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Research article

Analysis of road traffic accidents and casualties associated with electric bikes and bicycles in Guangzhou, China: A retrospective descriptive analysis

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ABSTRACT

Introduction: Electric bicycles (e-bikes) and bicycles in large Chinese cities have recently witnessed substantial growth in ridership. According to related accident trends, this study analyzed characteristics and spatial distribution in the period when e-bike-related accidents rapidly increased to propose priority measures to reduce accident casualties.
Methods: For e-bike- and bicycle-related accident data from the Guangzhou Public Security Traffic Management Integrated System, linear regression was used to examine the trends in the number of accidents and age-adjusted road traffic casualties from 2011 to 2021. Then, for the period when e-bike-related accidents rapidly increased, descriptive statistics were computed regarding rider characteristics, illegal behaviors, road types, collision objects and their accident liability. One-way analysis of variance (ANOVA) followed by Bonferroni's multiple comparison test. $P < 0.05$ was considered statistically significant. Finally, the density distribution of accidents was presented, and Moran's I (MI) was used for assessing spatial autocorrelation. Hotspots were identified based on an optimized hotspot analysis tool.
Results: Between 2011 and 2021, the number of accidents and casualty rate (per 100,000 population) increased for e-bikes but decreased for bicycles. After 2018, e-bike-related accidents increased rapidly, and bicycle-related accidents plateaued. Accident hotspots were concentrated in central city areas and suburban areas close to the former. Three-quarters of accidents occurred in motorized vehicle lanes. Most occurred on roads without physically segregated nonmotorized vehicle lanes. More than three-fifths of the accidents involved motor vehicles with at least four wheels. The prevalence (per 100 people) of casualties among e-bike rider victims and cyclist victims accounted for 92.0 % and 96.5 %, respectively. A total of 71.6 % of e-bike-related accidents involved migrant workers. Riding in motorized vehicle lanes was the most common illegal behavior.
Conclusions: Although e-bike-related and bicycle-related accidents presented similar characteristics, the sharp increase in e-bike-related accidents requires attention. To improve e-bike safety,

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governments should develop appropriate countermeasures to prevent riders from riding on motorways, such as improving road infrastructure, adjusting the driver's license system and addressing priority control areas.

1. Introduction

Since the 21st century, electric bicycles (e-bikes) have become one of the main modes of transport in China. According to industry estimates, in 2010, there were approximately 100 million e-bikes on Chinese roads. In 2022, this number was already 350 million, which means that, statistically, one in four Chinese individuals owns some form of e-bike [1].

In China, according to the Technical Safety Specifications for Electric Bicycles (GB17761-2018), an electric bicycle is defined as a two-wheeled bicycle that uses an on-board battery as an auxiliary energy source and has a designed speed of no more than 25 km/h, a maximum motor power of 400 W, a maximum voltage of 48 V, a vehicle mass within 55 kg, and a pedaling function, which can realize electric assistance and/or electric drive functions. E-bike riders and bicycle riders need not be in possession of a moped driving license. Although they are generally allowed to drive only on nonmotorized lanes, due to the inconsistent level of infrastructure in different regions and sections, they often mix in lanes with motor vehicles or pedestrians.

Both e-bike riders and cyclists are vulnerable road users since they benefit from little or no external protective devices that absorb energy during a collision [2]. E-bikes are more likely to be involved in a crash than bicycles are, which may be related to the greater mass and faster speed of e-bikes compared to classic bicycles [3]. In response, concerns have been raised about e-bike-related accidents.

The Global Status Report on Road Safety 2023 reported that 92 % of deaths occur in low- and middle-income countries [4]. An analysis by Wang, Lijun et al. of road traffic mortality in China revealed that vulnerable road users (i.e., pedestrians, motorcyclists, and cyclists) accounted for more than 70 % of road traffic deaths in China, with pedestrians representing 42 % of the total [5]. According to China's National Bureau of Statistics, between 2007 and 2022, the overall road traffic casualty rate decreased by 34.5 %, while the number of e-bike accidents increased by 3.5 times. In 2022, the overall number of road traffic casualties was 3.2 million, of which the proportion of e-bike-related accidents reached 13.8 %, an increase of 5.9 times compared with the proportion in 2007 [6]. In contrast, the change in bicycle-related accidents shows the opposite trend. From 2004 to 2019, the Chinese bicycle-related mortality rate decreased from 2.04 to 1.59 per 100,000 population according to Global Burden of Disease (GBD) data (Fig. A1). A similar phenomenon has occurred in other countries. DiMaggio et al. [7] reported that between 2000 and 2017, the proportion of bicycle-related accident casualties in the U.S. decreased, but e-bike-related accident casualties increased dramatically.

Aiming to provide accident prevention measures in various aspects, recent studies have investigated accidents involving e-bikes in comparison to those involving bicycles, analyzing their differences and commonalities [8–14].

According to police data from Zhangjiakou, China, the degree of accident injury associated with e-bikes is slightly lower than that associated with bicycles [8]. The studies by Frank Westerhuis and Maya Siman-Tov et al., however, have shown that e-bike riders are at greater risk for death and injuries, including head injuries and lower extremity injuries [9,10]. This may be because different data sources present different distributions of injury levels and accident incidence. Regarding sociodemographic data, the overall risk of bicycle- and e-bike-related injuries was greater among men than among women and among senior riders than among individuals in other age groups [8,9].

Riding behavior is an important factor that affects the degree of injury suffered by riders of two-wheeled vehicles and the occurrence of related accidents. The results of observational studies of e-bikes and bicycle users in Beijing and Suzhou, China [15,16], suggest that running red lights, driving in motor lanes, violating traffic signals, and using mobile phones are the most common illegal behaviors. Among these violations, such as running a red light and carrying passengers, are closely associated with the incidence of bicycle- and e-bike-related injuries [17]. However, Carole Rodon et al. found that the incidence of risky behaviors varied and was greater among e-cyclists than among cyclists, which may be related to psychological factors [11]. The Cycling Behavior Questionnaire (CBQ) has been confirmed effective for assessing the dangerous and positive cycling behaviors of cyclists in different countries; this tool can help evaluate and improve cycling safety through the human factors approach [18].

In terms of the characteristics of collisions, the most common type of accident is side crashes, followed by frontal crashes, with the former type typically being more severe [12]. Accidents associated with e-bikes or bicycles commonly occur when cyclists are turning off a road, turning onto a road, or crossing a road [13,19].

Previous studies have analyzed the factors influencing casualties and road traffic safety in e-bike accidents and bicycle accidents from various aspects. However, among the studies on e-bike-related accidents, a majority focus only on short periods (a few years at best) [20], and the analysis of proposed measures and related factors is based on sample surveys [17,21] or field observations [15]. As a consequence, these findings may not be generalizable to other regions.

According to the change trend of related accidents, this study analyzed salient characteristics and spatial distribution based on data from the period when the situation of e-bike-related accidents deteriorated rapidly to propose corresponding measures and areas for priority attention to effectively reduce accident casualties. Additionally, this paper provides reference measures for the governance of large cities in developing countries, which in turn will promote the development of Global Electric Mobility Program [22].

2. Methods

2.1. Study design

This was a retrospective study with a focus on descriptive statistics. First, a linear regression method was used to analyze the longitudinal trend of e-bike-related and bicycle-related accidents from 2011 to 2021. Then, based on the period when e-bike-related accidents rapidly increased (between 2018 and 2021), descriptive statistics were used to analyze and compare rider characteristics, illegal behaviors, road types and collision objects (and their liability for accidents). Finally, the density distribution of accidents was presented, and Moran's I (MI) was used for assessing spatial autocorrelation. Hot spots and cold spots were identified based on an optimized hotspot analysis tool.

This project was reviewed and approved by the Biomedical Ethics Committee of Southern Medical University, Guangzhou, China, in line with the requirements of the Declaration of Helsink.

2.2. Data sources

After handling an accident, the front-line traffic police of each team uploads the data to the Guangzhou Public Security Traffic Management Integrated System in accordance with the requirements of the accident handling navigation, and the data are uniformly summarized and stored by the Guangzhou Municipal Public Security Bureau. According to the accident handling process of the Road Traffic Safety Law of China, accident appraisals are officially divided into minor accidents (for which the parties are allowed to negotiate compensation without police intervention), general accidents and major accidents. Minor accidents include accidents involving only property damage or whose participants suffer injuries requiring no treatment. Due to known issues with underreporting, minor incidents were excluded from this analysis [23]. In this study, data involving e-bike-related and bicycle-related accidents over the years 2011–2021 were extracted from this platform, of which 7 e-bike-related and 4 bicycle-related minor accidents were excluded. Accidents were included in the analysis if at least one e-bike rider or one cyclist was involved and one of the crash partners was injured. The data collected included only general accidents and major accidents, which involved 4037 e-bike rider victims, of whom 3471 were injured or died, and 3664 cyclist victims, of whom 3407 were injured or died. Population data were obtained from the websites of the National Bureau of Statistics and the Guangzhou Municipal Bureau of Statistics.

2.3. Variables

Basic accident information (time, location, road type, accident outcome, collision object), personnel information, and illegal behavior information were collected and organized.

Since the Human Injury Degree Criteria were developed in China to assess the severity of traffic accident injuries, road traffic accident outcomes have been categorized as no injury, minor injury, serious injury or death. This study divided the rider victims into uninjured and casualty victims (including those with minor injuries, serious injuries, and deaths) based on the outcome of the accidents. The variables in this study included the number of accidents, population-based road traffic casualty rates (the number of casualties per 100,000 permanent residents) and the percentage of casualty cyclists or e-bike riders among rider victims involved in crashes registered by the police.

The areas were divided into central city areas and suburban areas according to the location in which the accident occurred. The different population types were divided into migrant workers and local residents based on their registration data, and overseas Chinese, Hong Kong, Macao and Taiwan residents and foreigners were excluded. Under China's economic and social reforms, migrant workers have become the product of internal migration driven by the prospect of employment and higher wages. Migrant workers were defined as labor migrants who moved from rural areas to urban centers and were not registered in urban areas, a special group under the Chinese registration system [24,25]. Specifically, these are workers who were still registered in rural areas and had been engaged in non-agricultural industries or had been working outside their registered places of residence for 6 months or more during the year. Based on the section of road where the accident occurred, the road types were divided into motorized vehicle lanes, roads in which motorized vehicles and bicycles, nonmotorized vehicle lanes, pedestrian crossings, pedestrian sidewalks, and others. We also analyzed whether there was a physically segregated nonmotorized vehicle lane at the site where the accident occurred.

Based on the illegal acts stipulated in the Road Traffic Safety Law of China, both e-bikes and bicycles were considered nonmotorized vehicles with the same driving rules and categories of violations. The allocation of liability determined by the traffic police was divided into three main situations: cases in which one party bore full or primary responsibility and the other party secondary or no responsibility; cases in which both parties bore equal responsibility; and cases in which the insufficient evidence of the accident made it impossible to determine responsibility for the accident. Based on the cause of the accident, the accidents were divided into collision accidents involving different road users and accidents due to other factors (such as the rider falling due to a loss of balance). Finally, the counterparts (collision objects) were divided into motor vehicles with at least four wheels, motorcycles, nonmotor vehicles (including e-bikes and bicycles), pedestrians, other vehicles, and noncollision objects.

2.4. Data analysis

2.4.1. Linear regression analysis

We calculated age-adjusted road traffic casualty rates of e-bike-related and bicycle-related accidents from 2011 to 2021 using the census population in 2020 as a reference. Due to the obvious differences in the trends of e-bike-related and bicycle-related accidents beginning around 2018, when the number and casualty rate of e-bike-related accidents exceeded those of bicycle-related accidents, the numbers of accidents and age-adjusted casualty rates were described by linear regression equations for the periods 2011–2017 and 2018–2021, respectively. We used the slope of the regression line and 95 % confidence intervals (CIs) to quantify the trends in changes in each period.

2.4.2. Descriptive analysis

In addition, to propose targeted measures for the current situation in Guangzhou, this study compared and analyzed 2442 e-bike-related and 1143 bicycle-related accidents from 2018 to 2021.

Studies have shown that the type of road at the site of the accident has an impact on the incidence of e-bike-related and bicycle-related accidents [26]. We used three types of charts to depict road types at the location of the accident and considered the presence or absence of a physically segregated nonmotorized lane, the road types where the accident occurred with physical separation, the liability for the counterparts (collision objects) in different types of collisions, and the number of rider violations.

We considered the percentage of casualty cyclists or e-bike riders (per 100 people) among the rider victims. Subgroup analyses were performed by area, population type, gender (male and female), age (<30 years, 30–60 years and >60 years), accident road type and counterpart (collision object). One-way analysis of variance (ANOVA) was used, followed by Bonferroni's multiple comparison test. $P < 0.05$ was considered to indicate statistical significance in determining whether there was a statistically significant difference in the percentage of casualty cyclists or e-bike riders (per 100 people) among the accident groups.

2.4.3. Accident density and spatial autocorrelation analysis

We mapped the neighborhood-level density of accidents based on the distribution of communities in the central area and suburban area of Guangzhou, which was calculated as the number of accidents/area (km2) of a neighborhood [27].

Then, spatial autocorrelation analysis of accident density was carried out, the global Moran index was used to determine the correlation between spatial elements and adjacent spatial elements in the whole study area, and the spatial distribution characteristics of regional variable values were displayed, including aggregate distribution, discrete distribution or random distribution [28]. The null hypothesis states that the spatial distribution of the studied phenomenon is random, while the alternative hypothesis states that the studied phenomenon is not random (there is spatial autocorrelation). Finally, optimized hotspot analysis was performed with ArcGIS 10.8 to identify statistically significant spatial clusters of high values (hot spots) and low values (cold spots) of accident density. The advantage of this model is that it automatically aggregates incident data, identifies an appropriate scale of analysis, and corrects for both multiple testing and spatial dependence.

3. Results

3.1. Trends in overall casualty rates

From 2011 to 2021, the e-bike-related casualty rate increased from 1.31 per 100,000 population to 3.76 per 100,000 population, while the bicycle-related casualty rate decreased from 3.39 to 1.85. The casualty rate of e-bike-related accidents increased significantly from 2018 to 2021, with an average annual increase of 0.703 casualties per 100,000 population, while the change in bicycle-related accidents plateaued ($\beta = 0.077$, 95 % CI $= -0.21$ to 0.365) (Fig. 1B). The average annual increase in e-bike-related accidents was 153.9, approximately nine times that of bicycle-related accidents (with an average increase of 17 per year) (Fig. 1A). From 2018 to 2021, 1749 and 751 of the e-bike-related and bicycle-related accident victims were migrant workers, accounting for 71.6 % and 65.7 %, respectively (Table 1).

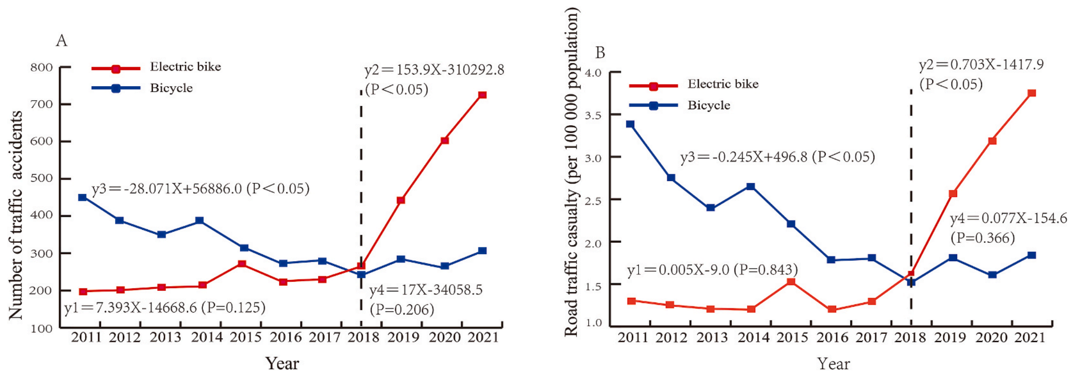


Fig. 1. General distribution trend of e-bike-related and bicycle-related accidents in Guangzhou, 2011 to 2021. A: Number of traffic accidents; B: Age-adjusted road traffic casualty (per 100,000 population).

Table 1
Number of rider victims and the percentage of casualty cyclists or e-bike riders (per 100 people) among rider victims involved in a crash, 2018–2021.

	Electric bicycle			Bicycle		
	No. of Victims (n = 2442)	Percentage	χ^2 (P-value)	No. of Victims (n = 1143)	Percentage	χ^2 (P-value)
Population type						
Migrant workers	1749(71.6 %)	85.1 %	0.503 (=0.478)	751(65.7 %)	93.3 %	3.886 (=0.049)
Local residents	693(28.4 %)	84.0 %		392(34.3 %)	90.1 %	
Gender						
Male	1522(62.3 %)	82.1 %	22.500 (< 0.001)	675(59.1 %)	89.2 %	21.055 (< 0.001)
Female	920(37.7 %)	89.2 %		468(40.9 %)	96.6 %	
Age						
< 30	667(27.3 %)	78.1%^{a}	46.385 (< 0.001)	199(17.4 %)	79.4%^{a}	72.268 (< 0.001)
30~60	1480(60.6 %)	85.9%^{b}		555(48.6 %)	91.9%^{b}	
> 60	295(12.1 %)	94.6%^{c}		389(34.0 %)	99.2%^{c}	
Area						
Suburban area	1726(70.7 %)	87.6 %	35.663 (< 0.001)	850(74.4 %)	93.6 %	9.491 (=0.002)
Central area	716(29.3 %)	78.1 %		293(25.6 %)	88.1 %	
Road type						
Motorized vehicle lane	1835(75.1 %)	86.7%^{a}	31.033 (< 0.001)	868(75.9 %)	94.2%^{a}	41.238 (< 0.001)
A road in which motorized vehicles and bicycles	383(15.7 %)	81.2%^{a,b}		175(15.3 %)	88.0%^{b}	
Nonmotorized vehicle lane	127(5.2 %)	76.4%^{b}		51(4.5 %)	84.3%^{a,b,c}	
Pedestrian crossing	60(2.5 %)	76.7%^{a,b}		30(2.6 %)	90.0%^{a,b,c}	
Pedestrian sidewalks	18(0.7 %)	55.6%^{b}		6(0.5 %)	83.3%^{a,b,c}	
Others	19(0.8 %)	84.2%^{a,b}		13(1.1 %)	53.8%^{c}	
Counterpart						
Motor vehicles having at least four wheels	1507(61.7 %)	95.5%^{a,e}	700.676 (< 0.001)	795(69.6 %)	99.1%^{a}	421.688 (< 0.001)
Motorcycle	372(15.2 %)	82.8%^{b}		184(16.1 %)	88.6%^{b}	
Nonmotor vehicle	359(14.7 %)	59.1%^{c}		106(9.3 %)	68.9%^{c}	
Pedestrian	108(4.4 %)	18.5%^{d}		28(2.4 %)	7.1%^{d}	
Others	24(1.0 %)	83.3%^{b,c,e}		12(1.0 %)	83.3%^{b,c}	
Noncollision object	72(2.9 %)	100.0%^{a}		18(1.6 %)	100.0%^{a,b,c}	
Total	2442(100 %)	84.8 %		1143(100 %)	92.2 %	

Note:1. “Noncollision object” means the accident was sustained in an event that did not involve a collision object because of the rider’s loss of balance or other causes.
2According to the Bonferroni adjustment method, with a corrected P value of 0.05, the possibility of a significant difference between the two groups was rejected if the same letters were present in the superscripts; otherwise, there was a significant difference.

3.2. Road types, collision objects and violations

More than three-quarters of both e-bike-related and bicycle-related accidents occurred in motorized vehicle lanes, reaching 75.1 % and 75.9 % (Fig. 2b–. A, Fig. 2B), respectively, and the percentage (per 100 people) of casualties among rider victims in motorized vehicle lanes was greater than that among rider victims on other road types, reaching 86.7 % and 94.2 %, respectively (Table 1). Most e-bike-related and bicycle-related accidents occurred on roads without physically segregated nonmotorized vehicle lanes, reaching 95.0 % and 94.1 %, respectively. In addition, of the accidents that took place on roads with physically segregated nonmotorized vehicle lanes, 80.4 % of the e-bike-related accidents and 89.5 % of the bicycle-related accidents occurred in the motorized vehicle lanes (Fig. 2c–. C, Fig. 2D).

This study revealed that 61.7 % of e-bike-related accidents and 69.6 % of bicycle-related accidents involved collisions with motor vehicles with at least four wheels, and the percentages (per 100 people) of casualties among rider victims of e-bikes and bicycles accounted for 95.5 % and 99.1 %, respectively. These percentages were significantly greater than those for collisions with motorcycles, nonmotor vehicles, and pedestrians (Table 1). In more than half of the collisions involving motor vehicles with at least four wheels, the drivers were at fault (Fig. 3A and. B).

In the 2018–2021 period, e-bike riders and cyclists presented basically similar violations, and the four most common shared violations were driving in motorized vehicle lanes, violating traffic signals, driving in the wrong direction, and crossing the road illegally (Fig. 4).

3.3. Areas

This study revealed that 70.7 % of e-bike-related accidents and 74.4 % of bicycle-related accidents occurred in suburban areas. The percentage (per 100 people) of casualties among rider victims in suburban areas was greater than that in central city areas (e-bikes: 87.6 % vs. 78.1 %, bicycles: 93.6 % vs. 88.1 %), as depicted in detail in Table 1.

However, the density of e-bike-related and bicycle-related accidents was greater in central city areas than in suburban areas. The

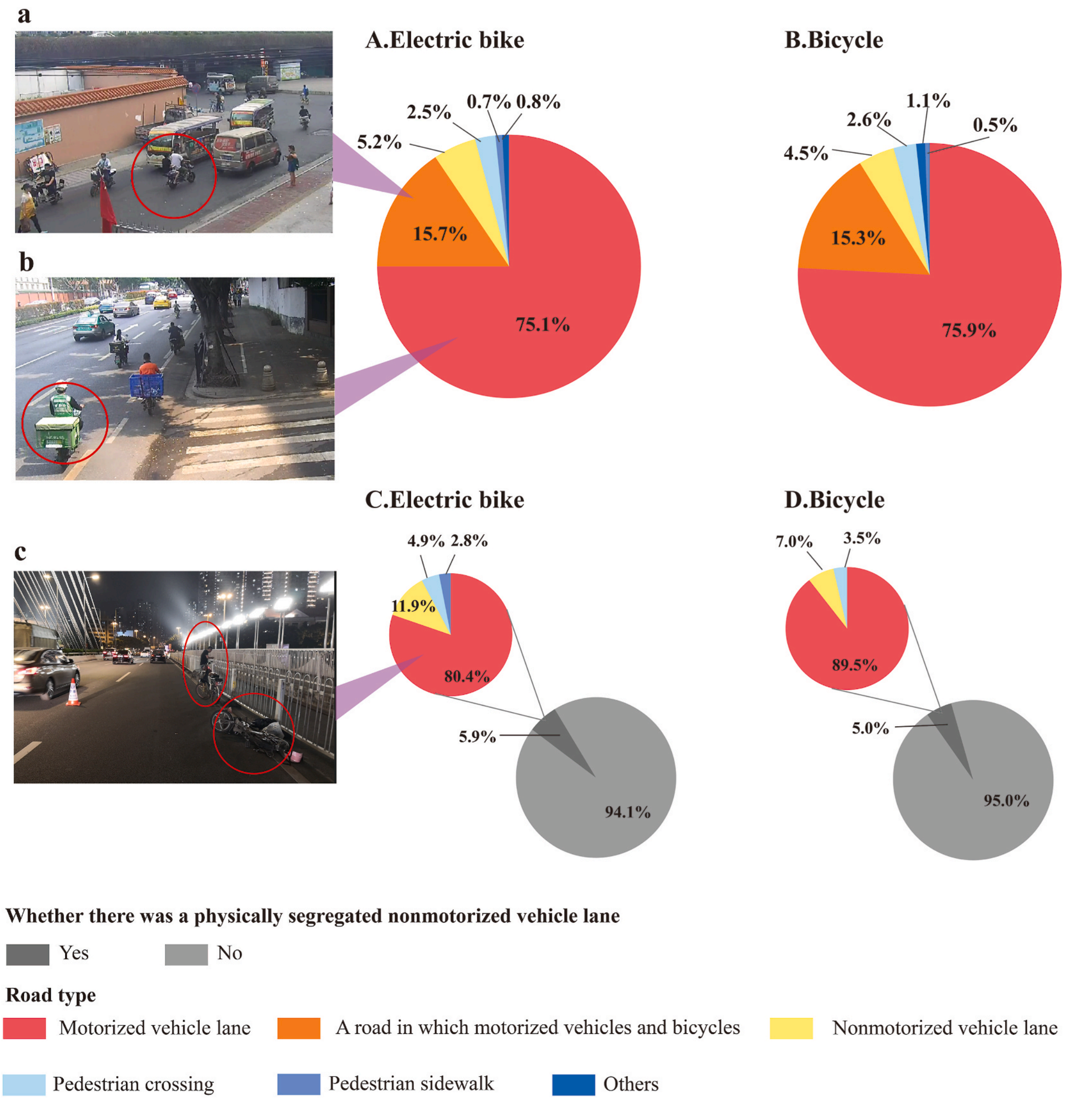


Fig. 2. Road types at the location of the accident and whether there was a physically segregated nonmotorized lane, 2018 to 2021. a: A road in which motorized vehicles and bicycles were mixed; b: Motorized vehicle lane; c: A motorized vehicle lane with a physically separated nonmotorized vehicle lane next to it.

distributions of areas with high accident density for e-bike-related and bicycle-related accidents were similar, and such accidents were basically located in central city areas and some suburban areas (Fig. 5A and. B).

As shown in Fig. 6, the global Moran indices are 0.2269 and 0.1638, respectively, and the spatial autocorrelation results for the accident density for e-bike-related and bicycle-related accidents showed that the spatial distribution was positively correlated. The spatial distribution of accident density exhibited a random distribution of <1 %. In addition, the hotspots of accidents were located in the central city and suburban areas close to the former (Fig. 7A and. B).

4. Discussion

We analyzed police data from 2011 to 2021 to analyze the trends, accident characteristics, and spatial distribution of e-bike-related and bicycle-related accidents. There were three key findings. First, the number of accidents and casualties related to e-bikes increased overall, while that of bicycle accidents decreased. After 2018, e-bike-related accidents worsened rapidly, while bicycle-related accidents flattened. Second, in general, the characteristics of e-bike-related accidents and bicycle-related accidents were similar and were characterized by collisions occurring in motorized lanes and on roads without physically separated nonmotorized lanes, collisions with motor vehicles with more than four wheels, and collisions with riders in motorized vehicle lanes. Finally, in terms of the spatial distribution, the areas with a high density of accidents and hotspot areas were concentrated in the central city area and suburban areas

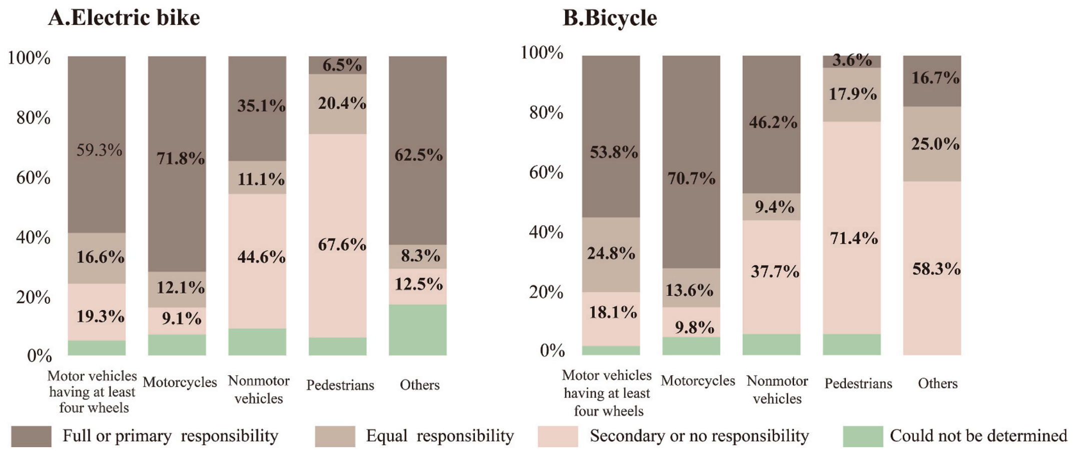


Fig. 3. Liability of counterparts (collision objects) in different types of collisions, 2018–2021.

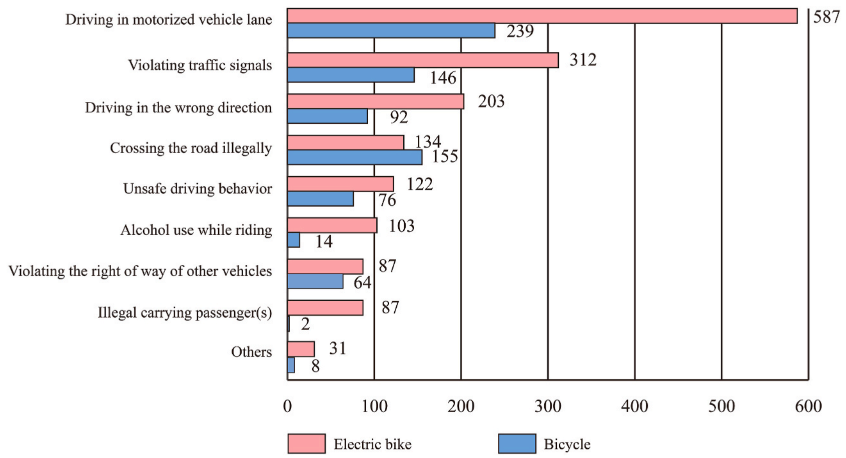


Fig. 4. Number of illegal behaviors of rider victims in e-bike-related and bicycle-related accidents, 2018–2021. Note 1: Crossing the road illegally refers to the following: The rider did not cross the road using the crosswalk or did not dismount the bicycle/electric bike and push it forward. Note 2: Unsafe driving behavior refers to driving behaviors that affect safety and include speeding, making sudden turns, and holding objects.

close to the former. However, more than 70 % of accidents occurred in peripheral urban areas with a higher risk of casualties.

4.1. Accident trends

This study showed that the number of bicycle-related accidents and casualty rates gradually decreased during the 2011–2017 period and stabilized after 2018. These findings are similar to the survey results of Lijun Wang et al. [5]. The number of e-bike-related accidents and casualties was basically stable during the 2011–2017 period but showed a rapid upward trend after 2018. Similar to previous studies, the results of this study are similar to previous studies in that the incidence of accidents associated with e-bikes has increased dramatically, contrary to the overall change in road traffic accident casualties [7,29,30].We attribute this change to the following primary reasons. **1.** In recent years, the production and sales of e-bikes have increased substantially since the Chinese government promoted environmentally friendly travel. **2.** E-bikes have the advantages of a low price, no need to test for a driver's license (no need to obtain a driver's license), long riding distance, labor savings and convenient parking [31]. These advantages cater to the needs of most low- and middle-income people [32], especially migrant workers [33], which has led the trend of replacing bicycles with e-bikes [34]. **3.** E-bikes are the main mode of transportation for takeaway delivery workers, and the rapid development of the takeaway industry has further promoted the use of e-bikes.

4.2. Road types, riders and collision objects

This study revealed that more than three-fifths of e-bike-related and bicycle-related accidents involved collisions with motor vehicles with at least four wheels, and the percentage (per 100 people) of casualties among rider victims was greater than 95 %. This is

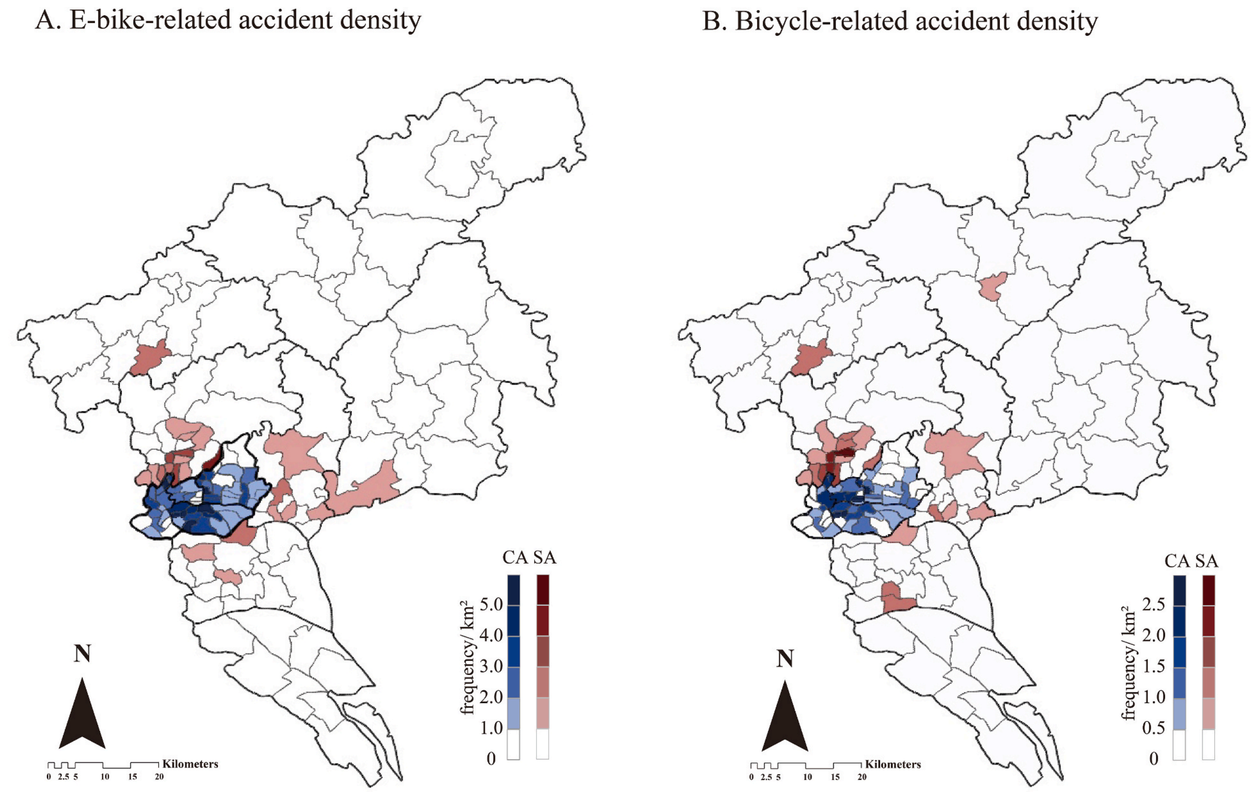
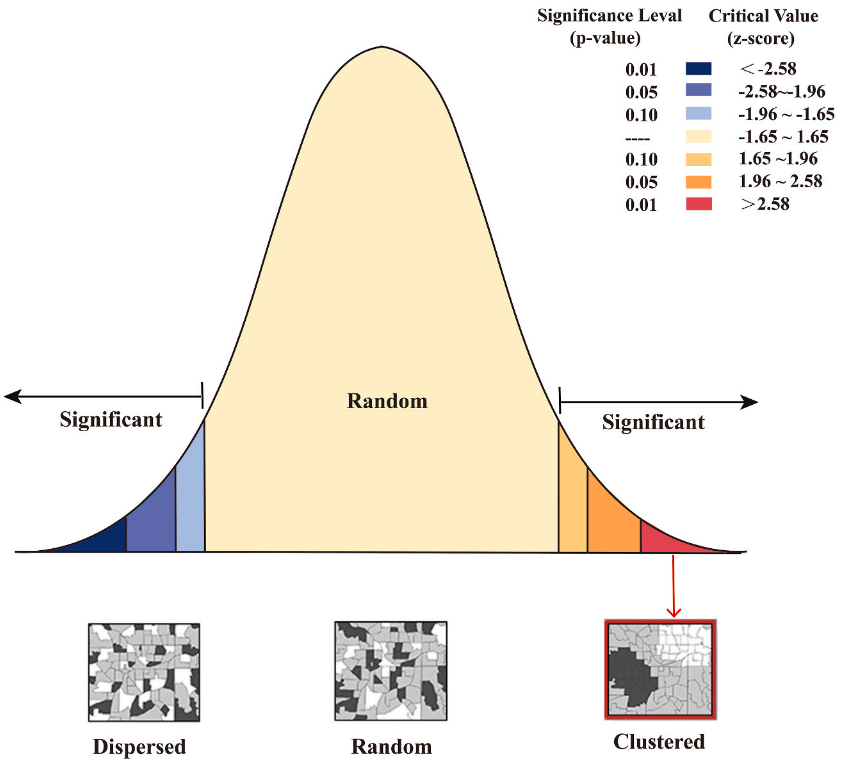


Fig. 5. Density distribution of e-bike-related and bicycle-related accidents in Guangzhou from 2018–2021. CA: Central area, SA: Suburban area.

similar to the findings of Qian Qian et al., where collisions with motor vehicles with four or more wheels represented the main type of accident, and the severity of injuries was found to be significantly greater than that of other collision types [19]. We believe that there are three reasons for this. First, motor vehicles drive at high speeds, and riders are vulnerable road users, with little to no energy available to mitigate the collision. Lin Hu et al. showed that when a passenger car and an e-bike collide, the rider is almost always seriously or fatally injured when the speed of the passenger car is above 50 km/h [35]. The study also revealed that vehicle drivers are most often at fault. Lu Bai et al. proposed that 77.7 % of collisions are caused by motor vehicle drivers and that the main violation is not giving the right of way to riders traveling on the main road when turning at intersections [36].

Second, this study revealed that approximately 3/4 of e-bike-related accidents occurred in motorized vehicle lanes. Our research group considers that these findings are directly related to the large increase in the number of e-bikes and the insufficient construction of nonsegregated lanes, especially during peak traffic hours, as riders must drive in motorized lanes for a smooth ride. Sun et al. reported that the flow density of e-bikes on nonmotorized vehicle roads can reach 1710 eb/h·m during peak traffic hours [37]. Weihua Zhang et al. showed that when the density of nonmotorized vehicle traffic is high, many riders tend to ride in motorized vehicle lanes [38]. In this context, only 5%–6% of accident sites had physically segregated lanes. For my part, this is related to the design requirements of secondary main roads and branch roads in China's urban road design (CJJ 37–2016). Glaser, Y.G. et al. showed that in the Shanghai area, road segregation tends to be present only on roads with higher speed limits and is usually not implemented on secondary arterial roads or branch roads [39]. Road planners usually prioritize traffic speed and efficiency over road safety, which is the same challenge that many fast-growing cities face. Therefore, we believe that road planners should pay attention to road safety construction and effectively reduce the occurrence of rider accidents by increasing the number of physically segregated lanes to separate motor vehicles from nonmotor vehicle riders. An analysis by Weihua Zhang et al. added evidence that landscape and physical segregation facilities can reduce the rider occupancy of motorized vehicle lanes by more than 80 % [38].

Finally, this study showed that of the accidents occurring on roads with physically segregated nomotorized lanes, the majority still occurred in the motorized vehicle lanes. Additionally, the most common behaviors of rider victims were actively driving in motorized vehicle lanes, which means that the high incidence of collisions with motor vehicles was related to the lack of road infrastructure and the low safety awareness of riders. Likewise, Zhang W. et al. and Zhen-bin Lin et al. showed that the average incidence of illegal lane occupation by nonmotor vehicles reached 36.1 %, which is a risk factor for rider injury [38,40]. Although these data showed that the main party at fault was the motor vehicle driver, Lin Hu et al. reported that the average collision speed of DAT accidents (30.7 km/h) was much lower than that of RAT accidents (38.7 km/h), and the severity of injuries in RAT accidents was greater [41]. In this regard, we believe that strengthening the safety education of riders is necessary, and riders should be required to attend driver training courses and acquire driving licenses similar to those of PTW drivers. It was previously found that e-bike riders with a driver's license are less



Victim Types	Morans's Index	z-score	p-value
E-bike	0.2269	17.3773	<0.00001
Bicycle	0.1638	5.8462	<0.00001

Fig. 6. Moran's spatial autocorrelation test statistics for e-bike-related- and bicycle-related accidents.

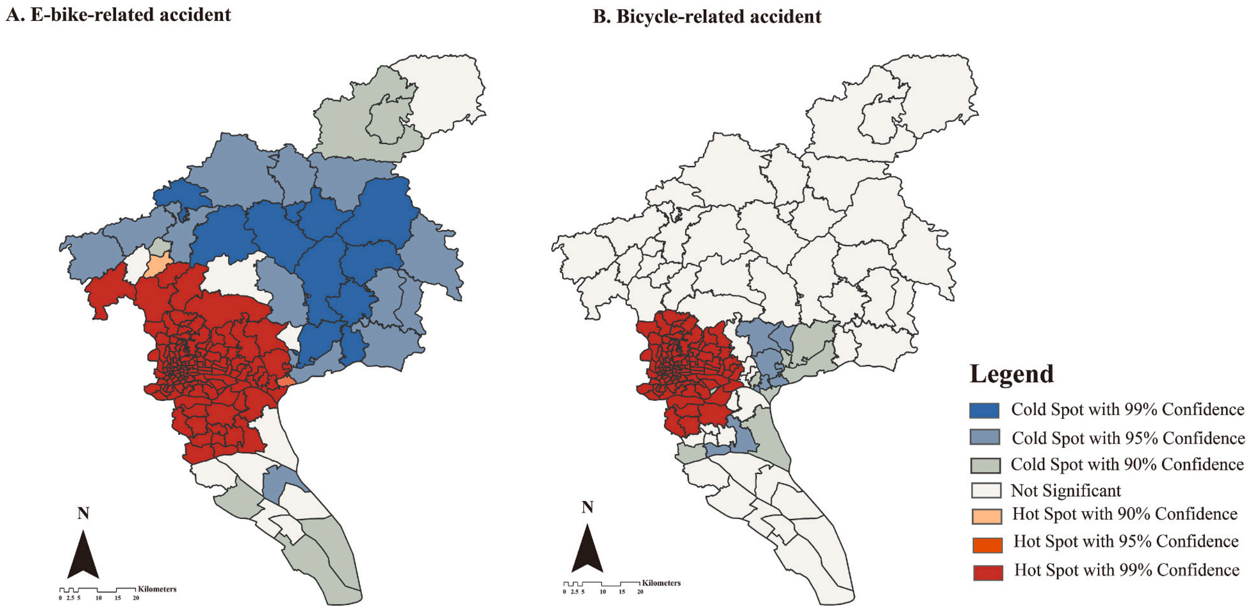


Fig. 7. Spatial distribution of e-bike- and bicycle-related accidents and hotspot clusters.

likely to be involved in an accident [42].

4.3. Spatial distribution of accidents

This study revealed that areas with a high density of accidents and hotspot areas were concentrated in the central city area and suburban areas close to the former. A previous study showed that the greater density of accidents in central city areas may be related to the dense population and road congestion in such areas [43]. Moreover, the increase in road mileage, motor vehicle use and population size was positively correlated with the change in the number of road traffic casualties [44]. Several researchers have suggested accident prevention measures for e-bike safety in areas with high traffic volume. Peng Chen et al. proposed that widening roads can effectively reduce the occurrence of accidents [45]. However, in central city areas, due to the high density of people, buildings and other urban facilities that are not easy to change, it is difficult to increase the road carrying capacity for nonmotorized vehicles by widening roads. It has also been suggested that lower speed limits can reduce the likelihood of accidents [19]. However, in high-traffic urban areas, speed limits might further exacerbate congestion and increase the risk of collisions. The results of this paper suggest that the number of e-bikes should be appropriately limited in hotspots, that physically segregated nonmotorized vehicle lanes should be actively developed, especially in streets with a high incidence of accidents, and that the use of public transportation facilities, such as buses and subways, should be encouraged.

Although the cold spots were in suburban areas, more than 70 % of the accidents occurred in suburban areas, and the percentage (per 100 people) of casualties among rider victims was greater than in central city areas. The reasons for this include, first, factors such as the greater number of e-bike and bicycle riders in suburban areas and the faster speed of motor vehicles (Fig. A2). Second, more migrant workers, the main users of e-bikes, lived in the outer urban areas [33]. According to the Guangzhou Municipal Bureau of Statistics, migrants represent 52.2 % (6.56 million) of the population in suburban areas, which is considerably greater than the 34.3 % (2.14 million) in central city areas. Migrant workers are not only the main users of e-bikes but also the main individuals involved in e-bike-related and bicycle-related accidents. According to China's National Bureau of Statistics, 82.9 % of migrant workers in China have no higher education. Studies by Wang, X. et al. and Wu, X. et al. showed that a lower level of education and less familiarity with traffic regulations are associated with greater risks of certain unsafe riding behaviors [46,47]. Therefore, we believe that in addition to actively building physically separated lanes in the outer urban areas, it is necessary to reduce the maximum speed limit of motor vehicles in the high-accident-density areas and promote awareness of traffic safety laws and regulations among riders, especially migrant workers.

4.4. Strengths and weaknesses

The major advantages of this study are as follows: 1. Based on relatively comprehensive and longitudinal data, a descriptive analysis of participants, roads and vehicles revealed that e-bike-related and bicycle-related accidents presented similar characteristics. Governments should focus on preventing nonmotorized vehicles from driving in motorized lanes, highlighting the importance of actively building physically separated lanes and requiring riders to obtain driving licenses. 2. The spatial distribution of accident density and the distributions of hot- and cold spots with different governance priorities were analyzed. The key areas for accident prevention were identified to reduce costs associated with the implementation of safety measures and increase the sustainability of accident prevention.

This article has several main limitations. **1.** The specific number of vehicles was unknown. Therefore, we could not calculate the accident rate or casualty rate based on the number of vehicles. **2.** The degrees of injury in this study were defined according to the standards for the Human Injury Degree Criteria set by the Chinese government. Different from the assessment criteria used in some studies (e.g., the Abbreviated Injury Scale Injury Severity Score (AIS-ISS) [14,48] or the length of hospital stay [49]), the Human Injury Degree Criteria tend to consider minor injuries those that reach the degree of moderate or serious in the AIS-ISS.3 Minor accidents in which participants suffered only minor abrasions that could be treated following simple procedures are often underreported in police data, limiting further the identification of traffic accident black spots and effective infrastructure improvements. Minor accidents in which the person involved suffered only minor abrasions and followed the simple procedure are often underreported in police data, limiting further identification of traffic accident black-spots and effective infrastructure improvements. 3. Because e-bike and bicycle riders are not required to have a driving license, the police data lacked records in this regard, which made it impossible for us to further compare the incidence of illegal behaviors between riders with and without a license.

5. Conclusion

During the 2018–2021 period, e-bike-related accidents presented a sharply worsening trend, while bicycle-related accidents plateaued. Based on a comprehensive analysis of the road type, collision type and rider's illegal behavior, this study found that preventing riders from driving on motorways should be the focus of governance. In this regard, this paper puts forward three governance suggestions: **1.** Governments should actively build physically separated lanes. **2.** For riders, they must attend driver training courses and acquire driving licenses like PTW drivers do. **3.** The spatial distribution characteristics of accidents may be considered for controlling nonmotor vehicle traffic accidents.

Disclosure statement

The authors report that there are no competing interests to declare.

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Ethical approval

This study was reviewed and approved by [the ethical review committee of Bioethics Committee, Southern Medical University (Guangzhou, China)], with the approval number: [no. NYLS2022-001], in line with the requirements of the Declaration of Helsink.

Data availability statement

The data associated with this study has not been deposited into a publicly available repository. Raw data was generated at the Guangzhou Public Security Bureau, Guangzhou, China, and the Guangdong Public Security Bureau, Guangzhou, China. The data is from the police platform, and the use of data is subject to strict approval procedures. Therefore, readers in need can contact the corresponding author Dongri Li, lidongri@smu.edu.cn.

CRediT authorship contribution statement

Nian Zhou: Writing – original draft, Software, Formal analysis. **Haotian Zeng:** Funding acquisition, Data curation. **Runhong Xie:** Funding acquisition, Data curation. **Tengfei Yang:** Writing – review & editing. **Jiangwei Kong:** Writing – review & editing. **Zhenzhu Song:** Visualization, Formal analysis. **Fu Zhang:** Funding acquisition, Data curation. **Xinbiao Liao:** Visualization, Formal analysis. **Xinzhe Chen:** Writing – review & editing, Formal analysis. **Qifeng Miao:** Writing – review & editing, Formal analysis. **Fengchong Lan:** Writing – review & editing, Formal analysis. **Weidong Zhao:** Writing – review & editing, Formal analysis. **Rong Han:** Visualization, Formal analysis. **Dongri Li:** Writing – review & editing, Writing – original draft, Supervision.

Declaration of competing interest

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

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Appendix A. Supplementary data

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