Statewide Injury Surveillance System (SWISS) Data.

As the most common type of moped crashes, two-vehicle crashes involving mopeds and various types of other vehicles accounted for nearly 60 % of all moped crashes, as displayed in Fig. 2. Notably, there is an overall upward trend in crashes, increasing from 1,688 in 2019 to 1,694 in 2021, although the number temporarily dropped to 1,356 in 2020 due to the pandemic.

Consequently, crash data from two-vehicle moped crashes in Florida were collected for the years 2019–2021. This data included the severity of injuries sustained in moped crashes along with detailed information on the riders, drivers of other vehicles, vehicles, roadways, and environmental attributes. A total of 2,678 two-vehicle moped-vehicle crashes are included in current study, with riders' injury severity outcomes classified into three groups by fatality, injury, and no injury.

Moreover, in two-vehicle crashes, 28, 33, and 38 moped riders suffered fatalities in the years 2019, 2020, and 2021, respectively, accounting for 2.9 %, 4.3 %, and 3.9 % of the total fatalities each year. To eliminate erroneous results in model estimation, the fatality and injury levels are merged into one category: Injury/Fatality.

Chi-square tests are conducted to ensure the validity of the study, which separates helmeted and non-helmeted riders, as illustrated in Table 2. The tests reject the null hypothesis that two-vehicle moped

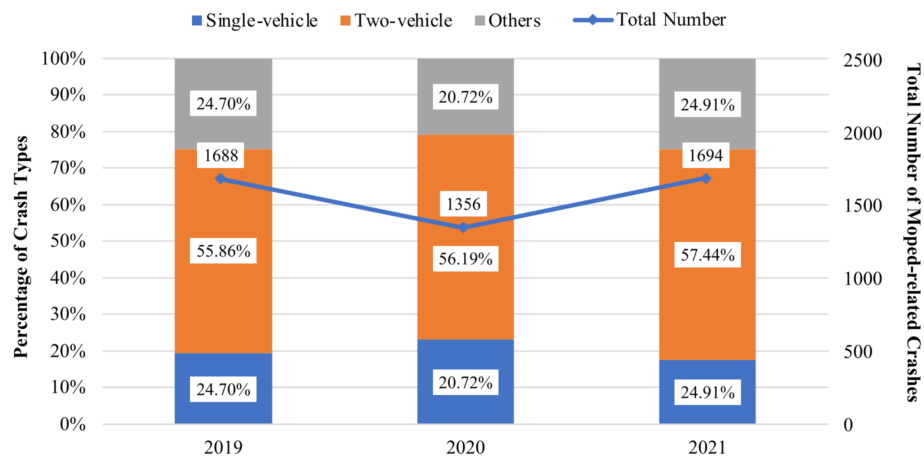


Fig. 2. Percentage of crash types and trend of moped related crashes across all years (2019–2021) in Florida.

Table 2
Chi-square test results for the moped riders involved in two-vehicle crashes with and without helmets across 2019–2021 (percentage of each sub-group shown in parentheses).

Classification	Injury severity	Year			Total
		2019	2020	2021	
Helmet	No Injury	40 (24.69 %)	32 (27.35 %)	41 (26.62 %)	113
	Injury/Fatality	122 (75.31 %)	85 (72.65 %)	113 (73.38 %)	320
	Subtotal	**162**	**117**	**154**	433
Non-helmet	No Injury	235 (30.09 %)	177 (27.44 %)	242 (29.55 %)	654
	Injury/Fatality	546 (69.91 %)	468 (72.56 %)	577 (70.45 %)	1591
	Subtotal	**781**	**645**	**819**	2245
Total Number		**943**	**762**	**973**	**2678**
Chi-square test		**2953.825 (4) [>99.99 %]**	**2440.863 (4) [>99.99 %]**	**3108.949 (4) [>99.99 %]**	

crashes, with and without helmets, suffer the same severity of injuries, demonstrating this under high confidence levels. Moreover, it is observed that the chi-square value in 2020 (2440.863) is relatively smaller than those for 2019 (2953.825) and 2021 (3108.949), indicating smaller differences between moped riders with and without helmets during the COVID-19 pandemic compared to before and after the pandemic.

It is noted that there was a significant decline in crash counts during the COVID-19 pandemic for both classifications, with and without helmets, as depicted in Table 2. Furthermore, fewer crashes occurred among moped riders with helmets compared to those without helmets, with the crash count ratio ranging from approximately 1/4.8 to 1/5.5 over the three years. Interestingly, riders with helmets suffered a higher percentage of injuries or fatalities compared with those without helmets, especially in 2019, with a difference value of 5.2 %. However, during the COVID-19 pandemic in 2020, the difference value was only 0.09 %, consistent with the patterns of chi-square test values shown in Table 2. This phenomenon highlights the potential effects of the COVID-19 pandemic on the crash rate and severity outcomes for moped riders, emphasizing the need to explore critical risk elements and temporal instability related to the pandemic, in order to develop new countermeasures for the riding safety of moped riders.

Furthermore, the explanatory variables collected are categorized as rider, driver, vehicle, roadway, environmental, crash, and temporal characteristics in Table A1, for before (2019), during (2020), and after (2021) COVID-19 pandemic.

3.2. *Crash involvement ratio (CIR)*

To examine the safety risk elements of moped riders in various categories, the quasi-induced exposure (QIE) method is utilized in current study. Such method is generally adopted for propensity analysis of specific crash types, including speeding (Zhang et al. 2024c), running red-light (Tavakoli et al., 2021), hit-and-run (Jiang et al., 2021) crashes. To eliminate selection bias in standard crash exposure methods, the quasi-induced exposure method offers flexibility in analyzing various types of crashes, boasts high-dimensional external validity, and enhances causal inference. This method significantly advantages the capture of detailed patterns and levels, including attributes of rider demographics, vehicles, and other detailed information. Consequently, the QIE method could greatly benefit the exploration of crash risks among moped riders.

Specifically, the quasi-induced exposure method posits that riders not at fault in crashes can serve as a control group, representing typical riding exposure for those wearing helmets. By comparing the characteristics of at-fault riders (non-helmeted in the current study) to those not at fault (helmeted in the current study), it becomes possible to isolate the effects of specific behaviors more accurately on the likelihood of causing a crash. Consequently, the crash involvement ratio (CIR) for specific riding categories can be expressed as follows:

$$CIR_i = \frac{\frac{NR_i}{\sum NR_i}}{\frac{HR_i}{\sum HR_i}} \quad (1)$$

where CIR_i denotes the risk propensity for the non-helmeted riders of specific riding category i, NR_i and HR_i respectively denote the numbers of non-helmeted and helmeted riders for specific riding category i, while $\sum NR_i$ and $\sum HR_i$ respectively are the total number of non-helmeted and helmeted riders.

Based on Eq. (1), the crash involvement ratio (CIR) values are calculated for various categories of riders. Table 3 shows that riders who are male, under 16 years old, operating mopeds over 10 years old, and experiencing distractions tend to have a higher propensity to ride without helmets, as indicated by the relatively high CIR values exceeding 1. Specifically, riders under 16 years old are prone to involve non-helmet riding with high ratio values of 2.83. Riders operating mopeds over 10 years old are prone to not wearing helmets. Moreover, riders without helmets are more inclined to engage in distracted riding and are also more likely to exceed speed limits.

Otherwise, significant temporal shifts also exit in the several riding

Table 3
Relative crash involvement ratio (CIR) of riders without helmet for various rider categories across 2019–2021.

Categories	Subgroup	Crash Involvement Ratio			
		2019	2020	2021	All year
Rider demographic information	Male	1.05	1.05	1.02	1.04
	Female	0.84	0.90	1.00	0.91
	Below 16 years old	3.22	2.09	3.20	2.83
	16–30 years old	0.96	1.19	1.16	1.08
	30–45 years old	1.46	0.94	1.08	1.15
	Above 45 years old	0.71	0.85	0.77	0.77
	Local	0.97	0.90	0.97	0.95
Riding behaviors	Operation error	0.88	0.99	0.98	0.94
	Distraction	1.23	1.92	1.71	1.57
	Over speed	3.94	0.95	5.64	2.25
Moped	Older than 10 years	1.44	1.42	1.14	1.32
Vehicle information	Car	1.24	1.03	0.98	1.08
	SUV	0.72	0.98	1.18	0.93
	Pickup	0.93	1.52	1.13	1.16
	Van	0.45	1.75	1.50	0.88
	Heavy truck	1.66	0.36	0.71	0.70
	Bus	1.24	0.09	0.94	0.58

categories across the three years, including age of moped riders, vehicle and crash cause, as displayed in Fig. 3. Riders aged below 16 years old are less prone to riding without helmets during the COVID-19 pandemic compared to before and after the pandemic period. Due to the heightened public health concerns caused by the pandemic, more emphasis was placed on protective behaviors, including the use of helmets (Petherick et al., 2021). Moreover, the pandemic led to reduced mobility and fewer opportunities for younger riders to travel unsupervised, thereby increasing compliance with helmet regulations among this age group.

During the pandemic, riders without helmets were less likely to engage in speeding, whereas after the pandemic. Especially, they were 5.93 times more likely to speed compared to during the pandemic. The reduced congestion during the pandemic likely inclined moped riders to speed less, as there were fewer destinations accessible due to lockdowns and restrictions (Abduljabbar et al., 2022). Likewise, the pandemic heightened awareness of health and safety, making riders more cautious in their operating speeds. Then, riders might have found more reasons to travel quickly from one place to another, increasing the occurrences of speeding after reopening of workplaces or shops. However, the reduced traffic also led to an increase in distracted riding of non-helmeted moped riders, leading to more collisions with other vehicles during the pandemic.

During the COVID-19 pandemic, riders without helmets were more likely to collide with pickups and vans, while significantly fewer collisions occurred with heavy trucks and buses. The pandemic led to a surge in local deliveries, increasing the presence of pickups and delivery vans transporting goods, groceries, and other essentials to minimize physical contact (Figliozzi and Unnikrishnan, 2021). These delivery vehicles often operated in residential and urban areas where mopeds are commonly used, thereby increasing the likelihood of collisions, especially with non-helmeted riders who may exhibit less caution.

With fewer commercial activities and reduced commuting during the pandemic, heavy trucks and buses were less frequent on the roads, decreasing the risk of collisions with moped riders. This reduction might be attributed to decreased operational capacity and increased remote work, which lessened the need for transporting goods and diminished the demand for public transportation services (Tirachini and Cats, 2020). Moreover, with the overall traffic volume reduced due to the pandemic, moped riders often benefited from less congested roads and were less likely to be in close proximity to larger vehicles (Thombre and Agarwal, 2021).

4. Methodology

To addresses the issue of unobserved heterogeneity in the moped crashes, this work examined the variability across observations using random parameters, their intercorrelations, and the determinants that influence the means of these parameters.

Building on previous research efforts, this study conducts a correlated joint random parameters bivariate probit model, which integrates heterogeneity of means, to analyze the factors that determine the injury severity outcomes and helmet usage of moped riders involved in two-vehicle moped-vehicle crashes. Building upon the univariate model, the bivariate probit model is detailed as follows (Washington et al., 2020),

$$Y_{i,1} = \beta_{i,1}\mathbf{X}_{i,1} + \varepsilon_{i,1}, y_{i,1} = 1 if Y_{i,1} > 0, 0 otherwise$$

$$Y_{i,2} = \beta_{i,2}\mathbf{X}_{i,2} + \varepsilon_{i,2}, y_{i,2} = 1 if Y_{i,2} > 0, 0 otherwise\# \quad (1)$$

where the binary outcomes $y_{i,1}$ and $y_{i,2}$ characterize the injury severity outcome and helmet usage of moped riders, respectively, while $Y_{i,1}$ and $Y_{i,2}$ represent the corresponding latent variables for each crash record i. The latent variables are linear functions of predictors $\mathbf{X}_{i,1}$ and $\mathbf{X}_{i,2}$, while

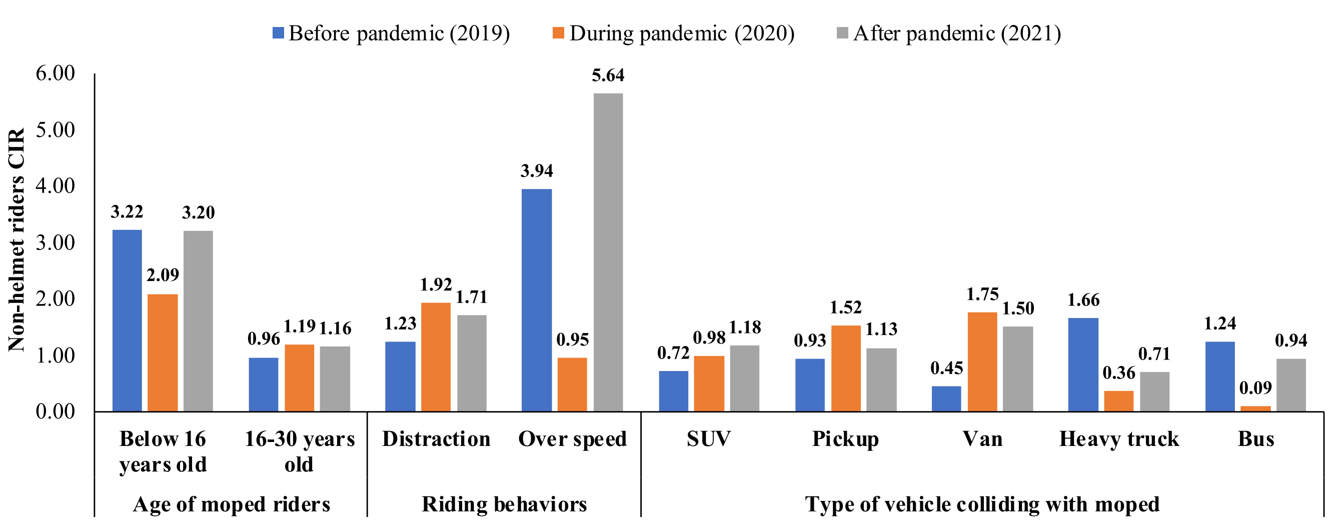


Fig. 3. Temporal shifts of relative crash involvement ratio of riders without helmet for significant variables in various categories.

$\beta_{i,1}$ and $\beta_{i,2}$ represent coefficients that measure the impact of the predictors on the latent variables. $\varepsilon_{i,1}$ and $\varepsilon_{i,2}$ are the error terms, assumed to follow a bivariate normal distribution, capturing the random variability not explained by the predictors:

$$\varepsilon = \begin{pmatrix} \varepsilon_{i,1} \\ \varepsilon_{i,2} \end{pmatrix} \backsim N\left[\begin{pmatrix} 0 \\ 0 \end{pmatrix}, \begin{pmatrix} 1 & \rho \\ \rho & 1 \end{pmatrix}\right] \tag{2}$$

Under the assumption of a joint normal distribution, the error terms $\varepsilon_{i,1}$ and $\varepsilon_{i,2}$ are characterized by having a mean of 0 and a variance of 1 each. The correlation coefficient ρ represents the degree of correlation between the errors across the equations. Furthermore, the cumulative bivariate function following normal probability distribution could be expressed as (Bhat, 2018),

$$\Phi(Y_{i,1}, Y_{i,2}; \rho) = \frac{\exp\left[-\frac{\left(Y_{i,1}{}^2 + Y_{i,2}{}^2 - 2\rho Y_{i,1} Y_{i,2}\right)}{2 - 2\rho^2}\right]}{\left[2\pi\sqrt{(1-\rho^2)}\ \right]} \tag{3}$$

In the context of the bivariate probit model, the joint probability that both $y_{i,1} = 1$ and $y_{i,2} = 1$ is specified as follows (Washington et al., 2020),

$$\begin{aligned} P\left(y_{i,1} = 1, y_{i,2} = 1\right) = P(\mathbf{X}_{i,1} < \mathrm{x}_{i,1}, \mathbf{X}_{i,2} < \mathrm{x}_{i,2}) &= \int_{-\infty}^{\mathrm{x}_{i,1}} \int_{-\infty}^{\mathrm{x}_{i,2}} \Phi(\mathrm{z}_{i,1}, \mathrm{z}_{i,1}; \rho) \mathrm{d}\mathrm{z}_{i,1} \mathrm{d}\mathrm{z}_{i,2} \\ &= F(\beta_{i,1}\mathbf{X}_{i,1}, \beta_{i,2}\mathbf{X}_{i,2}; \rho) \end{aligned} \tag{4}$$

Then, the log-likelihood function LL for the given model can be formally derived using the maximum likelihood estimation as follows (Bhat, 2018),

$$LL = \sum_{i=1}^{N} \begin{bmatrix} Y_{i,1} Y_{i,2} ln\Phi(\beta_{i,1}\mathbf{X}_{i,1}, \beta_{i,2}\mathbf{X}_{i,2}, \rho) + \left(1 - y_{i,1}\right) y_{i,2} ln\Phi(-\beta_{i,1}\mathbf{X}_{i,1}, \beta_{i,2}\mathbf{X}_{i,2}, -\rho) \\ + \left(1 - y_{2,1}\right) s_{i,1} ln\Phi(\beta_{i,1}\mathbf{X}_{i,1}, -\beta_{i,2}\mathbf{X}_{i,2}, -\rho) \\ + \left(1 - y_{i,1}\right)\left(1 - y_{i,2}\right) ln\Phi(-\beta_{i,1}\mathbf{X}_{i,1}, -\beta_{i,2}\mathbf{X}_{i,2}, \rho) \end{bmatrix} \tag{5}$$

where it aggregates across all observation i from 1 to N. This function evaluates the joint probability of the binary outcomes associated with each pair of observations $y_{i,1}$ and $y_{i,2}$.

Moreover, the model also accounts for multilayer unobserved heterogeneity by integrating the parameter β_i, as defined in (Mannering et al., 2016),

$$\beta_i = b + \lambda S_i + \Gamma \delta_i \tag{6}$$

where $\boldsymbol{b}$ denotes the average estimable parameter observed across all crashes. The vector S_i affects the mean of the parameter β_i, which is impacted by the explanatory variables. The vector λ consists of estimable parameters. The matrix Γ, a Cholesky decomposition, is utilized to delineate the covariance matrix associated with the random parameters. Additionally, δ_i serves as a disturbance term, characterized by a mean of 0 and a variance of σ^2.

In consideration of the standard deviation of the correlated random parameters, the formulation can be delineated as indicated (Ahmed et al., 2021; Fountas et al., 2018):

$$\sigma_r = \sqrt{\sum_{i=1}^{l} \sigma_{l,i}{}^2} \tag{7}$$

where σ_m denotes the standard deviation of the random parameter $\boldsymbol{r}$, $\sigma_{l,l}$ is the diagonal element of the Γ matrix, and $\sigma_{l,i}$ refers to the off-diagonal elements of the lower triangular matrix that are associated with the random parameter $\boldsymbol{r}$. These elements collectively represent the variance and covariance structure influencing the random parameter within the model.

Furthermore, the standard error of the standard deviation σ_r and the corresponding t-statistic of σ_r are derived as (Fountas et al., 2018):

$$SE(\sigma_r) = \frac{S_{\sigma_m}}{\sqrt{N}} \tag{8}$$

$$t(\sigma_r) = \frac{\sigma_r}{SE_{\sigma_r}} \tag{9}$$

where, S_{σ_m} is the standard deviation of σ_m for random parameter $\boldsymbol{r}$, while N denotes the number of observations. $t(\sigma_r)$ is the t-statistic for the standard deviation σ_r, used to test the significance of the standard deviation. Subsequently, the covariance between two correlated random parameters can be calculated using the following formula (Fountas et al., 2021):

$$Cor(\chi_{m1,n}, \chi_{m2,n}) = \frac{cov(\chi_{m1,n}, \chi_{m2,n})}{\sigma_{m1,n}\sigma_{m2,n}} \tag{10}$$

where, $cov(\chi_{m1,n}, \chi_{m2,n})$ represents the covariance between the parameters $\chi_{m1,n}$ and $\chi_{m2,n}$, while $\sigma_{m1,n}$ and $\sigma_{m2,n}$ are their respective standard deviations.

To estimate the models, a simulated maximum likelihood approach utilizing 1000 Halton draws was employed through the NLOGIT 6.0 software on Windows 10 operating system, balancing the trade-offs between estimation accuracy and computational efficiency (McFadden and Train, 2000). The normal distribution is preferred for achieving the most appropriate statistical fit when analyzing the distribution of random parameters (Milton et al., 2008).

Additionally, marginal effects are computed to ascertain the expected change in the probability of the dependent variable equaling 1, prompted by a one-unit adjustment in one of the independent variables while other variables remain constant. Within the context of the proposed joint random parameters bivariate probit model, the marginal effects E on the $j-th$ rear-end crash injury severity can be detailed as follows (Christofides et al., 1997; Greene, 2012),

Table 4
Goodness-of-fit measures comparison for the temporal unconstrained bivariate probit modeling approaches.

	Joint fixed parameters bivariate probit model (JFPBP)			Joint random parameters bivariate probit model (JRPBP)			Joint random parameters bivariate probit model with heterogeneity in means (JRPBPHM)			Correlated joint random parameters bivariate probit model with heterogeneity in means (CJRPBPHM)		
	2019	2020	2021	2019	2020	2021	2019	2020	2021	2019	2020	2021
Number of parameters (K)	23	21	21	25	23	23	26	25	24	27	26	25
Number of observations (N)	943	762	973	943	762	973	943	762	973	943	762	973
Log-likelihood at zero ($LL(0)$)	−1240.988	−1002.792	−1280.468	−1240.988	−1002.792	−1280.468	−1240.988	−1002.792	−1280.468	−1240.988	−1002.792	−1280.468
Log-likelihood at convergence ($LL(\beta)$)	−985.363	−774.263	−1024.024	−962.039	−746.865	−991.695	−943.885	−724.427	−969.212	−931.559	−712.002	−955.914
$\rho^2 = 1 - LL(\beta)/LL(0)$	0.206	0.228	0.200	0.225	0.255	0.226	0.239	0.278	0.243	0.249	0.290	0.253
Corrected ρ^2	0.186	0.206	0.183	0.204	0.232	0.207	0.218	0.253	0.224	0.227	0.265	0.234
Corrected AIC	2017.927	1591.775	2091.020	1975.496	1541.226	2030.553	1941.303	1500.620	1987.690	1918.770	1477.914	1963.201
Chi-square test	**JFPBP vs JRPBP**			**JRPBP vs JRPBPHM**			**JRPBPHM vs CJRPBPHM**					
	46.648 (2) [>99.99 %]	54.796 (2) [>99.99 %]	64.658 (2) [>99.99 %]	36.308 (1) [>99.99 %]	44.876 (2) [>99.99 %]	44.966 (1) [>99.99 %]	24.652 (1) [>99.99 %]	24.850 (1) [>99.99 %]	26.596 (1) [>99.99 %]			

$$E_{Y_{i,1}} = \overline{P_j\left(y_{i,1}, y_{i,2}\right)}\left[given\mathbf{X}_{i,1} = 1\right] - \overline{P_j\left(y_{i,1}, y_{i,2}\right)}\left[given\mathbf{X}_{i,1} = 0\right],$$
$$E_{Y_{i,2}} = \overline{P_j\left(y_{i,1}, y_{i,2}\right)}\left[given\mathbf{X}_{i,2} = 1\right] - \overline{P_j\left(y_{i,1}, y_{i,2}\right)}\left[given\mathbf{X}_{i,2} = 0\right]\# \quad (11)$$

These calculations help elucidate the influence of specific explanatory variables on the probability of severe injury outcomes in rear-end crashes, thereby facilitating more informed policy decisions and safety measures.

5. Results and discussion

5.1. Model comparison and temporal tests

To assess the necessity of adopting more complex modeling approaches, chi-square tests are conducted to compare the goodness-of-fit values. Table 4 presents the results of chi-square tests for four types of the temporal unconstrained bivariate probit modeling approaches, using comparisons based on the values of log-likelihood corrected ρ^2 and the corrected Akaike Information Criterion (AIC). For each subgroup, the correlated joint random parameters bivariate probit model with heterogeneity in means presents better model performance, evidenced by its higher ρ^2 and lower corrected AIC. Furthermore, the results of the chi-square tests also substantiate the necessity of developing such advanced model. The estimation results for the three periods are delineated in Table B1 based on the temporal unconstrained correlated joint random parameters bivariate probit model with heterogeneity in means. As shown in Table B1, the models produce ρ^2 values of 0.249, 0.290, and 0.253, respectively for before, during, and following the COVID-19 pandemic, respectively. However, the during COVID-19 pandemic model indicates a cross-equation correlation coefficients (ρ) of −0.108 while before and after COVID-19 pandemic models respectively produce ρ values of 0.195 and 0.149. These coefficients indicate that moped riders wearing helmets were more prone to injuries or fatalities before and after the pandemic, yet they experienced fewer such crashes during the pandemic. A possible explanation for this trend could be the fewer vehicles on the road during the pandemic (Francke, 2022), leading to simpler interactions between mopeds and other vehicles. Additionally, the pandemic may have influenced moped riders' behavior, prompting them to ride more cautiously and safely. This phenomenon is consistent with the findings depicted in Fig. 3, which shows a reduction in instances of speeding.

As shown in Table B1, a significant negative correlation of −0.939 is observed between rider operation error related to injury/fatality and the use of helmets on two-lane roadways before the COVID-19 pandemic. Such correlation suggests potential unobserved heterogeneity in the interaction between these two random parameters, indicating that moped riders experiencing operational errors while riding on two-lane roadways with helmets are less likely to suffer injuries or fatalities before COVID-19. Similarly, riders of mopeds with the front areas most damaged, who are not wearing helmets and riding on paved shoulders, are less likely to be injured or killed in moped-vehicle crashes after the COVID-19 pandemic. However, during the COVID-19 pandemic, moped riders on two-lane county roadways without helmets tended to have a higher likelihood of experiencing injuries and fatalities.

This correlation, uncovered using the correlated random parameters approach, provides valuable insights and encourages further investigation into the interactive unobserved heterogeneity affecting injury severity outcomes and use of helmets for drivers involved in moped-vehicle collisions. This unobserved heterogeneity, captured by the correlation, might be missed in models with fixed or uncorrelated random parameters in bivariate probit analyses. Such insights are crucial for developing more accurate and effective predictive models that better account for the complexities of real-world driving scenarios.

Table 5
Likelihood ratio test results of moped-vehicle crash models between different periods.

t_1	t_2		
	Before COVID-19 (2019)	During COVID-19 (2020)	After COVID-19 (2021)
Before COVID-19 (2019)	–	62.094 (26) [>99.99 %]	50.680 (25) [>99.99 %]
During COVID-19 (2020)	66.766 (27) [>99.99 %]	–	57.992 (25) [>99.99 %]
After COVID-19 (2021)	55.742 (27) [>99.99 %]	42.818 (26) [>99.99 %]	–

Note: Degrees of freedom and confidence level are respectively shown in parenthesis and brackets.

5.2. Temporal instability

To analyze the temporal instability, the transferability tests are utilized in the moped-vehicle crash model across the three periods, followed by the out-of-sample prediction. Moreover, the marginal effects are also presented to show the temporal shifts.

5.2.1. Transferability tests

To investigate the temporal variation in the estimated model across three distinct periods, two series of likelihood ratio tests are employed. The initial series involves pairwise tests that compare models from two different periods to assess whether the estimated parameters are consistent across the before, during, and after COVID phases (Behnood and Mannering, 2015):

$$\chi^2_{t_1} = -2\left[LL\left(\beta_{t_1t_2}\right) - LL\left(\beta_{t_1}\right)\right] \tag{12}$$

where $LL\left(\beta_{t_1t_2}\right)$ represents the log-likelihood at convergence of the model with parameters from period t_2 using data from period t_1, and $LL\left(\beta_{t_1}\right)$ denotes the log-likelihood at convergence using data solely from period t_1. The degrees of freedom correspond to the number of estimated parameters in the model $\beta_{t_1t_2}$ (Behnood and Mannering, 2015). Each model comparison yields two test results by reversing the subgroups t_1 and t_2. Table 5 presents the results of the pairwise tests between different periods for the moped-vehicle crash models, evaluating whether the null hypothesis of parameter stability over two-year intervals can be rejected. The models consistently show significant differences over a two-year span, allowing us to reject the null hypothesis with more than 99 % confidence. This high level of certainty indicates that the estimated parameters do experience significant fluctuations during the designated periods (before, during, and after COVID-19).

A second series of likelihood ratio tests is proposed to evaluate the temporal stability between a combined model and each individual model (Alnawmasi and Mannering, 2019; Islam and Mannering, 2020):

$$\chi^2_{t_2} = -2[LL(\beta_{alltime}) - LL(\beta_{t1}) - LL(\beta_{t2}) - LLL(\beta_{t3})]\# \tag{13}$$

where $LL(\beta_{alltime})$ represents the log-likelihood at convergence for the model spanning the three periods (before, during, and after COVID-19), and $LL(\beta_{ti})$ denotes the log-likelihood at convergence for the model using data from each respective period t. The degrees of freedom are calculated as the sum of the statistically significant parameters from each model, minus the number of statistically significant parameters in the combined model (Washington et al., 2020). The calculated χ^2 value is 224.864 with 31 degrees of freedom respectively, for models analyzing moped-vehicle crashes. These results enable us to reject the null hypothesis, which asserts the stability of statistically significant parameters across separate models for moped-vehicle crashes, with a confidence level exceeding 99.99 %.

5.2.2. Out-of-sample predictions

Besides transferability tests, out-of-sample predictions serve as an effective method for assessing temporal instability by forecasting injury/fatality rates and helmet usage across different periods (Hou et al., 2022; Wang et al., 2022c). To explore the overall impact of temporal variations, a moped-vehicle crash model from one period will be employed to predict injury severity and helmet usage using data from another period. The out-of-sample prediction simulation will be conducted using the estimated parameters from the base model, applying them in a simulation process with 1,000 Halton draws, as used in the initial model estimation.

Regarding temporal instability, Table 6 details the mean differences between the observed probabilities from the model and the predicted probabilities of injury/fatality and helmet usage. These predictions are based on applying the parameters from one period's moped-vehicle crash model to data from a subsequent period. Notably, applying the model parameters from before COVID-19 (2019) to predict moped-vehicle crashes during COVID-19 (2020) results in a decrease in the probability of injury/fatality outcomes by 0.00145 and an increase in helmet usage probability by 0.0048. Similarly, applying the model parameters from before COVID-19 (2019) to estimate data from after COVID-19 (2020) produces the same trend. Conversely, using parameters estimated during COVID-19 (2020) to predict data from after COVID-19 (2021) results in an increase in injury/fatality rates by 0.0123 and a decrease in helmet usage by 0.0019. Thus, the significant discrepancies observed in the table underscore substantial temporal instability associated with the COVID-19 pandemic, as demonstrated through the out-of-sample predictions.

Overall, the results from the transferability tests and out-of-sample predictions confirm the observed temporal instability issues related to the COVID-19 pandemic.

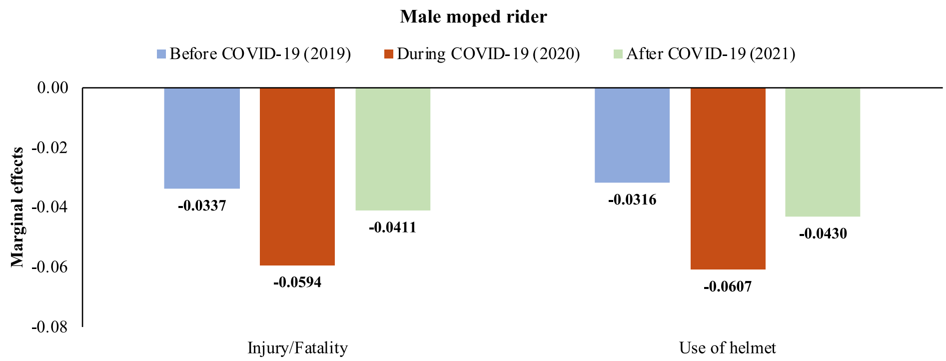
5.2.3. Marginal effects

Moreover, to show the temporal instability in the effects of contributing factors, marginal effects are calculated in Table B2 based on the temporal unconstrained modeling approaches. The effects of the COVID-19 pandemic are evident from the marginal effects of several variables. For instance, male riders are observed to consistently decrease the injury severity and helmet usage for the three periods, but the effects of such variable indicate shifts across three periods. To display visual comparison regarding temporal shifts, Fig. 4 displays the marginal effects for several contributing factors across the three periods. Male moped riders exhibited a lower likelihood of injury or fatality and were less likely to wear helmets during the COVID-19 pandemic compared to the periods before and after the pandemic, as shown in Fig. 4 (a). As mentioned earlier, the significant reduction in traffic density during the pandemic likely resulted in fewer opportunities for collisions between mopeds and vehicles, thereby reducing the risk of injuries or fatalities for male moped riders. During the pandemic, male moped riders might have felt safer and less compelled to wear helmets, particularly when enforcement of restrictions was lax.

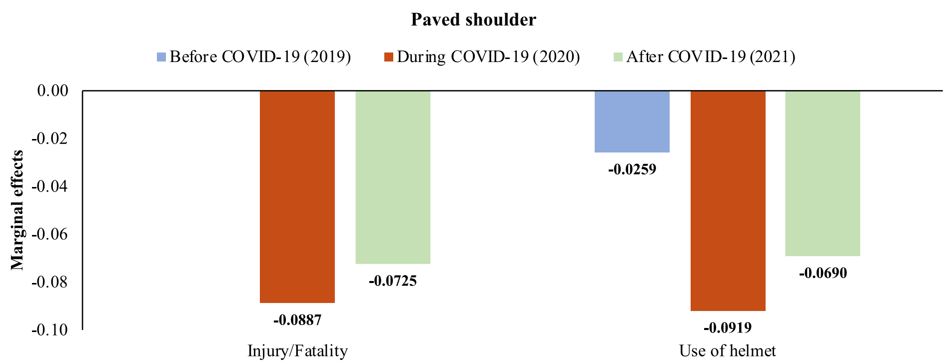
A similar phenomenon is observed with the paved shoulder indicator, suggesting that moped riders on roadways with paved shoulders were less likely to get injury or fatality and wear helmets during the

Table 6
Means of difference in probabilities for Injury severity and helmet usage concerning temporal instability for moped-vehicle crashes.

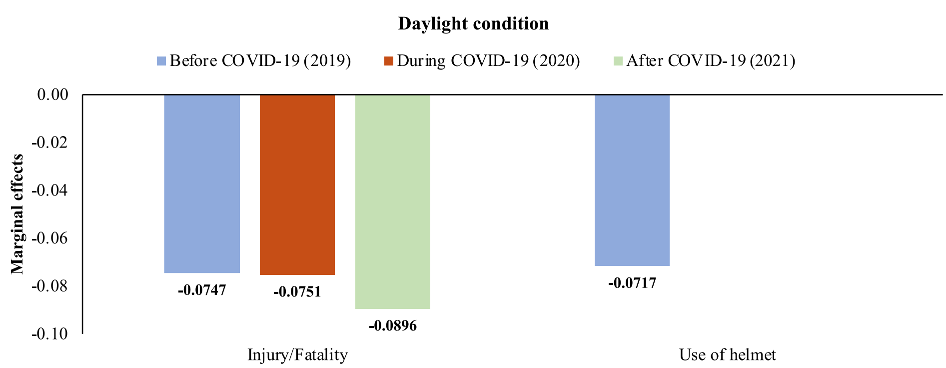
Predict period	Base period			
	Before COVID-19 (2019)		During COVID-19 (2020)	
	Injury/ fatality	Use of helmet	Injury/ fatality	Use of helmet
During COVID-19 (2020)	−0.0145	0.0048	–	–
After COVID-19 (2021)	−0.0021	0.0037	0.0123	−0.0019



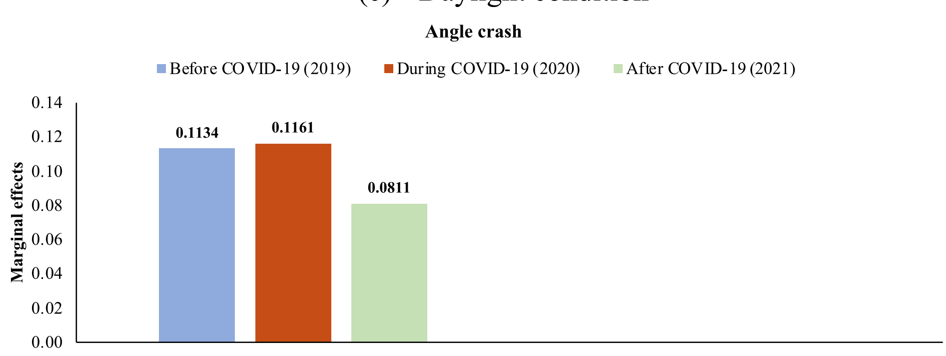
(a) The male moped rider



(b) Paved shoulder



(c) Daylight condition



(d) Angle crash

Fig. 4. The marginal effects of contributing factors consistently affecting the injury severity/helmet usage across three periods.

COVID-19 pandemic, as depicted in Fig. 4 (b).

Furthermore, the marginal effects of daylight condition and angle crash are displayed in Fig. 4 (c) and (d).

5.3. *Partially temporal constrained modeling approach*

Several variables display the same trend on injury severity or helmet usage for the three periods, as shown in Table B1, a partially temporal

Table 7
Partially temporal constrained modeling approaches to model injury severity and helmet usage of moped riders in moped-vehicle crashes (t-statistics in parentheses) based on unconstrained joint random parameters bivariate probit models with heterogeneity in means.

Variables	Estimated Parameters (t-stat)		Marginal Effects	
	Injury/ fatality	Use of helmet	Injury/ fatality	Use of helmet
Constant [2019]	1.169 (3.43)	−0.932 (−2.29)		
Constant [2020]	1.438 (2.31)	−1.209 (−3.43)		
Constant [2021]	0.836 (2.43)	−0.832 (−2.32)		
Variables producing the same parameter value across all years				
Male moped rider (1 if male, 0 otherwise) [2019, 2020, 2021]	−0.336 (−2.19)	−0.376 (−2.46)	−0.0478	−0.0528
Lane_2 indicator (1 if crash occurred on road with two lanes, 0 otherwise) [2019, 2020, 2021]		−0.265 (−2.35)		−0.0248
Daylight indicator (1 if daylight, 0 otherwise) [2019, 2020, 2021]	−0.263 (−2.31)		−0.0682	
Angle indicator (1 if angle crash, 0 otherwise) [2019, 2020, 2021]	0.374 (3.38)		0.0927	
Random parameters				
Rider operation error (1 if crash occurred due to operation error of rider, 0 otherwise) [2019]		0.377 (2.79)		0.0037
Standard deviation		***0.368 (2.13)***		
Lane_2 indicator (1 if crash occurred on road with two lanes, 0 otherwise) [2019]	−0.228 (−2.21)		−0.0432	
Standard deviation	***0.291 (3.23)***			
County indicator (1 if crash occurred on county road, 0 otherwise) [2020]	5.329 (2.32)		0.1352	
Standard deviation	***5.298 (2.24)***			
Paved shoulder indicator (1 if shoulder is paved, 0 otherwise) [2021]		−0.201 (−2.02)		−0.0719
Standard deviation		***0.242 (2.21)***		
Moped front indicator (1 if moped's most damage area is front, 0 otherwise) [2021]	0.432 (4.87)		0.0627	
Standard deviation	***0.442 (5.39)***			
Heterogeneity in the means of random parameters				
Lane_2 indicator (1 if crash occurred on road with two lanes, 0 otherwise): Old moped indicator (1 if moped age more than 10 years, 0 otherwise) [2019]	0.326 (2.01)			
County indicator (1 if crash occurred on county road, 0 otherwise): Old moped indicator (1 if moped age more than 10 years, 0 otherwise) [2020]	−2.649 (−2.09)			
Paved shoulder indicator (1 if shoulder is paved, 0 otherwise): Rider distraction (1 if crash occurred due to distraction of moped rider, 0 otherwise) [2021]		−0.458 (−2.71)		
Rider Characteristics				
Rider Below 16 years indicator (1 if rider age below 16 years, 0 otherwise) [2019, 2021]	−0.762 (−2.23)		−0.1687	
Rider 30–45 years indicator (1 if rider age between 30–45 years, 0 otherwise) [2019]		−0.432 (−3.21)		−0.0048
Rider 30–45 years indicator (1 if rider age between 30–45 years, 0 otherwise) [2020]	0.372 (1.98)		0.0729	
Rider Above 45 years indicator (1 if rider age above 45 years, 0 otherwise) [2021]	0.248 (2.17)		0.0028	
Rider distraction (1 if crash occurred due to distraction of moped rider, 0 otherwise) [2020]		−0.319 (−2.57)		−0.0038
Rider local indicator (1 if rider is local, 0 otherwise) [2020]		0.838 (2.73)		0.0049
Rider over speeding indicator (1 if rider exceeding the speed limit, 0 otherwise) [2021]		−0.692 (−2.29)		−0.0102
Driver Characteristics				
Driver 30–45 years indicator (1 if age between 30–45 years, 0 otherwise) [2019]	−0.254 (−2.59)		−0.0629	
Driver over speeding indicator (1 if driver exceeding the speed limit, 0 otherwise) [2021]	0.537 (1.97)		0.1274	
Moped Characteristics				
Old moped indicator (1 if moped age more than 10 years, 0 otherwise) [2019]		−0.567 (−2.01)		−0.0394
Vehicle Characteristics				
Passenger car indicator (1 if another vehicle is passenger car, 0 otherwise) [2019]	−0.282 (−2.68)		−0.0629	
Bus indicator (1 if bus, 0 otherwise) [2021]	−1.278 (−2.13)		−0.3829	
Old vehicle indicator (1 if auto age more than 10 years, 0 otherwise) [2019, 2020]	0.287 (2.83)		0.0892	
Roadway Characteristics				
Straight indicator (1 if straight alignment, 0 otherwise) [2020]	−1.109 (−2.19)		−0.3287	
Divided indicator (1 if crash occurred on divided road, 0 otherwise) [2020]	0.253 (2.33)		0.0529	
Other roadway type indicator (1 if roadway is other type, 0 otherwise) [2019, 2021]	−0.728 (−2.42)		−0.1563	
Dry surface indicator (1 if roadway surface is dry, 0 otherwise) [2019]		−0.322 (−2.07)		−0.0102
Paved shoulder indicator (1 if shoulder is paved, 0 otherwise) [2019, 2020]		−0.309 (−2.59)		−0.0348
Paved shoulder indicator (1 if shoulder is paved, 0 otherwise) [2020, 2021]	−0.278 (−2.58)		−0.0689	
Environmental Characteristics				
Clear indicator (1 if clear, 0 otherwise) [2021]		−0.329 (−2.38)		−0.0032

(continued on next page)

Table 7 (*continued*)

Variables	Estimated Parameters (t-stat)		Marginal Effects	
	Injury/ fatality	Use of helmet	Injury/ fatality	Use of helmet
Daylight indicator (1 if daylight, 0 otherwise) [2019]		−0.205 (−2.11)		−0.0573
Crash Characteristics				
Head-on indicator (1 if head-on crash, 0 otherwise) [2019]	0.610 (2.20)		0.1627	
Head-on indicator (1 if head-on crash, 0 otherwise) [2021]		−0.583 (−2.14)		−0.0089
Other crash type indicator (1 if other type of crash, 0 otherwise) [2020, 2021]	0.529 (2.92)		0.1682	
Moped rear indicator (1 if moped's most damage area is rear, 0 otherwise) [2020]		0.331 (2.08)		0.0042
Vehicle front indicator (1 if vehicle's most damage area is front, 0 otherwise) [2019, 2021]	0.279 (2.64)		0.0626	
Vehicle rear indicator (1 if vehicle's most damage area is rear, 0 otherwise) [2019, 2020]	−0.286 (−2.04)		−0.1024	
Vehicle rear indicator (1 if vehicle's most damage area is rear, 0 otherwise) [2020]		−0.319 (−2.04)		−0.1243
ρ	0.121 (2.24)			
Number of parameters (K)	53			
Number of observations (N)	2678			
Log-likelihood at zero	−3524.248			
Log-likelihood at convergence	−2565.524			
$\rho^2 = 1 - LL(\beta)/LL(0)$	0.272			
Corrected ρ^2	0.257			
Corrected AIC	5239.229			

Note: The confidence interval of the estimated parameters is 95%.

constrained structure is proposed to settle the temporal instability other than year-separate (unconstrained temporal) modeling approaches. In the partially temporal constrained structure, a series of likelihood ratio tests are estimated to identify whether the parameters stay temporally stable across two or three period. Notably, after testing the correlations of random parameters in such all-year model, the correlated joint structure could not be developed with relatively low confidence levels. Then, the partially temporal constrained uncorrelated joint random parameters bivariate probit model with heterogeneity in means was developed as shown in Table 7.

Several indicators, including male moped riders, two-lane roadways, daylight conditions, and angle crash types, are observed to maintain consistent parameter values across the three periods. Additionally, marginal effects are calculated to demonstrate the long-term impacts of contributing factors on injury severity and helmet usage. This approach is valuable for identifying temporally stable parameters, thus informing several safety improvement strategies from a policy perspective.

5.4. Random parameters and heterogeneity in means

In the partially temporally constrained model, five variables are observed to generate random parameters, whereas in the temporally unconstrained model spanning three periods, there are two random parameters for each period model. In the temporally unconstrained model, the lane-2 indicator, which is statistically significant, is identified as a fixed parameter during the COVID-19 period in the partially temporally constrained model.

Before the COVID-19 pandemic, the lane-2 indicator was found to yield a statistically significant random parameter for injury/fatality, with a mean (standard deviation) of −0.228 (0.291). This normal distribution suggests that 78.3 % of moped riders are less likely to experience injuries and fatalities, while the remaining 21.7 % are at a higher risk of injuries and fatalities when riding on two-lane roadways. Additionally, after the COVID-19 pandemic, the paved shoulder indicator is identified as a random parameter specifically related to helmet use, with the normal distribution indicating that 79.7 % of moped riders on roadways with paved shoulders are less likely to wear helmets.

Regarding heterogeneity in means, the old moped indicator is found to increase the mean of the lane-2 indicator by 0.326. This suggests that, before the COVID-19 pandemic, 5.2 % (78.3 % − 73.1 %) more moped riders on two-lane roadways experienced a higher likelihood of injury or fatality while riding on old mopeds. Furthermore, rider distraction reduces the mean of the paved shoulder indicator specific to helmet use after the COVID-19 pandemic by 0.458. Such interactions between variables and random parameters, captured through unobserved heterogeneity, indicate that riding mopeds that are 10 years older results in 10.8 % (79.7 % − 68.9 %) fewer moped riders on paved shoulders wearing helmets.

5.5. Estimation for injury severity

In the partially temporally constrained modeling approaches, male moped riders are associated with a lower likelihood of injury or fatality across all years, reducing the probability by 0.0528, as shown in Table 7. Males generally have stronger physical builds but are more likely to engage in riskier riding behaviors compared to females, a finding that aligns with previous studies on motorcyclists (Rifaat et al., 2012; Shaheed and Gkritza, 2014). Male riders may adjust their behavior in response to perceived risks, such as reducing speed or being more cautious in high-risk situations (Cordellieri et al., 2016). Their improved control over the moped, especially in challenging conditions, can help reduce the severity of crashes.

Riding under daylight condition decreases the injury/fatality likelihood by 0.0682 across the three periods. This is consistent with recent studies (Chang et al., 2022a; Wang et al., 2022), as the improved visibility provided by daylight conditions enables moped riders and vehicle drivers to perceive potential hazards more clearly, thereby reducing the risk of injury or fatality in crashes.

Additionally, an angle crash between a moped and a vehicle tends to increase the likelihood of injury or fatality by 0.0927 across the three periods. Moped riders face a higher risk of being ejected from their mopeds in angle crashes, making them more likely to be thrown onto the road or against other objects (Clarke et al., 2004). Angle crashes often occur at intersections where higher speeds and a failure to notice or accurately assess hazardous situations can lead to high-impact collisions (Pai, 2009).

In addition to three variables that consistently affect injury severity outcomes over three years, some critical factors are also observed to increase injury levels during one or two periods. For example, riders aged 30–45 years old show an increased likelihood of injury/fatality by 0.0729 during the COVID-19 pandemic. With significant family and professional responsibilities, this age group may be more susceptible to stress and distractions from work, home, and pandemic-related challenges, which could adversely affect their riding behaviors (Lyon et al., 2024). Moreover, riders in this age group, likely commuting for essential services, may encounter riskier traffic situations than usual during the COVID-19 pandemic.

Regarding driver attributes, drivers aged among 30 and 45 years old tend to decrease the riders' Injury/Fatality likelihood by 0.0629 before the COVID-19 pandemic. Compared to younger drivers, individuals in this age group typically have significant driving experience, make better driving decisions, and are less likely to engage in aggressive behaviors such as speeding, abrupt lane changes, and risky overtaking (McNally and Bradley, 2014). Colliding with vehicle exceeding the speed limit would increase the riders' injury/fatality likelihood by 0.1274 after the

COVID-19 pandemic. This aligns with the motorcycle research by Li et al. (2021) and Ijaz et al., (2022), which found that speeding increases motorcyclist injury severity under over speeding conditions. Old moped aged over 10 years experienced lower likelihood of Injury/Fatality by 0.0394 before the pandemic. A possible reason could be the lower operating speed and shorter travel distances of older mopeds, which may reduce the severity of injuries when colliding with other vehicles.

Regarding vehicle attributes, colliding with passenger car tends to decrease the riders' injury/fatality likelihood by 0.0629 before the COVID-19 pandemic. Passenger cars equipped with advanced safety features, such as antilock braking systems and collision avoidance systems, provide enhanced protection to other road users in the event of a collision (Hamsini and Kathiresh, 2021; Huang et al., 2020). Buses are observed to decrease the riders' injury/fatality likelihood by 0.3829 after the COVID-19 pandemic. This finding is reasonable as buses generally operate at lower speeds, especially in urban areas where moped usage is prevalent. Their fixed routes and frequent stops make their movements more predictable to other road users, including moped riders. Additionally, bus drivers are typically professionally trained and experienced in defensive driving techniques (Sullman et al., 2015), which can aid in preventing severe collisions. Moreover, colliding with old vehicles over 10 years, would consistently increase the riders' injury/fatality likelihood by 0.0892 before and during the pandemic. The older vehicles lack modern safety features such as advanced braking systems and structural reinforcements, which could otherwise mitigate the impact of a collision (Fu et al., 2021).

Concerning the roadway attributes, straight alignment decreases the moped riders' injury/fatality likelihood by 0.3287 during the COVID-19 pandemic. Offering better visibility for both moped riders and other drivers, straight road alignments are less complex to navigate compared to curves and intersections. Moped riders could maintain a steady speed and stable control, which reduces the risk of sudden maneuvers or braking (Chen et al., 2018; Dozza et al., 2023). Traffic volumes during the pandemic would also decrease the likelihood of encountering dangerous situations, further lowering the risk of severe outcomes. Moreover, riding on divided road tends to increase the injury/fatality likelihood by 0.0529 during the pandemic. Divided roads often have higher speed limits, which can lead to more severe outcomes in moped-vehicle crashes due to the greater force of impact. The pandemic altered typical traffic patterns, with more people possibly using personal vehicles to avoid public transport. This shift could result in unusual traffic flow on divided roads, thereby increasing the likelihood of crashes due to unfamiliarity or increased congestion at certain times (Lee et al., 2023). Another potential reason could be the more aggressive and casual riding behaviors that emerged under the reduced traffic conditions on divided roads during the pandemic. Roadways with paved shoulders tend to consistently decrease the Injury/Fatality likelihood by 0.0689 during and after the COVID-19 pandemic. Paved shoulders offer moped riders additional space to maneuver (Srinivasan and Lloyd, 2011), such as moving onto the shoulder to avoid a collision. They also serve as a buffer zone between traffic lanes and roadside obstacles or hazards. This buffer reduces the likelihood of moped riders veering off the road and colliding with fixed objects, thereby significantly lowering the risk of severe injuries or fatalities.

Regarding the crash characteristic, head-on collision increases the Injury/Fatality by 0.1627 before the COVID-19 pandemic. The vehicle front indicator shows the similar tendency before and after the COVID-19 pandemic, showing that vehicle's most damage area is rear would increase the Injury/Fatality likelihood by 0.0626. The combined speed of mopeds and other vehicles results in a significantly higher impact force compared to other types of collisions. Lacking protective structures such as airbags and crumple zones, moped riders are particularly vulnerable to severe injuries or fatalities in these high-energy crashes. The nature of a head-on collision often causes the moped rider to be ejected from the vehicle due to the sudden deceleration and impact force. Ejection significantly increases the risk of severe injuries or fatalities, even for helmeted riders (Kent et al., 2022).

Otherwise, the most damage area being the rear decreases the riders' Injury/Fatality by 0.1024 before and during the COVID-19 pandemic. When a moped strikes a larger vehicle, the impact force on the rider is typically lower than in other types of collisions, such as head-on crashes, due to the larger vehicle absorbing more of the impact. In situations where a moped collides with the rear or side of a vehicle, the speed differential is often smaller, leading to a less severe impact compared to high-speed head-on collisions. Additionally, when a moped strikes a larger vehicle, the rider may be deflected rather than coming to a sudden stop, further reducing the severity of the collision.

5.6. *Estimation for helmet usage*

Regarding helmet usage, several indicators have been observed to be significant across the three periods. Notably, male moped riders appear less likely to wear helmets consistently across the three periods. A possible reason might be the perception among male riders that wearing helmets is unnecessary because they feel less vulnerable. This finding is consistent with the research on motorcyclists by Zamani et al. (2009).

The likelihood of helmet-wearing is observed to decrease in moped-vehicle occurred on 2-lane roadways across the three periods. The potential reason could be that two-lane roadways (one lane in each direction) are perceived as less dangerous compared to multi-lane highways with higher traffic volumes and speeds (Intini et al., 2018). Additionally, two-lane roadways in rural or suburban areas often experience less stringent or less frequent traffic enforcement. Riders on these roads may prioritize convenience and comfort, thus choosing to forgo helmets.

Additionally, riders aged 30–45 years are less likely to wear helmets before the COVID-19 pandemic in moped-vehicle crashes. This finding might be explained by safety attitude, while this age group perceive themselves as experienced and skilled, leading to overconfidence and a reduced perceived need for protective gear like helmets (Knudsen, 2009). Moreover, moped riders affected by distractions were also less likely to wear helmets during the COVID-19 period.

Local moped riders are more likely to wear helmets during the pandemic, as they become increasingly conscious of the heightened safety concerns. Helmets were regarded as essential personal protective equipment for moped riders, emphasizing their role in enhancing safety during this period.

Riding a moped over 10 years old and riding on roads with a dry surface respectively led to a decreased likelihood of helmet usage by 0.0394 and 0.0102 in collisions with vehicles before the pandemic.

The presence of paved shoulders is negatively associated with helmet usage before and during the COVID-19 pandemic. Paved shoulders may provide moped riders with a false sense of security, encouraging more relaxed riding where helmets are perceived as unnecessary or uncomfortable, especially in warmer weather. Similarly, dry roadway surface is also negatively linked to helmet usage before the COVID-19 pandemic.

Additionally, moped riders are less likely to wear helmets on clear days after the COVID-19 pandemic. Furthermore, riders involved in moped-vehicle crashes during the daytime experience a decrease in helmet usage likelihood by 0.0573 before the pandemic. The naturally better visibility during daytime leads moped riders to perceive a lower risk of crashes. Additionally, the clear days in Florida feature warmer weather conditions, making it uncomfortable for moped riders to wear helmets (Yannis et al., 2012).

Notably, mopeds with the most damage to the rear area are generally associated with a higher likelihood of helmet wearing. However, during the pandemic, vehicles with the most damage to the rear area in moped-vehicle crashes exhibit a lower likelihood of helmet wearing by 0.1243. Moped riders who engage in more aggressive riding without helmets are more likely to collide with other vehicles from the rear (Wang et al., 2023). This tendency is linked to their riding at higher speeds, changing lanes more quickly, and adhering less to safe following distances

(Watson et al., 2007).

6. Conclusions

To explore the correlation between helmet usage and injury severity outcomes, a series of joint bivariate probit models were developed. With injury severity and helmet usage as two dependent variables, temporal unconstrained models were estimated based on moped-vehicle crashes in Florida before, during, and after the COVID-19 pandemic. The correlated joint random parameters bivariate probit models demonstrated superiority based on chi-square tests, along with higher ρ^2 values and lower corrected AIC values. Moreover, temporal instability related to the COVID-19 pandemic was validated through transferability tests and out-of-sample predictions. Marginal effects from the temporal unconstrained models also provided robust evidence of temporal shifts in several variables.

To demonstrate the long-term impacts of contributing factors on injury severity and helmet usage, a partially temporally constrained uncorrelated joint random parameters bivariate probit model with heterogeneity in means was utilized. Based on the findings, several advisable recommendations could be implemented. It is advisable for moped riders to participate in educational programs, especially targeting male and middle-aged groups. Strengthened inspections and mandatory scrapping should be adopted for older mopeds. It is recommended that road surfaces be paved over the shoulder to benefit the separation between mopeds and vehicles. Stop signs should be installed for mopeds at intersections, and specific traffic lights or warning signs should be added to alert drivers to the presence of mopeds. At major or busy intersections, the establishment of moped-specific lanes is suggested, along with the implementation of high-tech methods including cameras and sensors, to reduce the chances of cross-collisions.

Nevertheless, some limitations do exist in this study. The models were estimated based solely on data from moped-vehicle crashes in Florida. This focus might limit the generalizability of the findings to other regions with different traffic conditions, regulations, and cultural attitudes toward safety. The accuracy of the reports used could affect the reliability of the results, while the unrecorded non-injured moped crashes could introduce biased effects on the findings. Moreover, future research could be enhanced by integrating questionnaire surveys with safety analysis. This approach would expand the depth and breadth of the data, offering more nuanced insights into the behavioral factors and personal perceptions that influence safety outcomes.

CRediT authorship contribution statement

Chenzhu Wang: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation. **Mohamed Abdel-Aty:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Formal analysis. **Pengfei Cui:** Writing – original draft, Validation, Supervision, Investigation, Formal analysis. **Lei Han:** Writing – review & editing, Investigation, Formal analysis.

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.

Data availability

Data will be made available on request.

Appendix A. Descriptive statistics of significant variables

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Table A1

Descriptive statistics of significant variables for moped-vehicle crashes before, during and after COVID-19 pandemic.

Variables	Before COVID-19 (2019)		During COVID-19 (2020)		After COVID-19 (2021)	
	Frequency	Percentage	Frequency	Percentage	Frequency	Percentage
Injury/Fatality proportion for moped riders	668	70.84 %	553	72.57 %	690	70.91 %
Helmet usage for moped riders	162	17.18 %	117	15.35 %	154	15.83 %
Rider Characteristics						
Male moped rider (1 if moped rider is male, 0 otherwise)	746	79.11 %	639	83.86 %	787	80.88 %
Rider Below 16 years indicator (1 if rider age below 16 years, 0 otherwise)	31	3.29 %	25	3.28 %	36	3.70 %
Rider 16–30 years indicator (1 if rider age between 16–30 years, 0 otherwise)	366	38.81 %	265	34.78 %	343	35.25 %
Rider 30–45 years indicator (1 if rider age between 30–45 years, 0 otherwise)	257	27.25 %	217	28.48 %	269	27.65 %
Rider Above 45 years indicator (1 if rider age above 45 years, 0 otherwise)	288	30.54 %	255	33.46 %	325	33.40 %
Rider local indicator (1 if rider is local, 0 otherwise)	879	93.21 %	671	88.06 %	885	90.96 %
Rider operation error (1 if crash occurred due to operation error of rider, 0 otherwise)	738	78.26 %	563	73.88 %	712	73.18 %
Rider distraction (1 if crash occurred due to distraction of moped rider, 0 otherwise)	131	13.89 %	116	15.22 %	172	17.68 %
Rider over speeding indicator (1 if rider exceeding the speed limit, 0 otherwise)	20	2.12 %	25	3.28 %	31	3.19 %
Driver Characteristics						
Male vehicle driver (1 if male, 0 otherwise)	551	58.43 %	484	63.52 %	589	60.53 %
Driver below 16 years indicator (1 if age below 16 years, 0 otherwise)	50	5.30 %	51	6.69 %	71	7.30 %
Driver 16–30 years indicator (1 if age between 16–30 years, 0 otherwise)	247	26.19 %	213	27.95 %	252	25.90 %
Driver 30–45 years indicator (1 if age between 30–45 years, 0 otherwise)	246	26.09 %	202	26.51 %	278	28.57 %
Driver Above 45 years indicator (1 if age above 45 years, 0 otherwise)	408	43.27 %	296	38.85 %	372	38.23 %
Driver operation error (1 if crash occurred due to driver' operation error, 0 otherwise)	799	84.73 %	658	86.35 %	817	83.97 %
Driver distraction (1 if crash occurred due to distraction of vehicle driver, 0 otherwise)	170	18.03 %	146	19.16 %	167	17.16 %
Driver over speeding indicator (1 if driver exceeding the speed limit, 0 otherwise)	30	3.18 %	19	2.49 %	28	2.88 %
Hit-and-run indicator (1 if drivers run after hitting moped, 0 otherwise)	74	7.85 %	72	9.45 %	31	3.19 %
Moped Characteristics						
Old moped indicator (1 if moped age more than 10 years, 0 otherwise)	183	19.41 %	159	20.87 %	190	19.53 %
Vehicle Characteristics						
Passenger car indicator (1 if passenger car, 0 otherwise)	559	59.28 %	439	57.61 %	552	56.73 %

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Table A1 (*continued*)

Variables	Before COVID-19 (2019)		During COVID-19 (2020)		After COVID-19 (2021)	
	Frequency	Percentage	Frequency	Percentage	Frequency	Percentage
SUV indicator (1 if sport utility vehicle (SUV), 0 otherwise)	202	21.42 %	154	20.21 %	225	23.12 %
Pick up indicator (1 if pick up, 0 otherwise)	65	6.89 %	75	9.84 %	84	8.63 %
Van indicator (1 if van, 0 otherwise)	38	4.03 %	32	4.20 %	36	3.70 %
Heavy truck indicator (1 if heavy truck, 0 otherwise)	8	0.85 %	9	1.18 %	19	1.95 %
Bus indicator (1 if bus, 0 otherwise)	7	0.74 %	3	0.39 %	5	0.51 %
Other indicator (1 if other types of vehicles, 0 otherwise)	6	0.64 %	50	6.56 %	52	5.34 %
Old vehicle indicator (1 if auto age more than 10 years, 0 otherwise)	323	34.25 %	298	39.11 %	339	34.84 %
Roadway Characteristics						
Level indicator (1 if level grade, 0 otherwise)	925	98.09 %	737	96.72 %	949	97.53 %
Straight indicator (1 if straight alignment, 0 otherwise)	911	96.61 %	745	97.77 %	945	97.12 %
Lane_1 indicator (1 if crash occurred on road with one lane, 0 otherwise)	19	2.01 %	22	2.89 %	26	2.67 %
Lane_2 indicator (1 if crash occurred on road with two lanes, 0 otherwise)	425	45.07 %	344	45.14 %	444	45.63 %
Lane_3 indicator (1 if crash occurred on road with three or more lanes, 0 otherwise)	498	52.81 %	396	51.97 %	503	51.70 %
One-way indicator (1 if crash occurred on one-way road, 0 otherwise)	57	6.04 %	32	4.20 %	49	5.04 %
Divided indicator (1 if crash occurred on divided road, 0 otherwise)	364	38.60 %	312	40.94 %	378	38.85 %
National indicator (1 if crash occurred on national road, 0 otherwise)	79	8.38 %	54	7.09 %	59	6.06 %
Interstate indicator (1 if crash occurred on interstate road, 0 otherwise)	8	0.85 %	12	1.57 %	14	1.44 %
State indicator (1 if crash occurred on state road, 0 otherwise)	217	23.01 %	161	21.13 %	206	21.17 %
County indicator (1 if crash occurred on county road, 0 otherwise)	111	11.77 %	107	14.04 %	145	14.90 %
Other road indicator (1 if crash occurred on other type of road, 0 otherwise)	24	2.55 %	20	2.62 %	22	2.26 %
Urban areas indicator (1 if roadway is urban, 0 otherwise)	747	79.22 %	587	77.03 %	772	79.34 %
Dry surface indicator (1 if roadway surface is dry, 0 otherwise)	856	90.77 %	687	90.16 %	904	92.91 %
Wet surface indicator (1 if roadway surface is wet, 0 otherwise)	87	9.23 %	73	9.58 %	68	6.99 %
Other surface indicator (1 if roadway surface is other types, 0 otherwise)	0	0.00 %	2	0.26 %	1	0.10 %
Paved shoulder indicator (1 if shoulder is paved, 0 otherwise)	385	40.83 %	340	44.62 %	453	46.56 %
Environmental Characteristics			0	0.00 %	0	0.00 %
Clear indicator (1 if clear, 0 otherwise)	796	84.41 %	651	85.43 %	846	86.95 %
Cloudy indicator (1 if cloudy, 0 otherwise)	93	9.86 %	72	9.45 %	86	8.84 %
Rainy indicator (1 if rainy, 0 otherwise)	53	5.62 %	37	4.86 %	38	3.91 %
Other weather indicator (1 1 if other weather conditions, 0 otherwise)	1	0.11 %	2	0.26 %	3	0.31 %
Daylight indicator (1 if daylight, 0 otherwise)	640	67.87 %	494	64.83 %	658	67.63 %
Lighted under dark indicator (1 if lighted roadway during nighttime, 0 otherwise)	220	23.33 %	178	23.36 %	225	23.12 %
Non-lighted under dark indicator (1 if not lighted during nighttime, 0 otherwise)	30	3.18 %	45	5.91 %	39	4.01 %
Crash Characteristics						
Angle indicator (1 if angle crash, 0 otherwise)	400	42.42 %	304	39.90 %	341	35.05 %
Head-on indicator (1 if head-on crash, 0 otherwise)	53	5.62 %	47	6.17 %	55	5.65 %
Rear-end indicator (1 if rear-end crash, 0 otherwise)	242	25.66 %	218	28.61 %	274	28.16 %
Sideswipe indicator (1 if sideswipe crash, 0 otherwise)	134	14.21 %	103	13.52 %	179	18.40 %
Other crash type indicator (1 if other type of crash, 0 otherwise)	112	11.88 %	90	11.81 %	124	12.74 %
Intersection indicator (1 if in intersection area, 0 otherwise)	50	5.30 %	30	3.94 %	36	3.70 %
Moped front indicator (1 if moped's most damage area is front, 0 otherwise)	487	51.64 %	391	51.31 %	536	55.09 %
Moped rear indicator (1 if moped's most damage area is rear, 0 otherwise)	83	8.80 %	86	11.29 %	99	10.17 %
Moped other areas indicator (1 if moped's most damage area is other areas, 0 otherwise)	373	39.55 %	285	37.40 %	338	34.74 %
Vehicle front indicator (1 if vehicle's most damage area is front, 0 otherwise)	338	35.84 %	287	37.66 %	360	37.00 %
Vehicle rear indicator (1 if vehicle's most damage area is rear, 0 otherwise)	143	15.16 %	115	15.09 %	167	17.16 %
Vehicle other areas indicator (1 if vehicle's most damage area is other areas, 0 otherwise)	462	48.99 %	360	47.24 %	446	45.84 %
Temporal Characteristics						
Hurricane indicator (1 if crash occurred in hurricane season (June to November), 0 otherwise)	394	41.78 %	333	43.70 %	377	38.75 %
Weekend indicator (1 if crash occurred on weekend, 0 otherwise)	222	23.54 %	184	24.15 %	243	24.97 %
Day indicator (1 if crash occurred during daytime, 0 otherwise)	668	70.84 %	523	68.64 %	676	69.48 %

Appendix B. Temporal unconstrained modeling approaches

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Table B1

Temporal unconstrained modeling approaches to model injury severity and helmet usage of moped riders in moped-vehicle crashes (t-statistics in parentheses) based on joint random parameters bivariate probit models with heterogeneity in means.

Variables	Before COVID-19 (2019)		During COVID-19 (2020)		After COVID-19 (2021)	
	Injury/ fatality	Use of helmet	Injury/ fatality	Use of helmet	Injury/ fatality	Use of helmet
Constant	0.869 (5.43)	−0.522 (−2.42)	1.521 (2.81)	−1.390 (−4.12)	0.464 (2.71)	−0.552 (−3.25)
Rider Characteristics						
Male moped rider (1 if male, 0 otherwise)	−0.305 (−1.98)[1]	−0.323 (−2.00)	−0.467 (−2.71)	−0.421 (−2.76)	−0.362 (−2.33)	−0.319 (−2.32)
Rider Below 16 years indicator (1 if rider age below 16 years, 0 otherwise)	−0.660 (−2.77)				−0.587 (−2.47)	

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Table B1 (*continued*)

Variables	Before COVID-19 (2019)		During COVID-19 (2020)		After COVID-19 (2021)	
	Injury/ fatality	Use of helmet	Injury/ fatality	Use of helmet	Injury/ fatality	Use of helmet
Rider 30–45 years indicator (1 if rider age between 30–45 years, 0 otherwise)		−0.367 (−3.00)	0.252 (2.05)			
Rider Above 45 years indicator (1 if rider age above 45 years, 0 otherwise)						0.225 (2.14)
Rider distraction (1 if crash occurred due to distraction of moped rider, 0 otherwise)				−0.307 (−2.45)		
Rider local indicator (1 if rider is local, 0 otherwise)				0.776 (2.70)		
Rider over speeding indicator (1 if rider exceeding the speed limit, 0 otherwise)						−0.748 (−2.44)
Driver Characteristics						
Driver 30–45 years indicator (1 if age between 30–45 years, 0 otherwise)	−0.245 (−2.41)					
Driver over speeding indicator (1 if driver exceeding the speed limit, 0 otherwise)					0.591 (2.04)	
Moped Characteristics						
Old moped indicator (1 if moped age more than 10 years, 0 otherwise)		−0.662 (−2.03)				
Vehicle Characteristics						
Passenger car indicator (1 if another vehicle is passenger car, 0 otherwise)	−0.246 (−2.53)					
Bus indicator (1 if bus, 0 otherwise)					−1.767 (−2.17)	
Old vehicle indicator (1 if auto age more than 10 years, 0 otherwise)	0.202 (2.02)		0.427 (3.52)			
Roadway Characteristics						
Straight indicator (1 if straight alignment, 0 otherwise)			−1.031 (−2.11)			
Lane_2 indicator (1 if crash occurred on road with two lanes, 0 otherwise)		−0.279 (−2.57)				−0.222 (−2.14)
Divided indicator (1 if crash occurred on divided road, 0 otherwise)			0.281 (2.48)			
Other roadway type indicator (1 if roadway is other type, 0 otherwise)	−0.858 (−2.76)				−0.767 (−2.45)	
Dry surface indicator (1 if roadway surface is dry, 0 otherwise)		−0.336 (−2.10)				
Paved shoulder indicator (1 if shoulder is paved, 0 otherwise)		−0.310 (−2.81)	−0.256 (−2.33)	−0.289 (−2.29)	−0.267 (−2.71)	
Environmental Characteristics						
Clear indicator (1 if clear, 0 otherwise)						−0.346 (−2.76)
Cloudy indicator (1 if cloudy, 0 otherwise)			0.390 (2.07)			
Daylight indicator (1 if daylight, 0 otherwise)	−0.235 (−2.27)	−0.192 (−2.07)	−0.198 (−2.15)		−0.409 (−3.71)	
Crash Characteristics						
Angle indicator (1 if angle crash, 0 otherwise)	0.388 (3.79)		0.387 (3.12)		0.293 (2.70)	
Head-on indicator (1 if head-on crash, 0 otherwise)	0.625 (2.36)					−0.600 (−2.04)
Other crash type indicator (1 if other type of crash, 0 otherwise)			0.475 (2.37)		0.748 (4.32)	
Moped rear indicator (1 if moped's most damage area is rear, 0 otherwise)				0.320 (2.19)		
Vehicle front indicator (1 if vehicle's most damage area is front, 0 otherwise)	0.288 (2.71)				0.271 (2.52)	
Vehicle rear indicator (1 if vehicle's most damage area is rear, 0 otherwise)	−0.270 (−2.07)		−0.304 (−2.02)	−0.337 (−2.19)		
Random parameters						
Rider operation error (1 if crash occurred due to operation error of rider, 0 otherwise)		0.377 (2.79)				
Standard deviation		***0.368 (2.13)***				
Lane_2 indicator (1 if crash occurred on road with two lanes, 0 otherwise)	−0.248 (−2.48)			−0.521 (−2.15)		
Standard deviation	***0.301 (4.14)***			***0.520 (4.59)***		
County indicator (1 if crash occurred on county road, 0 otherwise)			7.979 (2.46)			
Standard deviation			***6.860 (2.75)***			
Paved shoulder indicator (1 if shoulder is paved, 0 otherwise)						−0.203 (−2.08)

(*continued on next page*)

Table B1 (*continued*)

Variables	Before COVID-19 (2019)		During COVID-19 (2020)		After COVID-19 (2021)	
	Injury/ fatality	Use of helmet	Injury/ fatality	Use of helmet	Injury/ fatality	Use of helmet
Standard deviation						***0.266 (2.37)***
Moped front indicator (1 if moped's most damage area is front, 0 otherwise)					0.672 (5.41)	
Standard deviation					***0.630 (6.46)***	
Correlation of random parameters						
Elements of the Cholesky matrix (t-stats in parentheses), and correlation coefficients [in brackets]	−0.345 (−6.10) [-0.939]		0.264 (2.64) [0.315]		−0.222 (−2.04) [-0.834]	
Heterogeneity in the means of random parameters						
Lane_2 indicator (1 if crash occurred on road with two lanes, 0 otherwise): Old moped indicator (1 if moped age more than 10 years, 0 otherwise)	0.314 (2.12)					
County indicator (1 if crash occurred on county road, 0 otherwise): Old moped indicator (1 if moped age more than 10 years, 0 otherwise)			−2.624 (−2.10)			
Lane_2 indicator (1 if crash occurred on road with two lanes, 0 otherwise): Bus indicator (1 if bus, 0 otherwise)				1.240 (2.04)		
Paved shoulder indicator (1 if shoulder is paved, 0 otherwise): Rider distraction (1 if crash occurred due to distraction of moped rider, 0 otherwise)						−0.437 (−2.64)
ρ	0.195 (3.28)		−0.108 (−2.69)		0.149 (2.91)	
Number of parameters (K)	27		26		25	
Number of observations (N)	943		762		973	
Log-likelihood at zero	−1240.988		−1002.792		−1280.468	
Log-likelihood at convergence	−931.559		−712.002		−955.914	
$\rho^2 = 1 - LL(\beta)/LL(0)$	0.249		0.290		0.253	
Corrected ρ^2	0.227		0.265		0.234	
Corrected AIC	1918.770		1477.914		1963.201	

Note:

[1]The confidence interval of the estimated parameters is 95 %. The values mean the parameter estimates while the t-statistics values are shown in the parentheses. For instance, "Male moped rider (1 if male, 0 otherwise)" obtains a parameter estimate of −0.305 with a t-statistics of −1.98 specific to injury/fatality level in Before COVID-19 (2019) model.

Table B2

Marginal effects of contributors based on temporal unconstrained correlated joint random parameters bivariate probit models with heterogeneity in means.

Variables	Marginal Effects					
	Before COVID-19 (2019)		During COVID-19 (2020)		After COVID-19 (2021)	
	Injury/ fatality	Use of helmet	Injury/ fatality	Use of helmet	Injury/ fatality	Use of helmet
Rider Characteristics						
Male moped rider (1 if male, 0 otherwise)	−0.0337	−0.0316	−0.0594	−0.0607	−0.0411	−0.0430
Rider Below 16 years indicator (1 if rider age below 16 years, 0 otherwise)	−0.1778				−0.1808	
Rider 30–45 years indicator (1 if rider age between 30–45 years, 0 otherwise)		−0.0059	0.0896			
Rider Above 45 years indicator (1 if rider age above 45 years, 0 otherwise)						0.0037
Rider operation error (1 if crash occurred due to operation error of rider, 0 otherwise)		0.0069				
Rider distraction (1 if crash occurred due to distraction of moped rider, 0 otherwise)				−0.0037		
Rider local indicator (1 if rider is local, 0 otherwise)				0.0085		
Rider over speeding indicator (1 if rider exceeding the speed limit, 0 otherwise)						−0.0126
Driver Characteristics						
Driver 30–45 years indicator (1 if age between 30–45 years, 0 otherwise)	−0.0779					
Driver over speeding indicator (1 if driver exceeding the speed limit, 0 otherwise)					0.1612	
Moped Characteristics						
Old moped indicator (1 if moped age more than 10 years, 0 otherwise)		−0.0439				
Vehicle Characteristics						
Passenger car indicator (1 if another vehicle is passenger car, 0 otherwise)	−0.0574					
Bus indicator (1 if bus, 0 otherwise)					−0.3786	
Old vehicle indicator (1 if auto age more than 10 years, 0 otherwise)	0.0633		0.1049			
Roadway Characteristics						
Straight indicator (1 if straight alignment, 0 otherwise)			−0.3512			
Lane_2 indicator (1 if crash occurred on two lanes on each side of road, 0 otherwise)	−0.0512	−0.0467		−0.0025		−0.0036
Divided indicator (1 if crash occurred on divided road, 0 otherwise)			0.0675			
County indicator (1 if crash occurred on county road, 0 otherwise)			0.1511			
Other roadway type indicator (1 if roadway is other type, 0 otherwise)	−0.1321				−0.2037	
Dry surface indicator (1 if roadway surface is dry, 0 otherwise)		−0.0151				
Paved shoulder indicator (1 if shoulder is paved, 0 otherwise)		−0.0259	−0.0887	−0.0919	−0.0725	−0.0690
Environmental Characteristics						

(*continued on next page*)

Table B2 (*continued*)

Variables	Marginal Effects					
	Before COVID-19 (2019)		During COVID-19 (2020)		After COVID-19 (2021)	
	Injury/ fatality	Use of helmet	Injury/ fatality	Use of helmet	Injury/ fatality	Use of helmet
Clear indicator (1 if clear, 0 otherwise)						−0.0041
Cloudy indicator (1 if cloudy, 0 otherwise)			0.0945			
Daylight indicator (1 if daylight, 0 otherwise)	−0.0747	−0.0717	−0.0751		−0.0896	
Crash Characteristics						
Angle indicator (1 if angle crash, 0 otherwise)	0.1134		0.1161		0.0811	
Head-on indicator (1 if head-on crash, 0 otherwise)	0.1802					−0.0093
Other crash type indicator (1 if other type of crash, 0 otherwise)			0.1738		0.1742	
Moped front indicator (1 if moped's most damage area is front, 0 otherwise)					0.0774	
Moped rear indicator (1 if moped's most damage area is rear, 0 otherwise)				0.0033		
Vehicle front indicator (1 if vehicle's most damage area is front, 0 otherwise)	0.0591				0.0803	
Vehicle rear indicator (1 if vehicle's most damage area is rear, 0 otherwise)	−0.0822		−0.1204	−0.1167		

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