Front. Eng. Manag. 2025, 12(2): 394–413
https://doi.org/10.1007/s42524-024-0302-8

RESEARCH ARTICLE

Yaqiu LI, Lon VIRAKVICHETRA, Junyi ZHANG, Haoran LI, Yunpeng LU

Jointly modeling the dependence of injury severity and crash size involved in motorcycle crashes in Cambodia using a copula-based approach

Abstract Escalating motorcycle crashes present a significant challenge due to the increase in motorcycle registrations and the corresponding increase in mortality rates. This issue is particularly acute in Cambodia, where motorcycles are the primary mode of transportation. In the analysis of motorcycle crashes, two key measures of severity are injury severity and crash size, notably the number of injuries. Typically, these indicators are analyzed independently to understand the impact and consequences of motorcycle accidents. Nevertheless, it is critical to recognize that both observed and unobserved factors may concurrently affect these crash indicators, indicating a possible interrelationship between injury severity and motorcycle crash size. Neglecting the joint occurrence of these variables can result in biased and incorrect parameter estimation. This research contributes to the existing body of knowledge by simultaneously analyzing the factors influencing both injury severity and motorcycle crash size. This approach further distinguishes itself by considering the interdependence between these two results utilizing a copula-based approach. Six models based on copulas were developed using the ordered logit model, which was designed to capture the ordinal nature of injury severity and crash size. By analyzing motorcycle crash data from 2016 in Cambodia, the Frank copula framework was identified as the most effective among the five approaches. The findings revealed that factors such as motorcycle-to-pedestrian collisions, head-on collisions, X junctions, and national roads significantly increase both motorcyclist injury severity and crash size. These insights are valuable for policymakers in formulating targeted strategies to improve motorcycle safety within transportation systems.

Keywords traffic accident, crash, motorcycle, injury severity, crash size

Received Nov. 25, 2023; revised Jan. 9, 2024; accepted Jan. 21, 2024

Yaqiu LI
School of Transportation, Southeast University, Nanjing, 211189, China; Graduate School of Advanced Science and Engineering, Hiroshima University, 1-5-1 Kagamiyama, Higashihiroshima 739-8529, Japan

Lon VIRAKVICHETRA
Graduate School of Advanced Science and Engineering, Hiroshima University, 1-5-1 Kagamiyama, Higashihiroshima 739-8529, Japan

Junyi ZHANG (✉)
School of Transportation, Southeast University, Nanjing 211189, China
E-mail: zjy890321@seu.edu.cn

Haoran LI
School of Automobile and Traffic Engineering, Wuhan University of Science and Technology, Wuhan 430065, China; Tsinghua University Suzhou Automotive Research Institute, Suzhou 215200, China

Yunpeng LU
School of Automobile and Traffic Engineering, Wuhan University of Science and Technology, Wuhan 430065, China

This research was supported by the start-up research fund of Southeast University, China (RF1028623308).

1 Introduction

Every year, the annual global fatality count resulting from traffic crashes reaches approximately 1.3 million, with nonfatal injuries accounting for nearly 50 million people. Astonishingly, approximately 93% of these incidents transpire in nations with low to middle incomes, as documented by the World Health Organization (WHO, 2018). Remarkably, South-east Asia alone contributes a quarter of worldwide traffic fatalities, with 316,000 lives lost in vehicular accidents (WHO, 2017). More than half of these fatalities involve motorcycles and tricycles (WHO, 2018), emphasizing the urgent necessity for stricter motorcycle and tricycle safety regulations and policies in the region.

The escalating concern for road safety in South-east Asia closely corresponds with the significant surge in the utilization of motorcycles and tricycles over the past two decades. This upsurge is predominantly attributed to the cost-effectiveness of motorcycles in comparison to four-wheeled automobiles, rendering them a more attainable mode of transportation for a substantial portion of the population in this area. Among these nations, Cambodia stands out for having the highest risk of road safety concerns, primarily due to its elevated mortality rate (Roehler et al., 2015). This can be attributed to issues such as the burgeoning number of vehicles, an imbalanced ratio between road infrastructure and vehicles, and suboptimal driving behavior (UNDP, 2020).

Motorcycles dominate as the primary mode of transportation in Cambodia, with annual motorcycle registrations consistently constituting more than 75% of total vehicle registrations from 2011 to 2019, significantly outnumbering their four-wheeled counterparts (MPWT et al., 2022). Additionally, there was a substantial 66.67% increase in motorcycle registrations during the same period (MPWT et al., 2022). Motorcyclists, in contrast to occupants of four-wheeled vehicles, face a considerably greater risk of injury due to the limited protective measures available to them. Despite their vulnerability as road users, motorcyclists often do not receive adequate attention in terms of road safety initiatives. This discrepancy underscores the crucial necessity of investigating the factors contributing to motorcycle crashes, particularly in developing countries such as Cambodia.

2 Literature review

2.1 Motorcycle traffic safety research

Limited research pertaining to motorcycle traffic safety issues has been conducted, particularly in the context of developing countries. Current research on motorcycle safety primarily emphasizes the analysis of risk factors associated with motorcycle crashes, categorized as motorcycle crash-related factors, human factors, road environment factors, or temporal factors.

Regarding motorcycle crash-related factors, the type of obstacle encountered during a collision could impact the injury severity of riders (Yamamoto and Shankar, 2004). The severity of rider injuries tends to increase in cases involving right-angle collisions and motorcycle-truck crashes (Rifaat et al., 2012). Additionally, research has indicated that single motorcycle crashes are more likely to result in severe injuries (Blackman and Haworth, 2013). In terms of human factors, a significant number of motorcycle riders lose their lives due to factors such as speeding (Mohamad et al., 2022; Zubaidi et al., 2022), drunk driving (Lao and Lukusa, 2023), and failure to wear helmets (Zambon and Hasselberg, 2006; Lin and Kraus, 2009; Ngoc et al., 2023; Lao and Lukusa, 2023). Unsafe driving behaviors, including unlicensed driving, mobile phone use while riding, and driving while fatigued, also increase the likelihood of rider injuries (Doan and Hobday, 2019; Truong et al., 2019; Nguyen-Phuoc et al., 2020; Truong et al., 2020; Khan et al., 2022). Furthermore, the factors influencing injury severity among motorcycle riders and pillion riders may vary depending on age (Dapilah et al., 2017; Islam, 2021). Previous research has indicated that teenage motorcycle riders have a higher incidence and fatality rate in crashes (Walshe et al., 2017; Banz et al., 2019) due to their propensity for engaging in risky driving behaviors such as speeding, not wearing helmets, unlicensed driving, and lack of driving experience (Bonander et al., 2015; Urawit Piyapromdee et al., 2015; Curry et al., 2017; Boulagouas et al., 2020; Goodwin et al., 2022). Very young and older motorcycle riders are also more prone to being at fault in motorcycle crashes (Stutts et al., 2004; Haque et al., 2009; Clarke et al., 2010; Talving et al., 2010; Anstey et al., 2012). Motorcycles inherently lack sufficient protection for both riders and pillion riders, rendering them more vulnerable to injuries in the event of a crash. Consequently, the implementation of measures such as wearing helmets and reflective clothing plays a crucial role in mitigating injury severity and reducing fatalities in motorcycle crashes (Peek-Asa et al., 1999; Shaheed et al., 2013; Erhardt et al., 2016; Rice et al., 2017; Park et al., 2019; Wali et al., 2019). Se et al. (2021) conducted a study utilizing four years of motorcycle collision data from Thailand spanning the period from 2016 to 2019. Road characteristics also significantly contribute to determining the severity of driver injuries in motorcycle crashes. Research has consistently demonstrated that crashes occurring at intersections are more likely to cause severe injury to motorcycle riders (Abdel-Aty and Keller, 2005; Abrari Vajari et al., 2020; Rifaat et al., 2012). Specifically, speeding at intersections has been identified as a contributing factor to serious injuries for riders (Zubaidi et al., 2022). Research has shown that temporal variations in motorcyclist injury severity exist among weekdays, weekends, and holidays (Se et al., 2021; 2022), with greater severity levels found in weekend crashes (Blackman and Haworth, 2013).

2.2 Research on crash size

In traffic crashes, both injury severity and crash size are recognized as pivotal variables. Numerous prior studies have independently modeled these crash result variables. While there has been substantial research into how risk factors affect motorcycle injury severity or crash size, there is currently a scarcity of related research regarding the interdependency between injury severity and crash size in motorcycle crashes. Commonly employed variables for gauging crash size in traffic accidents include variables such as the number of injuries and fatalities, the total number of vehicles involved in the crash, and the total number of damaged vehicles (Lee et al., 2008). These variables provide a quantitative assessment of the scale and impact of crashes. Motorcycles are frequently utilized as taxis in numerous developing countries and serve as a prevalent and accessible mode of transportation for daily commuting (Wu and Loo, 2016; Nguyen-Phuoc et al., 2019; Martin et al., 2023), necessitating the consideration of casualty numbers in motorcycle crash analysis. Due to the absence of protective measures for both riders and pillion riders, the incidence of casualties in motorcycle crashes tends to surpass that in car crashes (Sirajudeen et al., 2022). Previous research has revealed a significant correlation between the number of vehicles and passengers involved in crashes and the likelihood of injury (Broyles et al., 2003; Savolainen and Mannering, 2007). Tamakloe et al. (2020) proposed a copula-based joint modeling method that takes into account the correlation between crash severity and the number of vehicles involved in crashes. Crash severity was categorized into four levels: fatal injury, severe injury, moderate injury, and property damage only. Their findings also demonstrated a positive correlation between these two variables. Factors that can escalate crash severity often lead to an increase in the number of vehicle collisions. Hassan and Al-Faleh (2013) employed structural equation modeling (SEM) to investigate the variables impacting crash size. Their results indicated that certain variables (e.g., the day of the week) not only impacted crash severity but also directly affected crash size. Yuan et al. (2019) established that factors such as the environment, road conditions, vehicles, and driver characteristics can impact crash size and truck occupant injury severity. However, there were notable disparities in how each risk factor influenced these two variables. A substantial correlation exists between larger motorcycle crash sizes and the involvement of heavy vehicles as the responsible party, female drivers, and elderly drivers (Kashani et al., 2020). Correspondingly, research has demonstrated that these factors can also escalate the severity of driver injuries in motorcycle crashes (Pai et al., 2018; Pervez et al., 2021). These studies offer methodological guidance for investigating the relationship between injury severity and motorcycle crash size.

Nonetheless, it is important to acknowledge the presence of commonly observed and unobserved factors that can influence both crash size and injury severity. Presently, in the field of motorcycle crash analysis, the interplay between crash size and injury severity is an area that has not been extensively explored. Furthermore, it is vital to consider these factors and their potential impact on both the severity of injury caused by casualties and the size of crashes concurrently to gain a comprehensive understanding of the dynamics inherent in motorcycle crashes. This study contributes to addressing this research gap.

2.3 Application of copula in traffic crash analysis

Models that simultaneously consider multiple interrelated dependent variables offer a more precise estimation of coefficients when analyzing crash data than univariate models (Park and Lord, 2007; Ma et al., 2008). By jointly modeling the relationships between dependent variables such as injury severity and crash size, this approach effectively captures the complexity and interdependencies present in the data. This method is particularly advantageous for addressing and elucidating correlations that may arise due to endogeneity issues. Endogeneity concerns often stem from factors such as omitted or unobserved variables, measurement errors, or potential causal relationships between the variables under scrutiny. By collectively incorporating these variables, the model furnishes a more comprehensive and accurate representation of the underlying dynamics in traffic crash scenarios.

Commonly employed bivariate analysis methods include the bivariate probit model (Yamamoto and Shankar, 2004; De Lapparent, 2008; Lee and Abdel-Aty, 2008; Russo et al., 2014; Abay, 2015; Fountas et al., 2019; Chiou et al., 2020; Xiao et al., 2021); the binary logit model (Sze and Wong, 2007; Gkritza, 2009; Hu et al., 2010; Moudon et al., 2011; Elsemesmani et al., 2020; Hassanzadeh et al., 2020; Vissoci et al., 2020); and copula-based models (Yasmin et al., 2014; Ayuso et al., 2016; Wali et al., 2018; Wang et al., 2019; Tamakloe et al., 2020; Ahmad et al., 2023; Huang et al., 2023). Initially, employed primarily in the financial sector for assessing the risk of investment portfolios such as stocks, bonds, and real estate (Kole et al., 2007), the copula method is now widely adopted in traffic crash data analysis due to its ability to identify and quantify potential correlations among diverse random variables. Table 1 presents a compilation of research findings related to traffic crashes based on copula analysis.

The copula model has demonstrated superior fitting performance in comparison to traditional binary probit models (Huang et al., 2023; Phuksuksakul et al., 2023). Through the utilization of copula methods, researchers can overcome the restrictive assumptions inherent in simple or traditional binary negative binomial regression models and more effectively capture the potential correlations between dependent variables and unobserved factors (Ahmad et al., 2023). The versatility of copulas in modeling joint distributions renders them a valuable alternative to traditional univariate or bivariate models.

While prior research has successfully applied the copula method to model and analyze injury severity in car crashes (Eluru et al., 2010), there is a noticeable dearth of research employing copulas to model and analyze motorcycle injury severity and crash size. In this study, our objective is to investigate how human factors, road environment conditions, and other variables simultaneously influence both the severity of injury caused by casualties and the number of crashes in motorcycle incidents using a copula approach. This research contributes significantly by addressing the current gap in the literature

Table 1 Previous traffic crash-related research using copula-based approaches.

Author	Study region and period	Bivariate dependent variables	Key findings
Yasmin et al. (2014)	Victoria, Australia (2006–2010)	Injury severity, collision type	Proposed and estimated a joint model for injury severity and collision type.
Ayuso et al. (2016)	Insurance data in Spain	Temporary disability, permanent motor injuries	Positive dependence is observed between the occurrence of temporary and permanent injuries.
Wali et al. (2018)	Virginia (2013)	Injury severity of at-fault, not-at-fault drivers	The driving errors committed by at-fault drivers have a more significant negative impact on injury severity than those of not-at-fault drivers.
Wang et al. (2019)	Connecticut (2016–2017)	Injury severity, crash type, vehicle damage, and driver error	The four dependent variables exhibit strong correlations.
Tamakloe et al. (2020)	Republic of Korea (2010–2016)	Bus involved crash severity, number of vehicles involved	Positive dependence is found between the two dependent variables.
Ghomi and Hussein (2021)	Hamilton city (2010–2017)	Frequency, severity of pedestrian in vehicle-pedestrian crashes	The frequency of collisions decreases at intersections along major transit routes when bus frequency increases. Conversely, intersections near schools see a higher incidence of collisions.
Ahmad et al. (2023)	District 3 of Pennsylvania (2015–2018)	Property-damage only injury and fatal, crash frequencies	Bivariate models with copulas outperform traditional bivariate and univariate models.
Huang et al. (2023)	Los Angeles County in California (2016–2019)	Primary and secondary crash severity	A significant dependency between primary crashes severity and secondary crashes severity, especially with high severity level
Phuksuksakul et al. (2023)	Queensland State (2012–2018)	Crash type, injury severity of pedestrian and bicyclist	The dependency between active traveler crash types and injury severity differs case by case; considering unobserved heterogeneity in external factors improves model fit.

and providing a more comprehensive understanding of the interdependencies and potential endogeneity among observed and unobserved factors.

3 Methodology

Sklar's theorem provides a fundamental concept in which the joint distribution function of multivariate random variables can be represented using marginal distributions combined with a copula function. The copula method, which captures the correlation between different random variables, has gained significant popularity in the field of statistical analysis of traffic crashes. In this study, we propose a bivariate regression model based on copulas to specifically examine the injury severity of motorcycle riders and pillion riders and the number of casualties in crashes. We investigate the effects of various factors, including crash characteristics, casualty characteristics, road conditions, temporal aspects, and more, on both of these variables. Through this research, our objective is to provide a deeper understanding of the complex dynamics that influence injury resulting from motorcycle crashes and to offer valuable insights into how to enhance motorcycle safety.

3.1 Overall framework

The research framework for this study is illustrated in Fig. 1. Our data set includes a comprehensive range of variables relevant to injury severity and motorcycle crash size. Initially, the data set involved the categorization of injury severity among casualties and motorcycle crash size. Subsequently, ordered regression analysis was employed to evaluate the influence of various factors on these aspects. This study explored the relationships among these variables in motorcycle crashes through copula-based modeling. The primary objective of this research is to identify the factors that significantly impact both the severity of injury caused by casualties and the size of crashes. Our aim is to provide valuable policy recommendations aimed at mitigating motorcycle crashes and facilitating the development of effective strategies and interventions.

3.2 The copula approach

The term "copula" was introduced by Sklar in 1959. The copula function serves as a linking function that effectively quantifies the dependence relationship between corresponding variables. It can construct a joint distribution function for any combination of identical or different marginal distribution functions, making it a straightforward and versatile method. These advantageous properties of the copula function have led to its widespread adoption in various fields. It offers a robust approach for creating multivariate joint distributions without imposing constraints on the type of marginal distribution. In general, the copula function is denoted as $C(u, v)$, where u, v refer to the random variables associated with injury severity and crash size during a crash, respectively. The copula function requires $C : [0, 1^2] \rightarrow [0, 1]$ and follows specific equations, as illustrated in Eqs. (1)–(3), constituting the bivariate copula model.

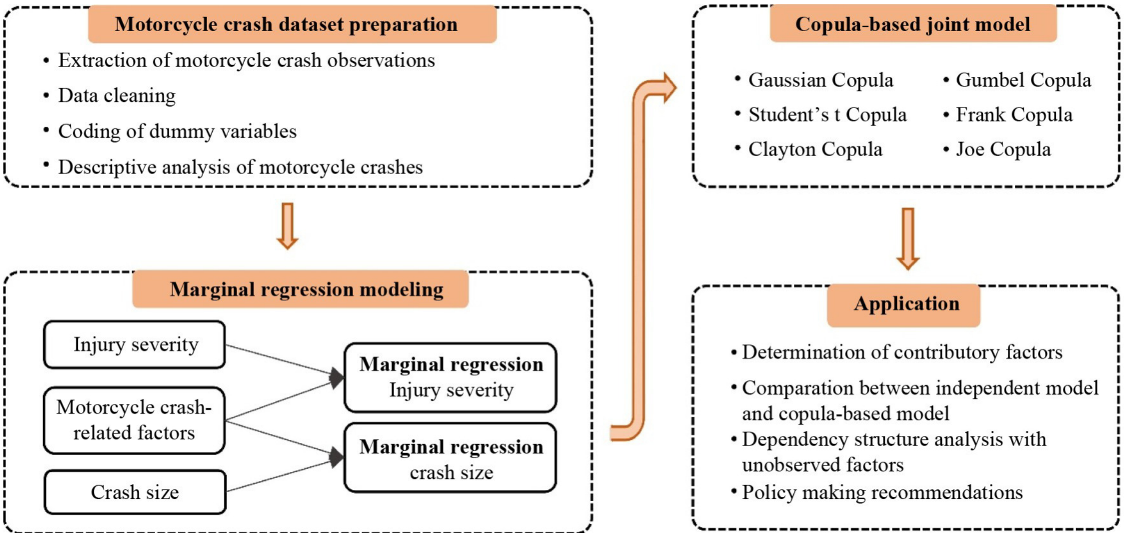

Fig. 1 The proposed research framework.

$$C(u,0)=C(0,v)=0,\ \forall u,\ v\in[0,1], \tag{1}$$

$$C(u,1)=u;\ C(1,v)=v,\ \forall u,\ v\in[0,1], \tag{2}$$

$$\begin{gathered}C(u_2,v_2)-C(u_1,v_2)-C(u_2,v_1)+C(u_1,v_1)\geqslant 0,\\ \forall 0\leqslant u_1\leqslant u_2\leqslant 1, 0\leqslant v_1\leqslant v_2\leqslant 1.\end{gathered} \tag{3}$$

According to Sklar's theory, given an n-dimensional multivariate distribution function with a marginal distribution $F_1(x_1), F_2(x_2), \ldots, F_n(x_n)$, there exists a copula function modeling their joint distribution, as shown in the following equation.

$$\begin{gathered}\forall (x_1,x_2,\ldots,x_n)\in R^n,\ F(x_1,x_2,\ldots,x_n)\\ =C\{F_1(x_1),F_2(x_2),\ldots,F_n(x_n)\}.\end{gathered} \tag{4}$$

If $F_i(x)$ is continuous, then the corresponding C is unique; otherwise, C is nonunique and determined by $F_i(x)$'s product of ranges. When the marginal function $F_i(x)$ and its inverse transformation $F_i^{-1}(x)$ are given, the corresponding copula function can be obtained from the following equation:

$$C(x_1,x_2,\ldots,x_n)=F(F_1^{-1}(x_1),F_2^{-1}(x_2),\ldots,F_n^{-1}(x_n)). \tag{5}$$

When the injury severity of motorcycle casualties and the number of casualties in each crash are represented by two evenly distributed random variables U and V, the two-dimensional copula can be written as follows:

$$C_\theta(u,v)=Prob(U<u,V<v), \tag{6}$$

where θ represents the parameter vector of the copula, which describes the correlation between two random variables, namely, the injury severity and crash size, in this research.

The construction of copula functions $C(u,v)$ is not limited to a single approach. There are six commonly recognized types of copula structures (Martey and Attoh-Okine, 2019). In this research, we establish a copula-based model by utilizing two elliptical copulas and four Archimedean copulas. The two elliptical copulas are the Gaussian copula and Student's t copula, while the four Archimedean copulas include the Clayton copula, Gumbel copula, Frank copula, and Joe copula. A detailed representation of the construction of these six copula frameworks with different mathematical functions and properties is presented in Table 2.

When evaluating the degree of dependence between variables, researchers commonly rely on metrics such as Kendall's tau and Spearman's rho. Kendall's tau coefficient is often preferred for its multiple advantages, as elaborated in Nelsen (2006). A comprehensive summary of the previously discussed copula groups can be found in Table 2.

As indicated in Table 2, Gaussian, Student's t, and Frank copulas are capable of accommodating both positive and negative dependencies, distinguishing them from the Clayton, Gumbel, and Joe copulas, which do not allow for negative dependence. Furthermore, the dependencies in the Gaussian, Student's t, and Frank copulas exhibit symmetry, whereas in the Clayton, Gumbel, and Joe copulas, they are asymmetric. In situations where injury severity and crash size exhibit strong correlations at high values but weak correlations at low values, the Gumbel and Joe copulas are the preferred choices (Nelsen, 2006). Conversely, for the reverse pattern, the Clayton copula is more suitable (Hernández-Alava and Pudney, 2016). Gaussian, Student's t, and Frank copulas prove to be especially valuable in ensuring high and symmetric dependencies around the mean of the distribution, with their symmetric tail dependence feature being particularly advantageous in crash analysis.

Table 2 Formulations and characteristics of copula frameworks

Copula	Formulation	Dependence parameter	Kendal's tau τ(θ)	Kendall's tau
Gaussian Copula	$\Phi_2\left(\Phi^{-1}(u),\Phi^{-1}(v);\rho\right)$	$\rho\in[-1,1]$	$\frac{2}{\pi}\arcsin\theta$	$[-1,1]$
Student's t Copula	$t_C\left(t^{-1}(u),t^{-1}(v);\rho,k\right)$	$\rho\in[0,1]$	$\frac{2}{\pi}\arcsin\theta$	$[-1,1]$
Clayton Copula	$\left(u^{-\theta}+v^{-\theta}-1\right)^{-\frac{1}{\theta}}$	$\theta\in[-1,\infty)\backslash 0$	$\frac{\theta}{\theta+2}$	$[0,1)$
Gumbel Copula	$\exp\left(-\left((-\ln(u))^{\theta}+(-\ln(v))^{\theta}\right)^{\frac{1}{\theta}}\right)$	$\theta\in[1,\infty)$	$1-\frac{1}{\theta}$	$[0,1)$
Frank Copula	$-\frac{1}{\theta}\ln\left(1+\frac{(\exp(-\theta u)-1)(\exp(-\theta v)-1)}{\exp(\theta)-1}\right)$	$\theta\in\mathbb{R}\{0\}$	$1-\frac{4}{\theta}+\frac{4}{\theta}\int_0^{\theta}\frac{x/\theta}{\exp(x)-1}\mathrm{d}x$	$(-1,1)$
Joe Copula	$1-\left[(1-u)^{\theta}+(1-v)^{\theta}-(1-u)^{\theta}(1-v)^{\theta}\right]^{\frac{1}{\theta}}$	$\theta\in(1,\infty)$	$1+\frac{4}{\theta^2}\int_0^1 x\log(x)(1-x)^{2(1-\theta)/\theta}\mathrm{d}x$	$[0,1)$

3.3 Injury severity model component

The independent injury severity model can be formulated as follows:

$$y_q^* = \alpha x_q + \varepsilon_q, \tag{7}$$

where q represents each casualty involved in a motorcycle crash; y_q represents the injury severity of each casualty; x_q represents the explanatory variable for a single injury severity; α represents the vector formed for the coefficients of the explanatory variable; and ε_q represents a random error that follows the extreme value distribution. The dependent variable y_q is determined by the following factors:

$$y_q = j,\ if\ \ \tau_{j-1} < y_q^* < \tau_j,\ \forall j\in(0,1,2), \tag{8}$$

where τ_j is the threshold value associated with the injury severity of each casualty. Thus, given the value of x_q, the probability of injury severity can be calculated by the following expression.

$$Prob(y_q = j) = \Phi(\tau_j - \alpha x_q) - \Phi(\tau_{j-1} - \alpha x_q), \tag{9}$$

where Φ represents the reverse of the logit function.

3.4 Crash size model component

This section explains how the probability of crash size is calculated. The independent crash size model component can be formulated as follows:

$$u_q^* = \beta z_q + \delta_q, \tag{10}$$

where u_q is the probability of a crash size in a single crash; u_q^* represents the calculated log odds ratio estimated by the formula; z_q is the explanatory variable in a single casualty; β represents the parameter vector formed by the coefficients of the corresponding explanatory variables; and δ_q is a random error term subject to the extreme distribution:

$$u_q = k,\ if\ \ \varphi_{k-1} < u_q^* < \varphi_k,\ \forall k\in(1,2,3,4), \tag{11}$$

where φ_k represents the threshold value corresponding to a specific casualty level. The probability of a crash being a single casualty can be calculated by the following formula:

$$Prob(u_q = k) = \Psi(\varphi_k - \beta z_q) - \Psi(\varphi_{k-1} - \beta z_q), \tag{12}$$

where Ψ represents the reverse of the logit function.

3.5 Copula-based joint modeling of injury severity and motorcycle crash size

The joint distribution of injury severity y_{qj} and crash size u_{qk} for the q^{th} casualty can be calculated by the following formula:

$$\begin{aligned} &Prob(y_{qj} = j, u_{qk} = k) \\ &= Prob(\varepsilon_q \leqslant \tau_j - \alpha x_q, \delta_q \leqslant \varphi_k - \beta z_q) \\ &\quad - Prob(\varepsilon_q \leqslant \tau_{j-1} - \alpha x_q, \delta_q \leqslant \varphi_k - \beta z_q) \\ &\quad - Prob(\varepsilon_q \leqslant \tau_j - \alpha x_q, \delta_q \leqslant \varphi_{k-1} - \beta z_q) \\ &\quad + Prob(\varepsilon_q \leqslant \tau_{j-1} - \alpha x_q, \delta_q \leqslant \varphi_{k-1} - \beta z_q), \end{aligned} \tag{13}$$

where the injury severity of the casualty is j and the crash size is k.

The likelihood function for this analysis can be calculated as the sum of the likelihoods for each individual motorcycle crash casualty:

$$LL = \prod_{q=1}^{Q}\prod_{j=1}^{J}\prod_{k=1}^{K}\left(Prob(y_{qj} = j, u_{qk} = k)\right)^{\lambda_{qjk}}, \tag{14}$$

where $\lambda_{qjk} = 1$, if the q^{th} crash results in the j^{th} injury severity and the k^{th} crash size; otherwise, $\lambda_{qjk} = 0$.

4 Empirical setting

Annual traffic crash data for the year 2016 were thoroughly recorded in the Road Crash Victim and Information System (RCVIS) by the Cambodian National Road Safety Committee. For the purpose of this research, only motorcycle crashes from that year were selected and extracted. Subsequently, the data set underwent a rigorous process of data cleaning, which included the removal of observations with missing variables or omitted values, as well as the preprocessing of each variable. After assessing the multicollinearity of the variables, the final data set included 5,309 casualties, which were categorized into 14 groups of 45 variables (average VIF = 1.87, max VIF = 3.65), as presented in Table 3.

The 45 variables analyzed in this study are primarily classified into four distinct groups:

(1) Crash characteristics: Counterpart vehicle type and collision position.

(2) Human characteristics: Rider or pillion rider, age, sex, occupation, helmet wearing, and human error.

(3) Roadway characteristics: Road geometric features, road type, road surface, and urban or rural location.

(4) Temporal characteristics: National holiday, day of the week.

An overview of the final motorcycle crash data set, categorized by group and variable, is provided in Table 3. It is important to note that in this research, the "festival" variable pertains to motorcycle crashes occurring during events such as the Khmer New Year, Pchum Ben Day, Water Festival, Chinese New Year, and International New Year. In the Road Traffic and Injury Form recorded by the Cambodian police for each traffic crash, "right angle motorcycle collision" represents a crash where the front of the motorcycle collides with the side of another motorcycle, while "side swipe motorcycle collision" signifies motorcycle collisions with another vehicle while traveling side by side in the same direction.

As depicted in Table 3, collisions involving motorcycles constitute the majority of motorcycle crashes, accounting for approximately 42% of the total number of crashes. Concerning collision types, head-on and right-angle collisions exhibit a greater frequency of casualties than other collision types. An analysis of casualty characteristics revealed that the age group between 20 and 29 years accounted for the largest portion of the entire data set, followed by individuals younger than 20 years and those in the 30–39 years age group. However, when considering gender, it becomes evident that male motorcyclists are significantly more susceptible to crashes than their female counterparts are. This gender disparity can be attributed to the tendency of males to engage in more audacious and aggressive driving behaviors (Ulfarsson and Mannering, 2004; Yan et al., 2021). A substantial portion of the casualties were caused by farmers. Additionally, speeding is a predominant human error leading

Table 3 Overview of the final motorcycle crash data set

Category	Variable	Injury severity			Crash size			
		Minor	Severe	Fatal	1	2	3	⩾ 4
Crash characteristics								
Counterparts								
	Hit motorcycle	251	1144	844	154	675	772	638
	Hit pedestrian	475	808	264	545	621	290	91
	Hit passenger vehicle	321	304	101	305	313	78	30
Collision type								
	Head on collision	526	915	405	405	664	435	342
	Rear end collision	250	422	258	273	346	198	113
	Right angle collision	218	755	451	311	496	399	218
	Side swipe collision	65	206	173	88	152	120	84
	Fall alone	88	93	33	108	78	18	10
Human characteristics								
Road user								
	Rider	979	1770	813	1336	1213	671	342
	Pillion rider	311	794	642	60	653	589	445
Age								
	Below 20 years old	234	565	426	187	389	368	281
	20–29 years old	488	974	608	558	729	492	291
	30–39 years old	263	495	233	291	363	211	126
	40–49 years old	147	240	93	179	171	85	45
	Above 50 years old	158	290	95	181	214	104	44

(*Continued*)

Category	Variable	Injury severity			Crash size			
		Minor	Severe	Fatal	1	2	3	⩾ 4
Gender								
	Male	1091	2010	1111	1235	1495	931	551
	Female	198	553	343	158	371	329	236
Occupation								
	Child	24	34	48	4	22	38	42
	Student	128	408	278	158	264	236	156
	Worker	307	533	313	303	438	265	147
	Vendor	44	87	43	62	69	24	19
	Farmer	559	1043	559	560	766	533	302
Wear helmet								
	Wearing helmet	285	653	325	430	455	249	129
Human error								
	Speeding	438	734	416	479	596	330	183
	Not respect right of way	75	261	139	117	166	132	60
	Driving against flow of traffic	153	286	123	126	200	117	119
	Dangerous overtaking	170	297	192	152	248	162	97
	Alcohol abuse	192	289	188	188	210	168	103
	Change lane without due care	32	100	71	40	82	48	33
	Change direction without due care	73	230	145	98	142	132	76
Roadway characteristics								
Road geometry								
	Straight road	1034	1949	1124	1087	1452	921	647
	Curve road	105	192	89	112	136	102	36
	X-intersection	55	196	98	91	98	114	46
	T-intersection	38	104	65	43	74	63	27
Road type								
	National road	886	1490	790	879	1140	702	445
	Provincial road	145	417	281	186	270	237	150
	Major road	33	75	32	46	52	21	21
	Minor road	53	157	89	78	102	69	50
	Local road	131	331	192	146	222	186	100
Road surface								
	Paved	1092	2145	1205	1193	1562	1035	652
	Cemented	51	93	66	60	70	45	79
Area								
	Urban	425	1087	665	573	764	50	339
	Rural	756	1287	676	712	958	657	392
Temporal characteristics								
Festival								
	Festival	139	361	212	137	236	165	174
Day of week								
	Weekday	846	1677	950	1396	1244	807	320
	Weekend	444	887	505	441	622	453	467

to motorcycle crashes and plays a prominent role in a significant number of casualty cases. Concerning safety measures, the proportions of drivers wearing helmets are consistently low across all categories of minor injuries, serious injuries, and fatalities. This finding underscores the critical importance of helmet usage as a protective measure for both riders and pillion riders. Furthermore, it can be concluded that a considerable proportion of motorcycle crashes occur on straight roads, national roads, paved roads, peak hours, and weekends.

In Cambodia, the RCVIS records the injury severity of each casualty using a five-point ordinal scale: no apparent injury, superficial injury, minor severity, severe severity, and death. Due to the low frequency of no apparent injury and superficial injury (only 5.58% and 1.36%, respectively), we combined no apparent injury and superficial injury into the minor severity category, resulting in three injury levels in total, as shown in Eq. (15). Let represent the injury severity; then, we have:

$$j = \begin{cases} 1,\ minor\ injury\ , \\ 2,\ severe\ injury\ , \\ 3,\ fatal\ injury\ , \end{cases} \tag{15}$$

where j = 1 represents a minor injury, j = 2 represents a severe injury, and j = 3 represents a fatal injury.

The RCVIS database includes additional data on the number of casualties associated with each motorcycle crash, ranging from 1 to 9. Due to the notably low incidence of larger crash sizes, we categorized crash size into four classes: one casualty (26.29%), two casualties (35.15%), three casualties (23.73%), and four or more casualties (14.82%), as indicated in Eq. (16). Let k represent the crash size; then, we have:

$$k = \begin{cases} 1,\ \text{if}\ casualty\ number = 1\ , \\ 2,\ \text{if}\ casualty\ number = 2\ , \\ 3,\ \text{if}\ casualty\ number = 3\ , \\ 4,\ \text{if}\ casualty\ number \geqslant 4\ , \end{cases} \tag{16}$$

where $k = 1, 2, 3$ indicates that the casualty number in this motorcycle crash is equal to 1, 2, and 3. $k = 4$ indicates that the casualty number in this crash is four or more. Overall, a consistent trend was not readily apparent in the relationship between injury severity and motorcycle crash size across all categories. However, a modest decrease in both injury severity and motorcycle crash size was observed for crash sizes less than or greater than two. Notably, crashes involving two casualties constituted the majority of cases, with severe injuries being the most prevalent category across all crash sizes. The distribution of injury severity percentages by crash size is illustrated in Fig. 2. There was a noticeable increase in the proportion of fatalities, which steadily increased from 11.39% to 42.69% with increasing crash size, while the incidence of minor injuries decreased from 38.04% to 10.55%. Furthermore, the percentage of severe injuries marginally decreased by 2% as the crash size increased from one to more than three. These patterns suggest a potential link between injury severity and crash size. According to our motorcycle crash database, the Kendall's tau_b correlation between injury severity and crash size was 0.256, which is significant at the 0.01 level. These findings emphasize the necessity of employing a copula-based approach to adequately capture the dependence between injury severity and motorcycle crash size.

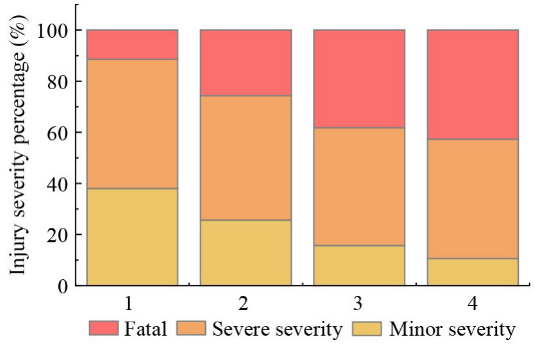

Fig. 2 Injury severity percentage distribution by crash size.

5 Results and discussion

In this research, seven models were constructed to estimate the relationships between the explanatory variables and dependent variables. Initially, an independent component model served as a benchmark for comparison. Subsequently, various copula structures are employed to compute and estimate the model parameters. It is anticipated that the correlation between injury severity and crash size obtained from different models will vary. The goodness-of-fit measures for each model are presented in Table 4, illustrating the variations among the different models. All the copula frameworks demonstrated improved performance, characterized by higher logarithmic likelihood values and lower Akaike information criterion (AIC) and Bayesian information criterion (BIC) values than did the independent models. This enhancement indicates that the utilization of copula-based bivariate models is more effective at capturing the causal relationships between explanatory variables and two dependent variables than at modeling each dependent variable independently. The superior performance of these copula models underscores their usefulness in complex analyses involving interdependencies among multiple result variables. Additionally, considering the relationship between these two dependent variables enhances the explanatory power of the model. The most suitable model is determined based on higher logarithmic likelihood (LL) values and

Table 4 Model performance measures

Model	LL	K	AIC	BIC
Gaussian Copula	−5353.14	42	10790.28	11066.52
Student's t Copula	−5367.58	42	10819.16	11095.40
Clayton Copula	−5498.27	42	11080.54	11356.78
Gumbel Copula	−5353.34	42	10790.68	11066.92
Frank Copula	**−5240.73**	42	10565.46	10841.70
Joe Copula	−5276.42	42	10636.84	10913.08
Independent model	−5384.54	41	10851.08	11120.74

lower BIC and AIC values. Based on the evaluation metrics presented in Table 4, the Frank copula framework emerges as the top-performing model among both the copula frameworks and the independent models. This finding aligns with the existing knowledge that the Frank copula tends to excel in scenarios characterized by symmetric upper and lower tail dependencies (Ayuso et al., 2016). The framework's efficacy in such situations underscores its appropriateness for modeling complex relationships, especially in cases where equal importance is given to both extremes of the data distribution. As a result, the subsequent analysis in this study will focus on investigating the effect of various contributory factors on injury severity and crash size. This examination will utilize insights obtained from both the independent component models and the Frank copula models. Concentrating on these models will provide a comprehensive understanding of how different factors influence motorcycle crash results, considering both the independent effects and the interdependencies modeled by the Frank copula.

Table 5 clearly illustrates that both the Frank copula model and the independent model exhibit similar trends in terms of the influence of each factor on the resulting variable. However, variations exist in the magnitudes of these influences. Furthermore, it is also evident that the total number of significant variable coefficients derived from the independent model is lower than that from the Frank copula-based model. The observed discrepancy between the models is likely due to the copula method's superior capability in capturing the complex interrelationship between the two result variables.

Table 6 presents the marginal effects of each variable on the two dependent variables as derived from both the Frank copula model and the independent model. It is important to note that only those influences that are statistically significant at the 95% significance level are included in this table. This focus on significant influences ensures that the variables presented are those with a demonstrably substantial effect on the dependent variables, underlining their relevance in the context of injury severity and crash size in motorcycle accidents.

The following section provides an in-depth discussion of the modeling results, offering a comprehensive analysis of the findings and their implications. We initiate the following results and discussion section by addressing the copula parameters, crash-related characteristics, human-related characteristics, road-related characteristics, and temporal characteristics, along with their modeling results and marginal effects on injury severity and crash size.

5.1 Copula parameters

Table 5 presents the parameter estimates from both the Frank copula model and the independent component model, focusing exclusively on variables that reached statistical significance at the 95% confidence level. The Kendall's tau value for the copula model is calculated to be 0.142, corresponding to a copula parameter theta of 1.304. This positive dependence parameter suggests a direct correlation between the severity of injuries (severe or fatal) and motorcycle crash size. In essence, as the probability of severe or fatal injuries increases, so does the number of casualties. This correlation between injury severity and the scale of the crash, in terms of the vehicles and occupants involved, aligns with findings from previous studies conducted by McLellan et al. (1996) and Broyles et al. (2003), further validating the observed trend in traffic accident dynamics.

The results derived from the copula parameter not only reinforce our initial hypothesis but also provide convincing evidence of the interdependency between the variables of injury severity and motorcycle crash size. This interdependency is a critical aspect to consider for a more accurate and comprehensive understanding of motorcycle crash results.

5.2 Crash-related characteristics

In our analysis of the effect of various crash characteristics on both injury severity and crash size, we focused on the effects of the counterpart type and collision type. Table 6 presents the marginal effects of these crash characteristics on injury severity, derived from both the Frank copula model and the independent model. Within both models, factors such as "hit motorcycle," "hit pedestrian," "hit passenger vehicle" as well as types of collisions like "head-on," "right-angle," "side-swipe," and incidents of "falling alone" were found to be statistically significant in relation to injury severity. This analysis sheds light on how specific crash types and collision participants influence the severity of motorcycle accidents. The marginal effects obtained from the copula model reveal intriguing dynamics in motorcycle crashes. Notably, when the crash counterpart is on another motorcycle, there is a slight increase in the risk of severe injury (by 0.0135) but a notable decrease in the risk of fatal injury (by 0.0764) compared to other types of collisions. This phenomenon can be attributed to the lack of protective structures on

Table 5 Model estimation results

	Independent model				Frank copula model			
	Injury severity		Crash size		Injury severity		Crash size	
	Parameter estimate	Z score	Parameter estimate	Z score	Parameter estimate	Z score	Parameter estimate	Z score
Crash characteristics								
Hit motorcycle (1 if the counterpart was a motorcycle, 0 otherwise)	−0.539	−5.663	2.534	32.438	−0.535	−5.389	1.771	37.227
Hit pedestrian (1 if the counterpart was a pedestrian, 0 otherwise)	0.655	6.653	0.261	3.475	0.243	6.560	0.332	2.053
Hit passenger vehicle (1 if the counterpart was a passenger vehicle, 0 otherwise)	1.153	10.342	–	–	1.051	8.552	–	–
Head on collision (1 if the collision type was head on, 0 otherwise)	0.474	5.962	0.312	3.185	0.395	3.643	0.455	3.626
Rear end collision (1 if the collision type was rear end collision, 0 otherwise)	–	–	0.341	3.266	–	–	0.289	5.679
Right angle collision (1 if the collision type was right angle collision, 0 otherwise)	−0.209	−2.577	0.338	3.362	−0.175	−1.910	0.259	6.128
Side swipe collision (1 if the collision type was side swipe collision, 0 otherwise)	−0.471	−4.247	0.435	3.500	−0.400	−3.491	0.273	2.742
Fall alone (1 if the motorcycle fell alone, 0 otherwise)	0.865	5.509	–	–	0.649	4.642	–	–
Casualty characteristics								
Rider (1 if the casualty was rider, 0 otherwise)	0.748	12.509	−1.876	−30.531	0.732	10.691	−1.238	−28.127
20−29 years old (1 if the casualty's age lay between 20 and 29 years old, 0 otherwise)	–	–	−0.365	−5.025	–	–	−0.309	−6.457
30−39 years old (1 if the casualty's age lay between 30 and 39 years old, 0 otherwise)	0.250	3.542	−0.504	−5.874	0.314	2.459	−0.649	−5.034
40−49 years old (1 if the casualty's age lay between 40 and 49 years old, 0 otherwise)	0.493	5.177	−0.855	−7.804	0.389	8.128	−0.729	−5.014
Above 50 years old (1 if the casualty's age was above 50 years old, 0 otherwise)	0.599	6.655	−0.850	−8.096	0.521	3.460	−1.102	−6.847
Child (1 if the casualty was a child, 0 otherwise)	–	–	0.758	3.735	–	–	0.490	2.036
Farmer (1 if the casualty was a farmer, 0 otherwise)	–	–	0.149	2.569	–	–	0.118	2.585
Helmet (1 if the casualty was wearing a helmet, 0 otherwise)	−0.367	−5.666	–	–	−0.284	−6.289	–	–
Speeding (1 if the casualty was speeding, 0 otherwise)	0.132	2.061	–	–	0.176	3.131	–	–
Against flow (1 if the rider drove against flow of traffic, 0 otherwise)	0.199	2.110	–	–	0.201	2.621	–	–
Roadway characteristics								
X junction (1 if the crash took place at a X junction road, 0 otherwise)	0.256	1.827	0.284	2.488	0.400	1.920	0.468	3.457
National road (1 if the crash took place at national road, 0 otherwise)	0.397	6.016	0.331	2.928	0.458	2.362	0.250	3.637
Provincial road (1 if the crash took place at provincial road, 0 otherwise)	–	–	0.310	2.463	–	–	0.329	6.383
Major road (1 if the crash took place at major road, 0 otherwise)	0.296	1.703	–	–	0.361	2.601	–	–
Minor road (1 if the crash took place at minor road, 0 otherwise)	–	–	0.343	2.223	–	–	0.362	2.460
Local road (1 if the crash took place at local road, 0 otherwise)	–	–	0.290	2.213	–	–	0.387	3.682
Urban (1 if the crash took place in urban, 0 otherwise)	−0.420	−7.381	–	–	−0.493	−8.364	–	–
Temporal characteristics								
Weekend (1 if the crash took place on Weekend, 0 otherwise)	–	–	0.182	3.285	–	–	0.159	3.143
Festival (1 if the crash took place during national festival, 0 otherwise)	–	–	0.288	3.671	–	–	0.438	5.997
Thresholds 1	−0.183	−1.210	−1.239	−8.431	−0.094	−8.464	−1.127	−2.457
Thresholds 2	2.279	14.704	1.012	6.902	2.457	6.457	1.238	3.238
Thresholds 3	–	–	2.806	8.556	–	–	3.128	5.124
Kendall's tau					0.142			

Table 6 Marginal effects for model estimates

	Independent model							Frank copula model						
	Crash severity			Injury number				Crash severity			Injury number			
	Minor	Severe	Fatal	1	2	3	⩾4	Minor	Severe	Fatal	1	2	3	⩾4
Crash characteristics														
Hit motorcycle (1 if the counterpart was a motorcycle, 0 otherwise)	0.0864	0.0105	−0.0969	−0.1577	0.0409	0.0647	0.0521	0.0629	0.0135	−0.0764	−0.1330	−0.0413	0.0728	0.1015
Hit pedestrian (1 if the counterpart was a pedestrian, 0 otherwise)	−0.1233	0.0266	0.0967	−0.0372	−0.0030	0.0167	0.0234	−0.1107	0.0144	0.0963	−0.0243	−0.0133	0.0157	0.0219
Hit passenger vehicle (1 if the counterpart was a passenger vehicle, 0 otherwise)	−0.2142	0.0394	0.1748	–	–	–	–	−0.1052	0.0091	0.0962	–	–	–	–
Head on collision (1 if the collision type was head on, 0 otherwise)	−0.0872	0.0158	0.0714	−0.0452	−0.0035	0.0213	0.0274	−0.0623	0.0083	0.0541	−0.0372	−0.0154	0.0167	0.0360
Rear end collision (1 if the collision type was rear end collision, 0 otherwise)	–	–	–	−0.0485	−0.0047	0.0224	0.0308	–	–	–	−0.0294	−0.0125	0.0107	0.0312
Right angle collision (1 if the collision type was right angle collision, 0 otherwise)	0.0356	−0.0010	−0.0346	−0.0487	−0.0040	0.0228	0.0299	0.1229	−0.0269	−0.0960	−0.0320	−0.0129	0.0110	0.0339
Side swipe collision (1 if the collision type was side swipe collision, 0 otherwise)	0.0809	−0.0035	−0.0774	−0.0618	−0.0066	0.0289	0.0396	0.1169	−0.0122	−0.1046	−0.0312	−0.0091	0.0127	0.0276
Fall alone (1 if the motorcycle fell alone, 0 otherwise)	−0.1527	0.0150	0.1377	–	–	–	–	−0.1460	0.0121	0.1339	–	–	–	–
Human characteristics														
Rider (1 if the casualty was rider, 0 otherwise)	−0.1514	0.0562	0.0951	0.1538	0.1777	−0.0482	−0.2833	−0.1134	0.0093	0.1041	0.1544	0.1774	−0.0472	−0.2845
20−29 years old (1 if the casualty's age lay between 20 and 29 years old, 0 otherwise)	–	–	–	0.0497	0.0088	−0.0224	−0.0360	–	–	–	0.0836	0.0166	−0.0351	−0.0651
30−39 years old (1 if the casualty's age lay between 30 and 39 years old, 0 otherwise)	−0.0441	0.0045	0.0396	0.0694	0.0110	−0.0317	−0.0488	−0.0623	0.0090	0.0533	0.0959	0.0157	−0.0315	−0.0802
40−49 years old (1 if the casualty's age lay between 40 and 49 years old, 0 otherwise)	−0.0870	0.0088	0.0782	0.1191	0.0176	−0.0549	−0.0818	−0.0504	0.0016	0.0487	0.0721	0.0022	−0.0310	−0.0433
Above 50 years old (1 if the casualty's age was above 50 years old, 0 otherwise)	−0.1063	0.0118	0.0945	0.1178	0.0183	−0.0544	−0.0816	−0.0777	0.0065	0.0713	0.1045	0.0148	−0.0537	−0.0656
Child (1 if the casualty was a child, 0 otherwise)	–	–	–	−0.1074	−0.0127	0.0503	0.0698	–	–	–	−0.0935	−0.0017	0.0171	0.0781
Farmer (1 if the casualty was a vendor, 0 otherwise)	–	–	–	−0.0213	−0.0021	0.0099	0.0134	–	–	–	−0.0176	−0.0102	−0.0119	0.0397

(*Continued*)

	Independent model							Frank copula model						
	Crash severity			Injury number				Crash severity			Injury number			
	Minor	Severe	Fatal	1	2	3	⩾4	Minor	Severe	Fatal	1	2	3	⩾4
Helmet (1 if the casualty was wearing a helmet, 0 otherwise)	0.0615	−0.0003	−0.0612	–	–	–	–	0.0372	−0.0079	−0.0293	–	–	–	–
Speeding (1 if the casualty was speeding, 0 otherwise)	−0.0232	−0.0023	0.0210	–	–	–	–	−0.0058	−0.0025	0.0083	–	–	–	–
Against flow (1 if the rider drove against flow of traffic, 0 otherwise)	−0.0348	0.0029	0.0319	–	–	–	–	−0.0355	0.0034	0.0321	–	–	–	–
Roadway characteristics														
X junction (1 if the crash took place at a X junction road, 0 otherwise)	−0.0447	0.0036	0.0410	−0.0403	−0.0045	0.0187	0.0261	−0.0445	0.0034	0.0411	−0.0455	−0.0083	0.0210	0.0328
National road (1 if the crash took place at national road, 0 otherwise)	−0.0746	0.0166	0.0580	−0.0481	−0.0023	0.0222	0.0281	−0.0745	0.0084	0.0661	−0.0412	−0.0070	0.0208	0.0275
Provincial road (1 if the crash took place at provincial road, 0 otherwise)	–	–	–	−0.0441	−0.0046	0.0207	0.0280	–	–	–	−0.0335	−0.0027	0.0251	0.0111
Major road (1 if the crash took place at major road, 0 otherwise)	−0.0516	0.0039	0.0477	–	–	–	–	−0.0679	0.0063	0.0616	–	–	–	–
Minor road (1 if the crash took place at minor road, 0 otherwise)	–	–	–	−0.0485	−0.0055	0.0225	0.0315	–	–	–	−0.0382	−0.0031	0.0179	0.0234
Local road (1 if the crash took place at local road, 0 otherwise)	–	–	–	−0.0411	−0.0044	0.0192	0.0264	–	–	–	−0.0260	−0.0022	0.0106	0.0176
Urban (1 if the crash took place in urban, 0 otherwise)	0.0685	0.0043	−0.0728	–	–	–	–	0.0386	0.0039	−0.0424	–	–	–	–
Temporal characteristics														
Weekend (1 if the crash took place on Weekend, 0 otherwise)	–	–	–	−0.0259	−0.0025	0.0121	0.0163	–	–	–	−0.0275	−0.0034	0.0109	0.0200
Festival (1 if the crash took place during national festival, 0 otherwise)	–	–	–	−0.0411	−0.0044	0.0193	0.0262	–	–	–	−0.0321	−0.0054	0.0148	0.0227

motorcycles, which leaves riders and pillion passengers more exposed in the event of a collision. When comparing motorcycle-to-motorcycle crashes with motorcycle-to-pedestrian and motorcycle-to-passenger vehicle collisions, it becomes evident that crashes involving two motorcycles tend to result in less fatal but more severe or minor injuries. This pattern aligns with the general expectation that motorcycle-to-motorcycle collisions predominantly lead to minor and severe crashes. The decreased crash effect when two motorcycles collide may explain this observation, a concept supported by existing research (De Lapparent, 2006; Waseem et al., 2019; Se et al., 2021). Regarding crash characteristics involving pedestrians and passenger vehicles, motorcycle crashes that "hit a pedestrian" or "hit a passenger vehicle" tend to result in a greater likelihood of severe and fatal injuries and a lower likelihood of minor injuries than motorcycle-to-motorcycle crashes. Furthermore, the marginal effects of crash characteristics involving pedestrians and passenger vehicles on injury severity are smaller in the copula model than in the independent ordered logit model component. This finding emphasizes the importance of accounting for the interrelationship between injury severity and crash size, as failing to do so may lead to an overestimation of the effects of casualties being riders on injury severity in motorcycle crash analysis.

For collision position types, factors such as “head-on collision,” “right-angle collision,” “side-swipe collision,” and “fall alone” significantly influence injury severity. In both models, “head-on collision” and “fall alone” collisions increase the risk of severe and fatal injuries while decreasing the risk of minor injuries. Conversely, “right-angle collision” and “side-swipe collision” increase the risk of minor injuries while decreasing the risk of severe and fatal injuries. Crashes involving “head-on collision” and “fall alone” tend to be more hazardous due to direct effects and a lack of external protection, respectively (Chang et al., 2021). The marginal effect of “fall alone” on fatal injury severity is twice that of “head-on collision,” highlighting the need for additional attention to mitigating accidents involving motorcycle users in such scenarios. Additionally, it is worth noting that the marginal effects of “head-on collision” and “fall alone” on fatal injury severity are smaller in the copula-based model than in the independent model, underscoring the potential for overestimation when ignoring the interrelationship between injury severity and crash size.

Table 6 also presents the marginal effects of various crash characteristics on crash size for both the independent and copula models. Factors such as “hit motorcycle,” “hit pedestrian,” “head-on collision,” “rear-end collision,” “right-angle collision,” and “side-swipe collision” significantly influence crash size in both models. These factors generally reduce the likelihood of the crash size being limited to one or two vehicles while increasing the probability of three or more motorcyclist-involved crashes. Specifically, crashes involving motorcycles or pedestrians and head-on collisions typically lead to larger crash sizes than other types of crashes. Although both models reveal similar trends in the effect of crash characteristics on crash size, there are differences in the magnitude of these effects. This variation suggests that neglecting the interrelationship between injury severity and crash size may lead to overestimating the impact of certain crash characteristics on smaller crash sizes (one or two vehicles) and underestimating their effect on larger crash sizes (three or more vehicles).

For instance, the marginal effects of “hit pedestrian,” “head-on collision,” “rear-end collision,” “right-angle collision,” and “side-swipe collision” on a crash size of two were underestimated in the independent model compared to the copula model. The differences in these marginal effects range from 0.0030 to 0.0133, 0.0035 to 0.0154, 0.0047 to 0.0125, 0.0040 to 0.0129, and 0.0066 to 0.0091.

5.3 Human-related characteristics

According to Table 6, human characteristics exert a notable influence on the severity of motorcycle crash injuries. In both models, the variable representing deaths who were riders demonstrated statistical significance. The marginal effects indicate that if the casualty is a rider, it reduces the likelihood of minor injuries in motorcycle crashes while increasing the risk of severe and fatal injuries. These findings suggest that “being the rider” involved in a crash may increase the chances of sustaining more severe injuries compared to “being a pillion rider” (Quddus et al., 2002). Notably, in the copula model, the marginal effects of casualties being riders on severe injury severity are smaller than the effects observed when using the independent ordered logit model component. However, these effects are greater in regard to fatal injury severity. Similarly, the variable representing “casualties aged more than 30 years” demonstrated statistical significance in both models. The marginal effects indicate that if a casualty falls within this age range, it increases the risk of severe and fatal injuries in motorcycle crashes. This disparity may be attributed to varying levels of experience among motorcyclists in different age groups. Riders aged 30 and older tend to possess more experience, potentially leading to overconfidence in their abilities when faced with uncontrolled circumstances. Furthermore, compared with the ordered logit model, the copula-based model reveals greater marginal effects of “casualties aged between 30 and 39 years” on severe and fatal injury severity. Conversely, the marginal effects of “casualties aged more than 40 years” on severe and fatal injury severity are smaller than those of the ordered logit model. The use of helmets is associated with a significant reduction in severe and fatal injury severity. These results emphasize that “wearing a helmet” can effectively mitigate the severity of injuries not only for riders but also for pillion riders (Se et al., 2022). Human errors such as “speeding” and riding against the flow of traffic also exert a substantial influence on injury severity. When a motorcycle speeds or rides against a flow, the likelihood of a fatal injury increases in both models. Although the marginal effects from both models follow the same trend, they exhibit different magnitudes of influence. This highlights that without considering the interrelationship between injury severity and crash size, the effects of “being a rider”, “age above 30 years”, “speeding”, and “riding against the flow” on fatality severity may be overestimated. Therefore, it is crucial to enhance safety measures for motorcyclists, especially those who are riders aged above 30 years and those engaging in speeding or riding against the flow, with the aim of promoting adherence to traffic regulations.

Additionally, human characteristics also emerge as statistically significant factors influencing crash size. “Riders”, in contrast to pillion riders, are more frequently involved in smaller-sized motorcycle crashes, which is a logical result considering that the presence of a pillion riders inherently increases the overall size of a motorcycle crash scenario. The analysis revealed that "children" and "farmers" have a greater propensity to be involved in crashes involving three or more casualties. Moreover, injured children are more likely to be involved in accidents involving more than two casualties. In contrast, individuals "aged more than 30 years" are more likely to be involved in crashes with fewer than three casualties than are their younger counterparts. Furthermore, distinct marginal effect scales for these casualty factors are observed across all injury severity levels in the two models. For example, there is a slight increase in the marginal effect of child and farmer casualties on crash sizes larger than four when transitioning from the independent model to the copula-based model. The probability of casualties occurring at ages > 20–39 among those involved in crashes involving four or more casualties is slightly greater in the copula model than in the independent model. Conversely, "casualties aged more than 40 years" have a lower probability of being involved in larger crash sizes in the copula model.

5.4 Road-related characteristics

In our research, we identified four roadway class factors, namely, X junction, national road, major road, and urban area, that significantly influence the severity of injuries sustained by motorcyclists. According to the marginal effects, casualties involved in motorcycle crashes occurring at "X junctions", "national roads", and "major roads" have a greater likelihood of sustaining severe and fatal injuries, while having a lower likelihood of minor injuries. However, it is noteworthy that the marginal effect of "urban areas" has a decreasing effect on motorcyclist fatal injury severity. The heightened risk of severe injuries at "X junctions" can be attributed to the more complex road environment in such locations, where riders are at greater risk of greater injury severity. Despite offering better riding conditions and safety features than other road types, "national roads" still present a considerable risk of fatal injuries. This increased risk is often due to the higher speed limits commonly found on national roads, as they are designed to serve traffic in community areas and urban regions (Xin et al., 2017; Champahom et al., 2020; Se et al., 2021). Consequently, motorcycle accidents on these roads tend to result in more severe injuries. Furthermore, our analysis reveals that the marginal effect of being in an "urban" area on the likelihood of sustaining a fatal injury is underestimated when the interrelationship between injury severity and crash size is not taken into account. This highlights the importance of considering such interdependencies for a more accurate assessment of risk factors in motorcycle crashes.

Regarding roadway characteristics and crash size, factors such as "X junction," "national road," "provincial road," "minor road," and "local road" also exhibited statistical significance. These factors significantly influence the number of casualties in motorcycle crashes. Specifically, at "X junctions", on "national, provincial, minor, and local roads", the marginal effects indicate that the probability of three or more individuals being injured increases, while the probability of smaller crash sizes decreases. The increased number of casualties in motorcycle crashes on these roads can be attributed to the greater likelihood of motorcycles carrying more pillion riders in such settings. When considering the interrelationship between injury severity and crash size, the marginal effects of "national road," "provincial road," "minor road," and "local road" on crash sizes involving more than three parties are observed to be smaller than those derived from the independent model. This implies that considering the interplay between injury severity and crash size is essential for avoiding overestimation or underestimation of the effect of these roadway characteristics on crash size.

5.5 Temporal characteristics

Temporal characteristics indeed play a pivotal role in motorcycle crashes. Specifically, the factors "weekend" and "festival" exert significant effects on crash size. When a motorcycle crash occurs during the weekend or a festival, the probability of three or more casualties being injured increases by 0.0109 and 0.0200 and 0.0148 and 0.0227, respectively. A noteworthy observation when comparing the independent model to the copula-based model is that the effect of the weekend on crash sizes involving four or more casualties tends to be underestimated, while the effect of festivals tends to be overestimated if we disregard the interrelationship between injury severity and crash size.

6 Policy recommendations

This section aims to provide recommendations for enhancing motorcycle safety, particularly in South-east Asian countries such as Cambodia. Policymakers are strongly advised to focus on factors that significantly elevate the risk of fatal injuries among motorcyclist casualties and those that increase the likelihood of larger crashes.

Motorcycle-to-pedestrian crashes have been shown to result in a significant increase in both fatal injuries and crash sizes when compared to motorcycle crashes involving other types of counterparts. Therefore, it is crucial to prioritize safety education initiatives targeted at both motorcyclists and pedestrians. The delineation of traffic flow between motorcycles and pedestrians in Cambodia may also prove effective in reducing the probability of motorcycle-pedestrian collisions.

Head-on collisions have been identified as factors that increase the risk of motorcyclists sustaining fatal injuries and being involved in larger crashes simultaneously. To address this issue, relevant regulations and law enforcement measures should be implemented to prevent vehicles and pedestrians from moving in opposite directions, thus reducing the number of fatal casualties and the number of crashes. Authorities should also consider implementing separate traffic directions using barrier medians on the road to enhance overall road safety.

In terms of human characteristics, it is crucial to recognize that being riders and having more casualties can increase injury severity while decreasing crash size when compared to pillion riders and younger casualties. This highlights the necessity for targeted awareness campaigns specifically tailored to riders and older motorcyclists, educating them about the heightened risks of fatal injuries.

Furthermore, the data showing a greater number of casualties occurring among individuals aged > 20 to 39 years suggest an urgent need for educational initiatives focused on this age group.

With regard to crash locations, incidents occurring at X junctions and on national roads tend to be more severe and more likely to involve larger crash sizes. This underscores the importance of targeted safety monitoring and the implementation of effective traffic signals at X junctions and on national roads to mitigate both the severity of injuries and crash sizes. Moreover, these findings call for more detailed investigations into crash-prone roadways to develop tailored safety measures.

Particular attention should be given to improving motorcycle safety during weekends and festivals, as the data indicate a significant increase in crash size during these periods. By addressing these specific times and locations with heightened safety measures and public awareness campaigns, the overall incidence and severity of motorcycle crashes can be effectively reduced.

7 Conclusions

This study conducted a comprehensive analysis, jointly modeling and examining the factors influencing both injury severity and crash size in motorcycle crashes. These factors were scrutinized across several categories, including crash characteristics, casualty characteristics, roadway characteristics, and temporal characteristics. This holistic approach facilitated a detailed understanding of the multifaceted nature of motorcycle crashes and the diverse elements that influence their severity and scale.

To achieve the study's objectives, an empirical analysis involved estimating models using six distinct copula frameworks and an independent model. The goodness-of-fit results indicated that the Frank copula was the most suitable for modeling motorcycle crash data in Cambodia. The interdependency parameter of the Frank copula revealed a positive association between injury severity and crash size, suggesting that factors contributing to increased injury severity, such as head-on collisions, also contribute to larger crash sizes and vice versa. These findings emphasize the complex interplay of various factors in motorcycle accidents, underlining the need for an integrated approach in safety analysis and policy formulation that considers these interdependencies.

The study identified specific scenarios, including "hit pedestrian" and "head-on collision," which led to significant increases in both injury severity and crash size. Right-angle and side-swipe collisions were associated with a substantial increase in injury severity. Additionally, being a rider and being aged older than 30 years were found to significantly elevate the severity of injuries sustained by casualties. In terms of road characteristics, "X junctions" and "national roads" were identified as factors that significantly increased both injury severity and crash size. Major roads were associated with a notable increase in severe and fatal injury severity, while provincial roads, minor roads, and local roads were more likely to be linked to crashes involving three or more casualties. These findings highlight specific vulnerabilities among certain groups of casualties, road types, and special days, calling for targeted interventions by authorities to improve motorcycle traffic management.

This research makes a significant contribution to the field of motorcycle safety, both methodologically and empirically. By accounting for the potential interdependency between injury severity and crash size, the study helps mitigate estimation biases and errors that could distort the results. The insights gained regarding the effects of different crash risk factors on injury severity and crash size are invaluable for traffic engineers and safety professionals, as they will enable the development of more effective countermeasures to enhance motorcycle safety. In essence, this study provides a nuanced understanding of motorcycle crash dynamics, offering practical implications for improving road safety measures and reducing the incidence and severity of motorcycle accidents.

However, certain limitations of this research must be acknowledged. First, the study relies on reported crash data, which may suffer from biases or underreporting, especially in cases of no or less severe injuries, a common issue in crash data sets (Yamamoto et al., 2008; Yasmin and Eluru, 2013). This could result in discrepancies between the observed and actual distributions of crash severity. Second, the copula-based framework assumes a fixed parameter, which, despite its superior fit compared to the independent model, may impact efficiency due to assumed constant dependencies between response variables. Third, endogeneity issues may arise during modeling (Mannering and Bhat, 2014), as riskier riders might exhibit more hazardous riding behaviors such as speeding, alcohol abuse, or not wearing helmets. Finally, the study evaluated only fixed parameter models, but the parameters may vary significantly among different riders and across different years. Future work should explore random parameter modeling methods considering this kind of heterogeneity. While these limitations are noteworthy, the study's findings still serve as a crucial reference for policymakers involved in motorcycle safety planning, particularly in developing countries.

Competing Interests The authors declare that they have no competing interests.

References

Abay K A (2015). Investigating the nature and impact of reporting bias in road crash data. Transportation Research Part A, Policy and Practice, 71: 31–45

Abdel-Aty M, Keller J (2005). Exploring the overall and specific crash severity levels at signalized intersections. Accident Analysis and Prevention, 37: 417–425

Abrari Vajari M, Aghabayk K, Sadeghian M, Shiwakoti N (2020). A multinomial logit model of motorcycle crash severity at Australian intersections. Journal of Safety Research, 73: 17–24

Ahmad N, Gayah V V, Donnell E T (2023). Copula-based bivariate count data regression models for simultaneous estimation of crash counts based on severity and number of vehicles. Accident Analysis and Prevention, 181: 106928

Anstey K J, Horswill M S, Wood J M, Hatherly C (2012). The role of cognitive and visual abilities as predictors in the multifactorial model of driving safety. Accident Analysis and Prevention, 45: 766–774

Ayuso M, Bermúdez L, Santolino M (2016). Copula-based regression modeling of bivariate severity of temporary disability and permanent motor injuries. Accident Analysis and Prevention, 89: 142–150

Banz B C, Fell J C, Vaca F E (2019). Complexities of young driver injury and fatal motor vehicle crashes. Yale Journal of Biology and Medicine, 92: 725–731

Blackman R A, Haworth N L (2013). Comparison of moped, scooter and motorcycle crash risk and crash severity. Accident; Analysis and Prevention, 57: 1–9

Bonander C, Andersson R, Nilson F (2015). The effect of stricter licensing on road traffic injury events involving 15 to 17-year-old moped drivers in Sweden: A time series intervention study. Accident Analysis and Prevention, 83: 154–161

Boulagouas W, García-Herrero S, Chaib R, Febres J D, Mariscal M Á, Djebabra M (2020). An investigation into unsafe behaviors and traffic accidents involving unlicensed drivers: A perspective for alignment measurement. International Journal of Environmental Research and Public Health, 17: 6743

Broyles R W, Narine L, Clarke S R, Baker D R (2003). Factors associated with the likelihood of injury resulting from collisions between four-wheel drive vehicles and passenger cars. Accident Analysis and Prevention, 35: 677–681

Champahom T, Jomnonkwao S, Watthanaklang D, Karoonsoontawong A, Chatpattananan V, Ratanavaraha V (2020). Applying hierarchical logistic models to compare urban and rural roadway modeling of severity of rear-end vehicular crashes. Accident Analysis and Prevention, 141: 105537

Chang F, Yasmin S, Huang H, Chan A H, Haque M M (2021). Injury severity analysis of motorcycle crashes: A comparison of latent class clustering and latent segmentation based models with unobserved heterogeneity. Analytic Methods in Accident Research, 32: 100188

Chiou Y C, Fu C, Ke C Y (2020). Modelling two-vehicle crash severity by generalized estimating equations. Accident Analysis and Prevention, 148: 105841

Clarke D D, Ward P, Bartle C, Truman W (2010). Older drivers' road traffic crashes in the UK. Accident Analysis and Prevention, 42: 1018–1024

Curry A E, Metzger K B, Williams A F, Tefft B C (2017). Comparison of older and younger novice driver crash rates: Informing the need for extended Graduated Driver Licensing restrictions. Accident Analysis and Prevention, 108: 66–73

Dapilah F, Guba B Y, Owusu-Sekyere E (2017). Motorcyclist characteristics and traffic behaviour in urban Northern Ghana: Implications for road traffic accidents. Journal of Transport & Health, 4: 237–245

De Lapparent M (2006). Empirical Bayesian analysis of accident severity for motorcyclists in large French urban areas. Accident Analysis and Prevention, 38(2): 260–268

De Lapparent M (2008). Willingness to use safety belt and levels of injury in car accidents. Accident Analysis and Prevention, 40: 1023–1032

Doan H T N, Hobday M B (2019). Characteristics and severity of motorcycle crashes resulting in hospitalization in Ho Chi Minh City, Vietnam. Traffic Injury Prevention, 20: 732–737

Elsemesmani H, Bachir R, El Sayed M J (2020). Association between trauma center level and outcomes of adult patients with motorcycle crash–related injuries in the United States. Journal of Emergency Medicine, 59: 499–507

Eluru N, Paleti R, Pendyala R M, Bhat C R (2010). Modeling injury severity of multiple occupants of vehicles: Copula-based multivariate approach. Transportation Research Record: Journal of the Transportation Research Board, (2165): 1–11

Erhardt T, Rice T, Troszak L, Zhu M (2016). Motorcycle helmet type and the risk of head injury and neck injury during motorcycle collisions in California. Accident Analysis and Prevention, 86: 23–28

Fountas G, Pantangi S S, Hulme K F, Anastasopoulos P Ch (2019). The effects of driver fatigue, gender, and distracted driving on perceived and observed aggressive driving behavior: A correlated grouped random parameters bivariate probit approach. Analytic Methods in Accident Research, 22: 100091

Ghomi, H., Hussein, M. (2021). An integrated clustering and copula-based model to assess the impact of intersection characteristics on violation-related collisions. Accident Analysis & Prevention, 159: 106283

Gkritza K (2009). Modeling motorcycle helmet use in Iowa: Evidence from six roadside observational surveys. Accident Analysis and Prevention, 41: 479–484

Goodwin A H, Wang Y C, Foss R D, Kirley B (2022). The role of inexperience in motorcycle crashes among novice and returning motorcycle riders. Journal of Safety Research, 82: 371–375

Haque Md M, Chin H C, Huang H (2009). Modeling fault among motorcyclists involved in crashes. Accident Analysis and Prevention, 41: 327–335

Hassan H M, Al-Faleh H (2013). Exploring the risk factors associated with the size and severity of roadway crashes in Riyadh. Journal of Safety Research, 47: 67–74

Hassanzadeh K, Salarilak S, Sadeghi-Bazargani H, Golestani M (2020). Motorcyclist risky riding behaviors and its predictors in an Iranian population. Journal of Injury & Violence Research, 12: 161–170

Hernández-Alava M, Pudney S (2016). bicop: A command for fitting bivariate ordinal regressions with residual dependence characterized by a copula function and normal mixture marginals. Stata Journal, 16(1): 159–184

Hu S R, Li C S, Lee C K (2010). Investigation of key factors for accident severity at railroad grade crossings by using a logit model. Safety Science, 48(2): 186–194

Huang H, Ding X, Yuan C, Liu X, Tang J (2023). Jointly analyzing freeway primary and secondary crash severity using a copula-based approach. Accident Analysis and Prevention, 180: 106911

Islam M (2021). The effect of motorcyclists' age on injury severities in single-motorcycle crashes with unobserved heterogeneity. Journal of Safety Research, 77: 125–138

Kashani A T, Jafari M, Bondarabadi M A, Dabirinejad S (2020). Factors affecting the accident size of motorcycle-involved crashes: A structural equation modeling approach. International Journal of Injury Control and Safety Promotion, 28: 16–21

Khan U R, Razzak J A, Jooma R, Wärnberg M G (2022). Association of age and severe injury in young motorcycle riders: A cross-sectional study from Karachi, Pakistan. Injury, 53: 3019–3024

Kole E, Koedijk K, Verbeek M (2007). Selecting copulas for risk management. Journal of Banking & Finance, 31(8): 2405–2423

Lao M, Lukusa T M (2023). Statistical approaches for assessing the effectiveness of safety devices use in preventing head injuries from motorcycle crashes. Case Studies on Transport Policy, 11: 100935

Lee C, Abdel-Aty M (2008). Presence of passengers: Does it increase or reduce driver's crash potential? Accident Analysis and Prevention, 40: 1703–1712

Lee J Y, Chung J H, Son B (2008). Analysis of traffic accident size for Korean highway using structural equation models. Accident Analysis and Prevention, 40: 1955–1963

Lin M R, Kraus J F (2009). A review of risk factors and patterns of motorcycle injuries. Accident Analysis and Prevention, 41: 710–722

Ma J, Kockelman K M, Damien P (2008). A multivariate poisson-lognormal regression model for prediction of crash counts by severity, using Bayesian methods. Accident Analysis and Prevention, 40: 964–975

Mannering F L, Bhat C R (2014). Analytic methods in accident research: Methodological frontier and future directions. Analytic Methods in Accident Research, 1: 1–22

Martey E N, Attoh-Okine N (2019). Analysis of train derailment severity using vine copula quantile regression modeling. Transportation Research Part C, Emerging Technologies, 105: 485–503

Martin E, Courtright T, Nkurunziza A, Lah O (2023). Motorcycle taxis in transition? Review of digitalization and electrification trends in selected East African capital cities. Case Studies on Transport Policy, 13: 101057

McLellan B A, Rizoli S B, Brenneman F D, Boulanger B R, Sharkey P W, Szalai J P (1996). Injury pattern and severity in lateral motor vehicle collisions: A Canadian experience. Journal of Trauma and Acute Care Surgery, 41(4): 708–713

Ministry of Public Works and Transport (MPWT), General Department of Land Transport (GDLT), Land Transport Department (LTD) (2022). Traffic Safety in Cambodia. The 13th Public and Private Joint Forum in Asian Region, 2022–11

Mohamad I, Jomnonkwao S, Ratanavaraha V (2022). Using a decision tree to compare rural versus highway motorcycle fatalities in Thailand. Case Studies on Transport Policy, 10: 2165–2174

Moudon A V, Lin L, Jiao J, Hurvitz P, Reeves P (2011). The risk of pedestrian injury and fatality in collisions with motor vehicles, a social ecological study of state routes and city streets in King County, Washington. Accident Analysis and Prevention, 43: 11–24

Nelsen R B (2006). An introduction to copulas. Springer

Ngoc A M, Minh C C, Nhu N T, Nishiuchi H, Huynh N (2023). Influence of the human development index, motorcycle growth and policy intervention on road traffic fatalities–A case study of Vietnam. International journal of transportation science and technology, 12(4): 925–936

Nguyen-Phuoc D Q, De Gruyter C, Nguyen H A, Nguyen T, Ngoc Su D (2020). Risky behaviours associated with traffic crashes among app-based motorcycle taxi drivers in Vietnam. Transportation Research Part F: Traffic Psychology and Behaviour, 70: 249–259

Nguyen-Phuoc D Q, Nguyen H A, De Gruyter C, Su D N, Nguyen V H (2019). Exploring the prevalence and factors associated with self-reported traffic crashes among app-based motorcycle taxis in Vietnam. Transport Policy, 81: 68–74

Pai C W, Lin H Y, Tsai S H, Chen P L (2018). Comparison of traffic-injury related hospitalisation between bicyclists and motorcyclists in Taiwan. PLoS One, 13(1): e0191221

Park E S, Lord D (2007). Multivariate poisson-lognormal models for jointly modeling crash frequency by severity. Transportation Research Record: Journal of the Transportation Research Board, 2019(1): 1–6

Park G J, Shin J, Kim S C, Na D S, Lee H J, Kim H, Lee S W, In Y N (2019). Protective effect of helmet use on cervical injury in motorcycle crashes: A case–control study. Injury, 50: 657–662

Peek-Asa C, McArthur D L, Kraus J F (1999). The prevalence of non-standard helmet use and head injuries among motorcycle riders. Accident; Analysis and Prevention, 31: 229–233

Pervez A, Lee J, Huang H (2021). Identifying factors contributing to the motorcycle crash severity in Pakistan. Journal of Advanced Transportation, 2021: 1–10

Phuksuksakul N, Yasmin S, Haque Md M (2023). A random parameters copula-based binary logit-generalized ordered logit model with parameterized dependency: Application to active traveler injury severity analysis. Analytic Methods in Accident Research, 38: 100266

Piyapromdee U, Adulyanukosol V, Lewsirirat S (2015). Increasing road traffic injuries in underage motorcyclists. Journal of Southeast

Asian Orthopaedics, 39: 3–7

Quddus M A, Noland R B, Chin H C (2002). An analysis of motorcycle injury and vehicle damage severity using ordered probit models. Journal of Safety Research, 33(4): 445–462

Rice T M, Troszak L, Erhardt T, Trent R B, Zhu M (2017). Novelty helmet use and motorcycle rider fatality. Accident Analysis and Prevention, 103: 123–128

Rifaat S M, Tay R, De Barros A (2012). Severity of motorcycle crashes in Calgary. Accident Analysis and Prevention, 49: 44–49

Roehler D R, Ear C, Parker E M, Sem P, Ballesteros M F (2015). Fatal motorcycle crashes: A growing public health problem in Cambodia. International Journal of Injury Control and Safety Promotion, 22: 165–171

Russo B J, Savolainen P T, Schneider W H IV, Anastasopoulos P C (2014). Comparison of factors affecting injury severity in angle collisions by fault status using a random parameters bivariate ordered probit model. Analytic Methods in Accident Research, 2: 21–29

Savolainen P, Mannering F (2007). Probabilistic models of motorcyclists' injury severities in single- and multi-vehicle crashes. Accident Analysis and Prevention, 39: 955–963

Se C, Champahom T, Jomnonkwao S, Chaimuang P, Ratanavaraha V (2021). Empirical comparison of the effects of urban and rural crashes on motorcyclist injury severities: A correlated random parameters ordered probit approach with heterogeneity in means. Accident Analysis and Prevention, 161: 106352

Se C, Champahom T, Jomnonkwao S, Kronprasert N, Ratanavaraha V (2022). The impact of weekday, weekend, and holiday crashes on motorcyclist injury severities: Accounting for temporal influence with unobserved effect and insights from out-of-sample prediction. Analytic Methods in Accident Research, 36: 100240

Shaheed M S B, Gkritza K, Zhang W, Hans Z (2013). A mixed logit analysis of two-vehicle crash severities involving a motorcycle. Accident Analysis and Prevention, 61: 119–128

Sirajudeen A O, Law T H, Wong S V, Ng C P (2022). The motorcycle deaths to passenger car deaths ratio and economic performance: A panel data analysis. Accident Analysis and Prevention, 165: 106533

Stutts J, Foss R, Svoboda C (2004). Characteristics of older motorcyclist crashes. Annual Proceedings—Association for the Advancement of Automotive Medicine, 48: 197–211

Sze N N, Wong S C (2007). Diagnostic analysis of the logistic model for pedestrian injury severity in traffic crashes. Accident Analysis and Prevention, 39: 1267–1278

Talving P, Teixeira P G R, Barmparas G, DuBose J, Preston C, Inaba K, Demetriades D (2010). Motorcycle-related injuries: Effect of age on type and severity of injuries and mortality. Journal of Trauma and Acute Care Surgery, 68: 441–446

Tamakloe R, Hong J, Park D (2020). A copula-based approach for jointly modeling crash severity and number of vehicles involved in express bus crashes on expressways considering temporal stability of data. Accident Analysis and Prevention, 146: 105736

Truong L T, Nguyen H T T, Gruyter C D (2019). Mobile phone use while riding a motorcycle and crashes among university students. Traffic Injury Prevention, 20: 204–210

Truong L T, Nguyen H T T, Tay R (2020). A random parameter logistic model of fatigue-related motorcycle crash involvement in Hanoi, Vietnam. Accident Analysis and Prevention, 144: 105627

Ulfarsson G F, Mannering F L (2004). Differences in male and female injury severities in sport-utility vehicle, minivan, pickup and passenger car accidents. Accident Analysis and Prevention, 36(2): 135–147

United Nations Development Programme (UNDP) (2020). Road Traffic Accidents in Cambodia

Vissoci J R N, Krebs E, Meier B, Vieira I F, de Andrade L, Byiringiro F, Rulisa S, Staton C (2020). Road traffic crash experience among commercial motorcyclists in Kigali, Rwanda. International Journal of Injury Control and Safety Promotion, 27: 181–187

Wali B, Khattak A J, Ahmad N (2019). Examining correlations between motorcyclist's conspicuity, apparel related factors and injury severity score: Evidence from new motorcycle crash causation study. Accident Analysis and Prevention, 131: 45–62

Wali B, Khattak A J, Xu J (2018). Contributory fault and level of personal injury to drivers involved in head-on collisions: Application of copula-based bivariate ordinal models. Accident; Analysis and Prevention, 110: 101–114

Walshe E A, Ward McIntosh C, Romer D, Winston F K (2017). Executive function capacities, negative driving behavior and crashes in young drivers. International Journal of Environmental Research and Public Health, 14: 1314

Wang K, Bhowmik T, Yasmin S, Zhao S, Eluru N, Jackson E (2019). Multivariate copula temporal modeling of intersection crash consequence metrics: A joint estimation of injury severity, crash type, vehicle damage and driver error. Accident Analysis and Prevention, 125: 188–197

Waseem M, Ahmed A, Saeed T U (2019). Factors affecting motorcyclists' injury severities: An empirical assessment using random parameters logit model with heterogeneity in means and variances. Accident Analysis and Prevention, 123: 12–19

World Health Organization (2017). Accelerating action for implementation of the decade of action for road safety. Technical Report

World Health Organization (2018). Global status report on road safety

Wu C Y, Loo B P (2016). Motorcycle safety among motorcycle taxi drivers and nonoccupational motorcyclists in developing countries: A case study of Maoming, South China. Traffic Injury Prevention, 17(2): 170–175

Xiao D, Yuan Q, Kang S, Xu X (2021). Insights on crash injury severity control from novice and experienced drivers: A bivariate random-effects probit analysis. Discrete Dynamics in Nature and Society, 2021: 1–13

Xin C, Guo R, Wang Z, Lu Q, Lin P S (2017). The effects of neighborhood characteristics and the built environment on pedestrian injury severity: A random parameters generalized ordered probability model with heterogeneity in means and variances. Analytic Methods in Accident Research, 16: 117–132

Yamamoto T, Hashiji J, Shankar V N (2008). Underreporting in traffic accident data, bias in parameters and the structure of injury severity models. Accident Analysis and Prevention, 40(4): 1320–1329

Yamamoto T, Shankar V N (2004). Bivariate ordered-response probit model of driver's and passenger's injury severities in collisions with fixed objects. Accident Analysis and Prevention, 36: 869–876

Yan X, He J, Zhang C, Liu Z, Wang C, Qiao B (2021). Temporal analysis of crash severities involving male and female drivers: A random parameters approach with heterogeneity in means and variances. Analytic Methods in Accident Research, 30: 100161

Yasmin S, Eluru N (2013). Evaluating alternate discrete outcome frameworks for modeling crash injury severity. Accident Analysis and Prevention, 59: 506–521

Yasmin S, Eluru N, Pinjari A R, Tay R (2014). Examining driver injury severity in two vehicle crashes – A copula based approach. Accident Analysis and Prevention, 66: 120–135

Yuan Y, Yang M, Gan Z, Wu J, Xu C, Lei D (2019). Analysis of the risk factors affecting the size of fatal accidents involving trucks based on the structural equation model. Transportation Research Record: Journal of the Transportation Research Board, (2673): 112–124

Zambon F, Hasselberg M (2006). Factors affecting the severity of injuries among young motorcyclists—A Swedish nationwide cohort study. Traffic Injury Prevention, 7: 143–149

Zubaidi H, Tamakloe R, Al-Bdairi N S S, Alnedawi A, Obaid I (2022). Exploring senior motorcyclist injury severity crashes: Random parameter model with heterogeneity in mean and variance. IATSS Research, 47(1): 1–13