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Understanding Electric Bike Accidents Through Safe System Approach in Guangzhou, China: A Mixed-Methods Study

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Abstract: Electric bike (e-bike) accidents have emerged as a significant road safety concern in recent years. Employing a mixed-methods approach, this study seeks to elucidate the mechanisms underlying e-bike accidents and to develop an e-bike safe system aimed at enhancing e-bike safety and accident prevention. Quantitative analysis was employed to identify key components and their relationships through an event-based examination of a structured accident dataset using a Bayesian network. Complementing this, qualitative methods—including observations and interviews—were conducted to gain deeper insights into how riders interact with other components within the system. This study was carried out in Guangzhou, a metropolitan city with an increasing use of e-bikes and e-bike-related accidents. The key findings of this study are as follows: 1. The safe system of e-bike safety comprises critical components, including infrastructure (roads and facilities), e-bikes, riding behavior, individual riders, and other road users. 2. E-bike accidents predominantly result from dysfunctions of the safe system. The alteration of one component influences other components, which may, in turn, provide feedback to the original component. 3. While riders' mistakes play a role, the interactions between riders and other components also contribute to the accidents. 4. At the individual rider level, barriers to safe riding include a lack of safety knowledge, low penalties for violations, and high opportunity costs associated with safe riding behaviors. Deficiencies in infrastructure, regulations, and law enforcement contribute to violations and risky riding practices. This study contributes to the current body of accident studies by developing an e-bike safe system.

Keywords: e-bike accidents; safe system approach; riding behavior; mixed-methods; Bayesian network

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Academic Editor: Vladimír Bureš

Received: 17 February 2025
Revised: 16 March 2025
Accepted: 1 April 2025
Published: 7 April 2025

Citation: Jia, B.; Li, J.; Wang, Q. Understanding Electric Bike Accidents Through Safe System Approach in Guangzhou, China: A Mixed-Methods Study. *Systems* **2025**, *13*, 261. https://doi.org/10.3390/systems13040261

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1. Introduction

1.1. Background

E-bike mobility has emerged as a transformative transportation mode in many developing countries in recent year [1]. Particularly in Asia/Pacific regions, the e-bike has become a dominant urban mobility mode [2] (pp. 3–4.). By 2023, the number of e-bikes in China reached 350 million [3]. E-bikes have been considered as an innovative and sustainable mode of urban transportation to reduce air pollution and enhance urban mobility and accessibility [4], but e-bike-associated accidents have raised debates in many places. This is particularly true in China, where the number of e-bike accidents has seen a significant increase [5].

Numerous studies have been conducted to investigate the contributing reasons behind both the widespread adoption and safety concerns associated with e-bikes. The convenience, environmental friendliness, and cost efficiency of e-bikes are the primary reasons for their widespread adoption [6,7]. The primary purpose of e-bike use includes commuting to and from work, as riders perceive them to be faster than bicycles; meanwhile, they are more convenient than public transportation and private cars [8,9]. In China, e-bikes are particularly valued as a flexible transport mode for short- to medium-distance travel [10]. For Chinese families, e-bikes are commonly used for tasks such as picking up and dropping off children or grocery shopping. Additionally, their cargo-carrying capacity enables business activities, such as delivery services [2] (pp. 16–17). Thus, the integration of e-bikes into the gig economy, particularly in food delivery, has further driven their expansion in China.

Yet, the rapid increase in e-bikes has posed significant challenges to existing transportation systems. Improving e-bike road safety is, therefore, essential for achieving a sustainable transportation transition. Investigating contributing factors leading to accidents dominates current e-bike accident research, and an event-based approach has been predominantly employed. Roads, environments, vehicles, and humans are mostly identified as influencing factors [11]. Linear regression models are frequently used to understand how these factors are relevant to accidents, with the assumptions that the factors are mutually independent. These studies have suggested that addressing individual factors could enhance e-bike safety. Subsequent research has demonstrated that accidents are not solely caused by single factors; rather, they result from the interactions among multiple factors [12]. With the advancement and widespread adoption of data-driven methods, such as machine learning, studies have been able to identify and analyze multiple factors simultaneously. These approaches have enabled researchers to construct models that illustrate how these factors are interconnected, providing deeper insights into the mechanisms underlying e-bike accidents.

Although event-based studies are effective in identifying direct causal factors, they cannot explain the mechanisms of how accidents occur [13]. Research into fundamental causes is typically conducted within the framework of riding behavior studies, with the majority of existing research primarily emphasizing socio-psychological aspects, which often utilizes qualitative methods [14–16]. However, the complex interactions between riders, e-bikes, infrastructure, and other environmental factors, and how these interactions contribute to accident causation, remain an area of ongoing investigation.

Understanding accidents requires a systemic perspective due to the interactive complexity of safety issues [13,17]. Accidents are often caused by dysfunctions of the system rather than isolated factors [13]. The safe system approach has been widely implemented and empirically validated as an effective framework for developing comprehensive strategies to address road safety and reduce accidents [18–22]. However, its application has primarily focused on motor vehicle accidents. Following the transition in the Netherlands' primary mode of transportation from motor vehicles to bicycles, increasing scholarly and practical attention has been directed toward the development and implementation of bicycle safe systems [23,24]. Furthermore, the safe system approach has been extensively applied and proven effective in the development of comprehensive safety strategies for both motorcycles and bicycles [25–27]. These studies suggest that the safe system varies across different transportation modes in terms of its components and their potential interactions. E-bike technology differs significantly from motor vehicles, motorcycles, and bicycles. However, the safe system method has rarely been applied to e-bike mobility. Therefore, conducting studies on e-bike accidents using a safe system approach would be insightful.

This study aims to adopt the safe system approach to explain how e-bike accidents occur and to provide a comprehensive framework to systematically enhance e-bike safety in Guangzhou, China, where both the frequency of accidents and the fatality rate (defined as

the percentage of accidents resulting in fatalities) have been steadily increasing, particularly in collisions involving motor vehicles [28]. The development of a safe system involves three key phases: problem identification, system conceptualization, and model formulation [29].

At the beginning, the literature review establishes a theoretical framework to guide the development of the e-bike safe system, which involves identifying critical factors, summarizing components, and examining their interrelationships. Subsequently, we conduct a thorough analysis of the existing literature to uncover these factors and their potential interactions, thereby establishing a solid theoretical foundation for our empirical research and facilitating the development of an effective e-bike safe system. The conceptual model of the e-bike safe system can be mutually reinforced and illustrated through alignment with existing studies [30].

Then, the investigation employs a mixed-methods approach to comprehensively examine the components and interactions within the e-bike system. Identifying the causal components of accidents is the first step of conducting a safe system [24,30]. Based on quantitative data, Study 1 utilizes a Bayesian Network (BN) model, an effective analytical tool for identifying relationships among various factors. However, as Study 1 relies on data from government sources, it does not incorporate riding behaviors, a critical component identified in prior research [24]. The event-based quantitative method in Study 1 does not fully consider technical–human–organizational perspectives. To address this limitation in Study 1, Study 2, a qualitative study, which is particularly effective for constructing theoretically grounded models, is implemented to analyze how riding behaviors are related. This complementary study focuses on understanding how riding behaviors interact with other components and contribute to e-bike accident mechanisms.

This integrative approach, synthesizing multiple valuable data sources, represents a well-established practice in systems methodology [31]. Through this rigorous analytical framework, the study aims to develop a comprehensive e-bike safe system designed to enhance our understanding of e-bike accidents and inform effective safety interventions. Building upon existing literature and empirical findings from Guangzhou, we propose an e-bike safe system in the discussion section to explain e-bike accident mechanisms. Finally, the conclusion summarizes our key findings, theoretical contributions, and practical policy recommendations.

1.2. E-Bike Accident Factors

1.2.1. Contextual Factors

Contextual factors typically encompass the environmental and socio-temporal conditions within which the transportation system operates, including meteorological conditions, institutional temporal structures, and spatial characteristic. E-bike accidents more frequently occur in urban areas compared to rural areas. Such accidents are more likely to happen during commuting and rush hours [32]. Moreover, riders are more prone to violating traffic rules during morning peak hours, often due to being in a hurry [33].

Weather conditions significantly impact both visibility and riding performance. On rainy days, riders are more prone to making mistakes due to slippery pavement, reduced visibility, and distractions caused by rain noise [33,34]. High temperatures and intense sunlight not only hinder riding performance but also heighten riders' impatience, increasing the likelihood of running red lights [11]. Conversely, on cold days, the number of e-bikes on the road decreases, as people tend to opt for motor vehicles instead [35].

1.2.2. Infrastructure

Road-related factors, such as road grade, number of lanes, alignment, intersection density, and lighting facilities, are frequently discussed in the context of e-bike accidents.

Accidents occur more often at intersections and crossings due to traffic conflicts and common rider violations, including running red lights and occupying carriageways [36,37]. Riding on carriageways, sidewalks, or narrow roads increases the risk of accidents, which often result in severe injuries in these settings [32]. Additionally, fatal accidents at night are frequently attributed to inadequate lighting facilities [38].

In China, cities with well-developed non-motorized lanes, such as Shanghai and Kunming, experience fewer e-bike accidents caused by traffic chaos and conflicts [39]. The separation of motor vehicles from two-wheeled vehicles effectively reduces conflicts and enhances riding safety [40,41]. Riders are less likely to engage in violation behaviors when using dedicated non-motorized lanes [11]. Among separation measures, physical barriers such as road fences and bollards prove to be more effective than simple road markings [33]. However, when the bicycle lane is only 1 m wide, it forces riders to slow down, potentially leading to impatience and causing them to ride outside the designated lanes [42]. Furthermore, narrow non-motorized lanes may increase conflicts among two-wheeled vehicles [10].

1.2.3. Motor Vehicles

Motor vehicles pose a significant risk to two-wheeled vehicles during reversing, lane changes, cut-ins, and turning maneuvers. Drivers often struggle to notice two-wheeled vehicles due to limited visibility and the complexity of reversing, especially in cars without reversing cameras [43,44]. During lane changes and cut-ins, e-bikes following from behind are prone to rear-end and side collisions [40,45]. Failure to yield is the primary cause of collisions when motor vehicles are making turns [36]. Furthermore, riding alongside large vehicles is particularly hazardous because of their limited visibility and extensive blind spots [46]. Studies conducted in Guilin and Taixing, China, reveal that accidents involving large vehicles frequently result in severe or fatal injuries for two-wheeled vehicle riders [38,47].

1.2.4. E-Bike Technology

The inherent characteristics of e-bikes play a significant role in influencing riding behaviors. Two-wheeled vehicles, including e-bikes, motorcycles, and bicycles, share many similarities but also exhibit notable differences. Initially, in China, regulations for e-bikes were designed to follow those established for bicycles [2]. However, e-bikes are larger, heavier, and faster than bicycles, requiring riders to possess greater maneuvering skills and exert more physical effort [32]. All types of e-bikes are classified as non-motorized vehicles, with a maximum speed limit of 25 km/h and a weight limit of 55 kg [48].

E-bikes are smaller and more flexible than motor vehicles, allowing riders greater freedom of movement. Riders can easily overtake other road users, switch between lanes, and navigate through traffic by weaving among motor vehicles. E-bikes can even surpass motor vehicles in speed during traffic jams. Riding two-wheeled vehicles differs greatly from driving motor vehicles. It demands greater kinesthetic control and attention, as riders must constantly maintain balance and stability with their hands, especially on windy days or rough roads [42,49]. Riders are also more vulnerable than drivers because they lack the same level of physical protection [21,42]. The vulnerability of riders is the fundamental factor leading to injures [24].

Although the patterns of e-bike accidents resemble those of bicycle accidents, injuries resulting from e-bike accidents tend to be more severe due to their higher speeds and greater weight [5,50,51]. Controlling e-bikes in emergency situations is also more challenging compared to bicycles [15]. Riders involved in e-bike accidents often report that they believe their accidents would not have occurred had they been riding bicycles [52].

Other significant safety concerns related to e-bike materiality include the physical separation of helmets from e-bikes during accidents and persistent technical challenges (i.e., battery, tires), performance, and safety [53].

1.2.5. Human Factors

In terms of human factors, riding behaviors are well examined. The violations and risky behaviors of riders are significant contributing factors to accidents [12]. Similar patterns have been observed in China. Studies on the risky riding behaviors of e-bike riders in China have identified the most common violations, including occupying carriageways, speeding, running red lights, wrong-way riding (riding against traffic), turning without signaling, drunk riding, and carrying passengers [5,15,16]. Among these, running red lights is the primary cause of conflicts and collisions at intersections, particularly during left turns, as China follows a left-hand driving system [36,40,47]. Running red lights occurs so frequently that many riders do not even perceive it as a risky behavior [54].

Speeding is a significant factor contributing to e-bike accidents [12]. The speed of e-bikes is often underestimated by both riders and drivers [52,55]. In China, although all e-bikes are required to operate at speeds below 25 km/h, many exceed this limit, with some capable of reaching speeds up to 60 km/h [48,56]. Observational studies conducted in Shanghai and Suzhou, China, reveal that 83.8% and 70.9% of on-road riders, respectively, were found to be speeding [57,58].

Using mobile phones for activities such as texting and navigation is one of the most common risky behaviors among riders. This behavior is particularly prevalent while riders are waiting at red lights at intersections [59]. In China, food delivery riders heavily rely on mobile phones during their trips, further increasing the risk of accidents [60].

In addition, riding e-bikes is a dynamic and complex process, in which riders continuously assess and respond to their surroundings. Thus, riding capacities and skills play important roles. Handling, maintaining balance, speeding, turning performance, and trajectory control are closely related to experience levels [61]. Riders' prior knowledge of traffic rules and laws, the purpose of their trip, and their awareness of social responsibilities are also closely associated with riding behavior [49,62]. Novice riders often lack the necessary knowledge and experience, making them prone to tension and errors. In contrast, experienced riders tend to act automatically based on their familiarity with riding, which may result in reduced sensitivity to their surroundings [49].

Riders are directly exposed to their surroundings and have minimal protection while riding. Helmets serve as the most basic form of protection, significantly reducing fatalities caused by head injuries, which are the leading cause of rider deaths in accidents [63]. However, in China, there is a lack of awareness regarding helmet usage among riders. Observational studies of e-bike riding practices in Suzhou and Shanghai, China, reveal that only 2.2% of riders in Suzhou and 13.5% in Shanghai were observed wearing helmets [57,58].

1.3. Safe System Arpproach to Traffic Accidents

The safe system approach was proposed by Sweden (Vision Zero) in 1997 and followed up by the Netherlands (Sustainable Safety) [64,65]; it aims to reduce fatal and severe injuries among road users has been proved to be sustainable and effective at addressing road accidents [24,66]. The safe system approach views accidents as part of a socio-technical system, considering all factors and their interactions as components within a unified system. Within this system, the failure of a single component or the interactions between components can cause the dysfunction of the system and lead to accidents. Additionally, external disturbances, such as hazards outside the system, can also cause accidents. The systemic accident model suggests that accidents should not be understood as isolated

events but rather as a lack of constraints on components and their interactions during system development and operation. Enforcing and maintaining constraints at every level of the system is essential to ensuring its safety [13,67].

The safe system approach to traffic safety considers road users, vehicles, speeds, roads, and post-crash care, with the ultimate goal of achieving zero fatalities [68]. Addressing issues related to severe injuries through a holistic approach has proven to be more effective than focusing on single factors in isolation. Based on previous practice studies, there are three key strategies to enhance system safety: improving a specific component within the system, enhancing other components that interact with the target component and their relationships, and optimizing the entire system as a whole [25,27,69].

The safe system approach acknowledges that humans make mistakes and that the responsibility for accidents is shared among various components of the system [20]. Although many accidents are directly caused by human errors, the ability of individuals to improve such situations is limited due to the complexity of the road transport system. It is challenging for humans to consistently meet safety demands in such a complex environment. Physical functions, cognitive abilities, and psychological states are inherently vulnerable and fallible, making it difficult for humans to always act correctly, even with the best intentions [21,70]. Therefore, improving other components within the system to assist humans and minimize their errors is essential [66].

Rooted in systems theory, the safe system approach has been developed as a comprehensive framework to systematically strengthen preventive measures against accidents. The advancement of the safe system approach has consistently complemented local policies. The safe system provides a guiding framework for road safety management issues, and after being implemented for a period of time, the effectiveness of problem-solving feeds back into the adjustments of the safe system itself [71]. The European Commission has embraced the safe system approach as the guiding framework to enhance road safety. Drawing on over 15 years of empirical evidence, the safe system approach has demonstrated its effectiveness in addressing road safety challenges in the Netherlands [23].

In Italy, the safe system approach has been integrated into road safety management systems, with a particular focus on enhancing road infrastructure quality; concurrently, annual safety performance indicators have been collected to monitor progress [72]. In the process of implementing the safe system approach, both the United States and Australia have dynamically integrated it with local policy adjustments over the years, achieving significant improvements in road safety [66,70,73].

1.4. Safe System Development

Previous safe system approaches have predominantly focused on motorized transportation. However, recent research has highlighted the necessity of developing distinct safe systems for different transportation modes, as each mode possesses unique components and interaction patterns that contribute to specific safety challenges [65]. Wegman and Schepers developed a safe system framework specifically tailored for bicycles [24]. Through comprehensive analysis of bicycle accidents in the Netherlands, they identified distinct characteristics that differentiate bicycle accidents from motor vehicle accidents. The bicycle risk factors led to four key components essential to the bicycle safe system: bicycle-specific infrastructure, motor vehicles and bicycles, risk-increasing factors (i.e., traffic violations), and helmet usage. It is particularly noteworthy that within the bicycle safe system framework, all forms of risky behaviors are systematically identified as risk-escalating factors.

While e-bikes share some similarities with conventional bicycles, they possess distinct characteristics, as outlined in Section 1.2.4. Additionally, it is also important to modify the

safe system according to different locations [18,73]. In an in-depth study on e-bike accidents in China, the authors, based on extensive accident data research, found that the speed of e-bikes is not significantly related to the occurrence of severe or fatal accidents [74]. More significantly, the unique design features of e-bikes substantially influence rider behavior across different user groups, necessitating the development of a dedicated safe system framework specifically tailored for e-bike safety. This study aims to address such a need.

2. Study Case

The study location, Guangzhou, Guangdong, is situated in southern China and has a total population of 18.67 million. In 2023, the number of e-bikes in Guangzhou reached 6 million, with an average daily travel volume of 6.85 million e-bike trips. The majority of e-bikes in Guangzhou are mopeds. In 2022, there were 5600 daily recorded e-bike violation cases, with misbehaving riders responsible for half of the e-bike accident law cases [75]. By 2023, 60–80% of orthopedic injuries were caused by e-bike accidents. Additionally, 65% of severe injuries and 75% of fatal injuries resulting from traffic accidents were related to e-bikes, with most of the deceased not wearing helmets [76,77].

E-bikes were officially banned in Guangzhou in 2004. However, with the expansion of the food delivery business in 2017, some delivery riders began using e-bikes for their operations. At the time, the local government did not enforce strict regulations on this practice. Consequently, e-bike usage gradually gained popularity among citizens for daily commuting. Furthermore, in the early city planning of central Guangzhou, separated non-motorized lanes were not included, leaving non-motorized vehicles (e.g., e-bikes and bicycles) without dedicated space on the roads. This resulted in a lag between the rapid surge in e-bike adoption and the implementation of effective management measures.

The combination of rapid e-bike proliferation, incomplete infrastructure, limited management experience, and citizens' lack of knowledge about proper riding behaviors and traffic rules—due to the long period of e-bike restrictions—has led to highly chaotic traffic conditions in central Guangzhou.

3. Study 1: A Quantitative Study of a Bayesian Network

3.1. Methodology

3.1.1. Bayesian Network

A Bayesian network (BN) classifier and inference are employed. A BN is a statistical model based on probability theory and graph theory, used to represent conditional dependencies among variables. It describes causal relationships between variables through a Directed Acyclic Graph (DAG), where nodes represent random variables, and edges represent conditional dependencies between variables. The structure with the highest posterior probability is considered to represent the most probable dependency relationship. The primary purpose of adopting this machine learning method is to identify relevant factors and linkages using an event-based approach. Machine learning techniques allow for a more comprehensive causation analysis of accident injury severities, as they do not assume variables (factors) to be mutually independent. Instead, both known and potential correlations among factors are taken into account during classification. The BN classifier effectively illustrates the interactions between variables, making it a powerful tool for analyzing traffic accident factors and severities [78,79].

Since the BN classifier requires the definition and input order of nodes (variables) prior to constructing the BN structure, a two-tailed significance test is applied to calculate and rank the Pearson correlations between each of the variables and severity before classification. A BN structure is then conducted based on these variables. Based on the classification results of the BN classifier, BN inference is employed to calculate the condi-

tional probabilities of severity for each variable, allowing the identification of dominant risk factors. The BN algorithm was implemented on the Jupyter Notebook 6.0.3 platform. The performance of the models is evaluated using four metrics: accuracy, sensitivity, specificity, and F1-measure. All four metrics are computed using a confusion matrix.

3.1.2. Data and Data Preprocessing

An official police-recorded structural dataset on e-bike accidents in Guangzhou, China, is utilized for quantitative analysis. Structural datasets are widely used in traffic accident severity analyses because they are highly informative, enabling researchers to uncover potential relationships between variables using machine learning methods [80]. The dataset includes 4424 complete records of e-bike collisions with motor vehicles from January 2017 to October 2018. Following the Chinese standard for Road Traffic Accident Information Investigation (GA/T 1082-2013) [81], 14 variables from the dataset were selected for analysis.

Studies on road traffic accidents typically begin by classifying the severity of accidents. Most previous research on accident severity has categorized severity into two levels, using one of the following two approaches: property damage only/slight injury versus severe injury/fatal injury, or property damage only/slight injury/severe injury versus fatal injury. However, the consequences and losses associated with slight injuries, severe injuries, and fatal injuries vary significantly. Therefore, based on existing standards and practical experience, we classify severity into three levels to better reflect reality: property damage only/slight injury, severe injury, and fatal injury.

Taking severity as the class variable, all 15 variables in this dataset are defined as nodes in a subsequent analysis. The detailed classification and description of each variable are discretized and encoded in Table 1.

Table 1. Variables description.

Factors	Variables	Code	Classification and Description
Time	Time	Tim	1: 0:00~6:00 am 2: 6:00~12:00 am 3: 12:00~18:00 pm 4: 18:00~24:00 pm
Driving	Driving status	Drv	1: Go straight 2: Reversing 3: Turning round 4: Turning 5: Lane changing 6: Avoiding obstacles
	Seatbelt	Bel	1: Seat-belted 2: Not seat-belted
Vehicle	Supplemental Restraint System (SRS)	Air	1: No SRS 2: Open without collision 3: Front open with collision 4: Lateral open with collision
Vehicle	Vehicle type	Veh	1: Passenger car 2: Truck 3: Trailer 4: Tractor 5: Wheel loader
	Overload	Ove	1: Yes 2: No

Table 1. *Cont.*

Factors	Variables	Code	Classification and Description
Road	Physical separation	Cro	1: No separation 2: Median strip 3: Separation between motor and non-motorized lanes 4: Median strip and separation between motor and non-motorized lanes
	Type of roads	Int	1: Intersection 2: Regular section 3: Narrow road or crossing
	Road alignment	Roa	1: Straight 2: Curve
	Grade of road	Typ	1: Highway 2: Arterial road 3: Secondary road 4: Tertiary road 5: Urban expressway 6: Regular urban road
	Traffic signal control	Con	1: Signal control 2: No signal control
Environmental	Weather	Wea	1: Sunny 2: Cloudy 3: Rainy
	Visibility	Vis	1: Within 50 m 2: 50~100 m 3: 100~200 m 4: Beyond 200 m
	Lighting	Lig	1: Daytime 2: Nighttime with lighting 3: Nighttime without lighting
Severity	Severity	Sev	1: Property loss or slight injury 2: Severe injury 3: Fatal injury

3.1.3. Imbalanced Dataset and Resampling Technique

First, the issue of class imbalance in traffic accident datasets must be addressed. Traffic accident datasets are typically imbalanced with respect to accident severity. Severe and fatal injury accidents represent minority classes because, in reality, they occur far less frequently than property damage only or slight injury accidents, which make up the majority classes. As a result, classifiers are often biased toward the majority classes, potentially neglecting the minority classes. Classification algorithms tend to achieve higher accuracy for the majority classes than for the minority classes [79]. However, the minority classes are associated with more serious consequences, making it crucial to identify the factors contributing to severe and fatal accidents. Therefore, it is essential to address the class imbalance in the original dataset to accurately analyze and identify factors affecting the minority classes.

Resampling techniques are among the most commonly used methods to address class imbalance problems. A previous study on severity analysis of imbalanced traffic accidents demonstrated that the Borderline-SMOTE technique outperformed both SMOTE and SMOTE-Tomek techniques [82]. Therefore, the Borderline-SMOTE technique is adopted in this study to balance the original dataset.

3.2. Results

3.2.1. Balanced Dataset and Pearson Correlation

The results of the balanced dataset, resampled using the Borderline-SMOTE technique, are presented in Table 2. Compared to the original dataset, the minority classes (severe and fatal injury accidents) are more prominent. The results of the two-tailed significance test for the balanced dataset are shown in Table 3. Variables are ranked based on the significance of their Pearson correlation with severity, in descending order, as follows: Veh, Typ, Air, Con, Drv, Cro, Lig, Tim, Wea, Vis, Ove, Roa, Int, and Bel. These variables are subsequently used as inputs for the BN classifier.

Table 2. Severity data distribution of original dataset and balanced dataset.

Dataset	Samples	Property Loss and Slight Injury Accidents	Severe Injury Accidents	Fatal Injury Accidents
Original dataset	4424	3873	162	389
Balanced dataset	7747	3873	1937	1937

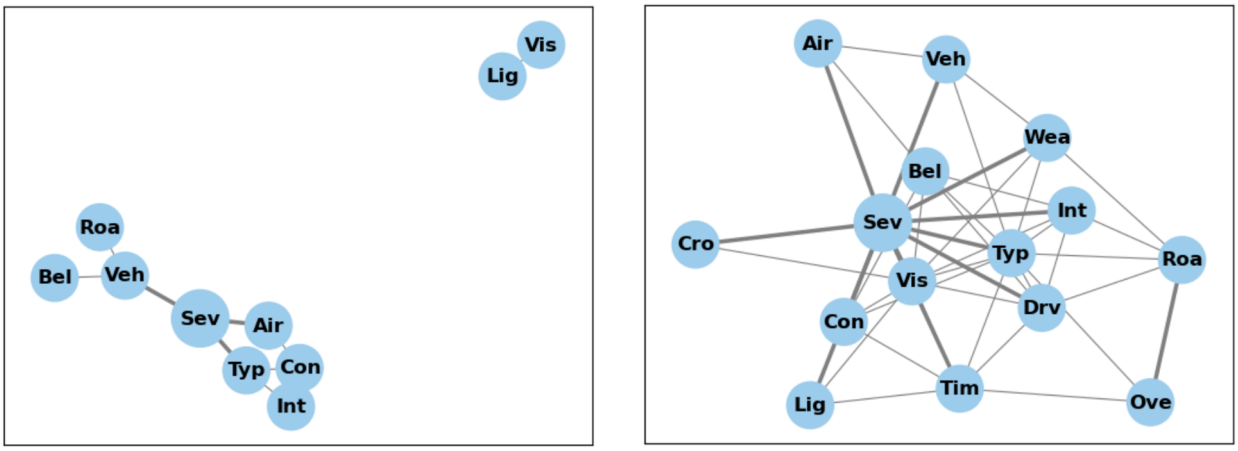
Table 3. Pearson correlation between variables and severity.

Number	Nodes (Variables)	Correlation with Severity
1	Tim	−0.098 **
2	Wea	0.095 **
3	Vis	−0.087 **
4	Lig	0.102 **
5	Con	0.146 **
6	Cro	−0.124 **
7	Int	0.064 **
8	Roa	0.072 **
9	Typ	−0.239 **
10	Air	−0.198 **
11	Drv	−0.137 **
12	Veh	0.282 **
13	Bel	0.058 **
14	Ove	−0.085 **

**: At 0.01 level (two-tailed), significantly.

3.2.2. BN Classifier

The BN structures for both the original and balanced datasets are constructed using 14 nodes (variables) from Table 3 along with severity, resulting in a total of 15 variables, to identify the connections between them. Based on the parameter estimation results of the BN structures, all 15 nodes were identified in the balanced dataset (Figure 1b), with 11 nodes directly influencing severity (Sev). In contrast, only 10 nodes were identified in the original dataset, of which just 3 are directly connected to the Sev node (Figure 1a, Table 4). This indicates that the imbalanced original dataset is inadequate for identifying some key variables.



(**a**) (**b**)

Figure 1. BN structure. (**a**) Original dataset. (**b**) Balanced dataset.

Table 4. Direct links between each variable and severity (Sev) of BN structure.

Original Dataset			Balanced Dataset		
Sev	→	Air	Sev	→	Air
-	-	-	Sev	→	Cro
Sev	→	Typ	Sev	→	Typ
-	-	-	Sev	→	Int
-	-	-	Sev	→	Tim
-	-	-	Sev	→	Vis
Sev	→	Veh	Sev	→	Veh
-	-	-	Sev	→	Lig
-	-	-	Sev	→	Con
-	-	-	Sev	→	Drv
-	-	-	Sev	→	Wea

The four performance measures (Table 5) calculated from the confusion matrix (Figure 2) for both the original and balanced datasets indicate that the balanced dataset, resampled using the Borderline-SMOTE technique, is more effective than the original dataset for identifying and classifying the minority classes (severe and fatal injury accidents). This finding further underscores that resampling is a crucial pre-processing step before analyzing traffic accident datasets.

Table 5. Performance measures.

Dataset	Severity	Accuracy	Sensitivity	Precision	F1-Measure
Original dataset	Property loss and slight injury	88.32%	0.957	0.941	0.949
	Severe injury		0.261	0.235	0.247
	Fatal injury		0.293	0.392	0.335
Balanced dataset	Property loss and slight injury	75.77%	0.860	0.815	0.837
	Severe injury		0.713	0.702	0.707
	Fatal injury		0.722	0.701	0.711

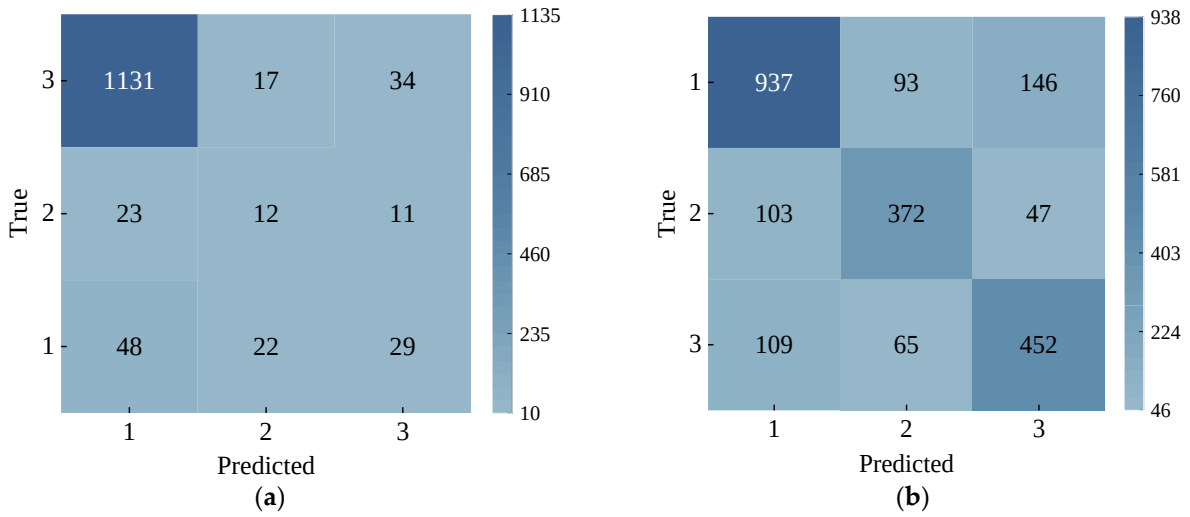


Figure 2. Confusion matrix. (**a**) Original dataset. (**b**) Balanced dataset.

3.2.3. BN Inference

Finally, a BN inference is used to calculate the conditional probabilities of severity under each variable, allowing the identification of dominant risk factors. The 11 variables and their respective situations are set as evidence when analyzing severity (Sev). Through BN inference, nine significant variables and 19 specific situations (considered as influencing factors) are identified (Table 6).

Table 6. Probabilities of severity under each variable of balanced dataset.

Values	Description	Probabilities of Severity		
		Property Loss or Slight Injury	Severe Injury	Fatal Injury
Cro = 2	Physical separation	0.2762	0.2967	0.4271
Typ = 1	Highway	0.1451	0.2515	0.6034
Typ = 2	Arterial road	0.2188	0.3229	0.4583
Typ = 3	Secondary road	0.2007	0.3314	0.4679
Typ = 5	Urban expressway	0.2331	0.2728	0.4941
Int = 1	Intersection	0.2500	0.3247	0.4253
Int = 2	Regular section	0.2495	0.3303	0.4202
Int = 3	Narrow road or crossing	0.2230	0.3485	0.4298
Tim = 1	0:00~6:00 am	0.2251	0.3472	0.4277
Tim = 2	6:00~12:00 am	0.1906	0.3601	0.4493
Tim = 4	18:00~24:00 pm	0.2022	0.3596	0.4382
Vis = 1	Within 50 m	0.1949	0.3458	0.4593
Veh = 2	Truck	0.2092	0.2947	0.4961
Veh = 3	Trailer	0.1747	0.3093	0.5160
Veh = 5	Wheel loader	0.1379	0.3909	0.4712
Lig = 3	Nighttime without lighting	0.1596	0.3754	0.4650
Drv = 2	Reversing	0.1325	0.3889	0.4786
Drv = 5	Changing lane	0.1510	0.3977	0.4513
Wea = 3	Rainy	0.1837	0.3642	0.4521

3.3. Key Components

The nine contextual factors, including 19 actual situations listed in Table 6, can be summarized as five components (Table 7) associated with accidents that result in severe and fatal injuries.

Table 7. Dominant components of severe and fatal injury accidents.

Components	Significant Factors	Variables
Other road users (Motor vehicles)	Driving status	Reversing, changing lanes
	Vehicle type	Truck, trailer, wheel loader
Time	Time	0:00~12:00 am, 18:00~24:00 pm
Individual	Visibility	Within 50 m
Weather	Weather	Rainy
Infrastructure (roads and facilities)	Physical separation	Median strip
	Road type	Highway, arterial roads, secondary roads, urban expressways
	Type of road sections	Intersections, narrow roads, crossings
	Lighting	Nighttime without lighting facilities

First of all, infrastructure is one of the key components identified through the model, including significant factors of physical separation, road type, road section, and lighting. The median strip in the road may potentially obstruct visibility [83]. In terms of road types, severe and fatal injury accidents occur more frequently on highways, arterial roads, secondary roads, and urban expressways. Notably, e-bikes are prohibited on highways, arterial roads, and urban expressways. However, many riders still use these roads due to the inability of the current traffic monitoring system to capture e-bikes, largely because of the lack of licensing. Another reason is the high-speed limits on these roads; highways and arterial roads have speed limits of 80–120 km/h, while secondary roads and urban expressways have speed limits of 60 km/h. The fatality rate in collisions between e-bikes and motor vehicles is positively correlated with driving speed [74]. Additionally, riders are more likely to speed on high-grade roads [84]. Accidents also occur more frequently at intersections, crossings, and on narrow roads due to traffic conflicts and frequent violations, which aligns with findings from previous studies [85]. Accident frequency is positively correlated with traffic density at intersections, as high density often leads to conflicts and chaos [86]. Guangzhou, in particular, has many areas with a high density of intersections and narrow roads [87].

The motor vehicles on the roads are also another key component leading to e-bike accidents. Collisions are more likely to occur when motor vehicles are reversing or changing lanes. Drivers are more prone to distraction while reversing and usually require sufficient time to complete such maneuvers [44,88]. However, some riders, particularly food delivery riders, tend to be aggressive and impatient [89]. They often believe they are fast enough to pass motor vehicles instead of yielding the right of way. Additionally, collisions between large trucks and e-bikes frequently result in severe or fatal injuries. Riders often feel tense around large trucks, increasing the likelihood of operational mistakes. Many riders report feeling terrified when riding near large trucks [90]. Therefore, separating riders from motor vehicles emerges as a critical safety intervention.

The findings regarding time, weather, and visibility are consistent with the results of previous studies. In Guangzhou, traffic density remains high throughout the day due to its large metropolitan population, with the evening peak having the highest traffic volume [56]. Additionally, riders are more likely to occupy carriageways when traffic density is high [33]. Fatal and severe accidents occur more frequently at night. Although traffic composition is less complex than during the daytime, more large trucks are on the roads at night due to daytime truck restrictions in Guangzhou. Moreover, nighttime riding is often accompanied by reduced concentration and slower reaction times among riders due to fatigue.

Poor visibility caused by insufficient lighting facilities at night and during rainy days further exacerbates the risk for both riders and drivers. E-bikes, in particular, are harder to notice due to their smaller size and weaker lighting systems. Mistakes in operation are more common when visibility is reduced [40]. Furthermore, physical conditions, such as fatigue, can further impact riding performance, particularly during nighttime or in rainy weather. Rainy days present additional challenges, as slippery pavements require riders to employ greater maneuvering skills and reduce their speed to maintain balance.

In summary, Study 1 identified the following critical factors contributing to severe and fatal e-bike accidents: physical separation, roads, lighting facilities, driving status of the vehicle, vehicle type, time, visibility and weather. These factors can be systematically refined into five core components: infrastructure, individual riders, other road users, time, and weather conditions. The analysis revealed the interactions among these components, particularly between infrastructure, other road users, and individual riders. Weather conditions were found to influence accident occurrence through their impact on both individual riders and infrastructure conditions.

In this quantitative study, riding behavior—widely recognized as a critical factor in e-bike safety—is excluded from analysis due to the lack of original data collection mechanisms. In addition, half of e-bike accidents are caused by illegal and violation behaviors in Guangzhou [75]. Thus, to further explore how riding behaviors interact with these components and how they systemically lead to e-bike accidents, on-road observations and interviews with e-bike stakeholders are conducted in Study 2.

4. Study 2: Qualitative Study

4.1. Methodology

A qualitative research approach is employed to achieve two primary objectives: first, to illuminate the complex interactions between riding behaviors and other system components, and second, to uncover potential relationships that were undetectable in the quantitative model due to inherent data limitations. Since, in qualitative research, data adequacy is determined by information saturation, data collection ceases when qualitative methods no longer provide novel insights or substantive information [91,92].

4.1.1. Observations

Based on a pilot survey conducted in central Guangzhou, we selected study areas and road sections characterized by dense pedestrian crowds, high volumes of motor vehicles, and significant e-bike traffic. These areas included residential, business, shopping, and school districts. The observational studies were carried out at one intersection (observation point 1, OP1) and one road section (observation point 2, OP2). Observations were conducted on 27 and 29 July 2020 over a 12 h period from 7:00 to 19:00.

Observational studies aim to capture the details of a phenomenon and explore the factors influencing it. Observational items included e-bike traffic volume, whether the e-bikes were regular or food delivery e-bikes, violation behaviors, uncivilized riding behaviors, traffic light conditions, time of day, and weather. Five experienced observers were recruited to record their observations by taking on-site notes. Additionally, photographs and videos were taken to supplement the observational records. These observation notes were coded as observational note 1 (ON1) and observational note 2 (ON2).

4.1.2. One-on-One Interview and Survey

One-on-one interviews with citizens and a field survey were conducted in various areas, including residential neighborhoods, the central business district (CBD), the old town, universities, and logistics hubs. Follow-up interviews were carried out during July 2020,

December 2022, February 2023, October 2024, and February 2025. Interviews are a primary method for collecting qualitative data, allowing researchers to directly obtain narrative accounts of the experiences and opinions of interviewees, who are often stakeholders relevant to the study.

In these interviews, participants shared their experiences related to e-bikes. The interviewees included 18 food delivery riders and 18 residents. Among the 18 food delivery riders, 14 are from Meituan Waimai, the largest food delivery platform in China that connects users with restaurants, and four are from Pupu Chaoshi, which is an online grocery delivery platform. The 18 residents are composed of eight motor vehicle drivers, two bicyclists, two pedestrians and six e-bike riders for daily commuting. The interviews focused on participants' narratives regarding their perceptions of on-road e-bikes and their personal experiences. Each interview lasted approximately 20–30 min. With participants' consent, notes were taken during the interviews to document their responses.

One on-site officer (referred to as TP1) from Guangzhou, with approximately 15 years of relevant experience, was invited to participate in an interview as an expert. TP1 possessed extensive knowledge and experience related to traffic accidents. The interview lasted 60 min, during which 10,130 words were recorded as notes. Detailed personal information about TP1 is not disclosed in this paper at the request of the interviewee to remain anonymous. During the interview, TP1 provided insights into the patterns of e-bike accidents and the contributing factors specific to Guangzhou. Additionally, TP1 provided some insights on the management challenges of e-bikes.

All participants were fully briefed regarding the research objectives and methodology, with explicit assurance of confidentiality regarding their personal information. Each respondent was assigned a unique identifier code (see Appendix A for detailed coding protocol).

4.2. Results

4.2.1. Patterns of E-Bike Traffic

During the 12 h observation period, the proportion of two-wheeled vehicles was relatively high. Two main groups of riders were identified: citizens using e-bikes for commuting, grocery shopping, picking up or dropping off children, and riders who rely on e-bikes for their livelihood, such as food delivery riders. The food delivery group was easily distinguishable, as they typically wore uniforms and carried a delivery box on the back of their e-bikes. In residential areas, the peak hours were observed to be 7:30–9:30, 12:00–13:00, and 17:00–21:00. The morning peak was primarily composed of people commuting to work. At noon, most riders were food delivery workers. The evening peak included both commuters returning home from work and food delivery riders. In commercial centers, the traffic pattern differed slightly from typical rush hours, as the majority of riders in these areas were food delivery workers. The morning rush hour began after shops opened, usually around 10:00. There was another peak around 12:00 due to food delivery activity, with the highest traffic volume occurring between 17:00 and 20:00. These peak traffic periods, characterized by both substantial e-bike volumes and frequent traffic disruptions on roadways, exhibit significant temporal correspondence with the e-bike accident patterns identified in Study 1.

Four types of accidents were most reported or observed. (1) E-bike rider hit another road user. For example, an elderly pedestrian complained, "I was scraped by a food delivery rider's box when I was crossing the road. He was too fast that I could not react." (RP2). A taxi driver added, "I always remind my passengers to check their surroundings before getting out because I'm worried that riders would not slow down." (RD7). One respondent stated: "I use an e-bike for daily commuting because it is convenient, but I have

encountered some dangers. I was hit by another e-bike from behind while waiting at a traffic light, and both of us fell." (RE1). (2) Collisions between e-bikes and motor vehicles. Accidents were also observed when e-bikes and motor vehicles were trying to occupy the same empty space. One collision was observed at OP2, where an e-bike was trying to cut in-between two vehicles on a carriageway, and it was hit by the rear car. One fatal accident was reported in the logistics distribution center: "It was unfortunate that a truck with a trailer was making the right turn at the intersection, and the trailer hit the rider. Maybe the driver could not see the rider due to the blind spot." (RE2). (3) Collisions among e-bikes. It is frequently observed that two e-bike riders collide with each other while they are riding. They normally treat the collision easily and only stop a few minutes and then continue to ride. (4) Loss of control of riders. One rollover accident of a food delivery rider was observed at OP1, "The food delivery rider was trying to catch up with the last seconds of green light at intersection, he was making the turn too fast that he could not control the e-bike and fell down".

Both observational data and interview responses consistently indicate that the material properties of e-bikes constitute a critical factor in risk scenarios, yet this dimension remains unaccounted for in structured quantitative official records.

4.2.2. Riding Behaviors and Other Components

- E-bike technology and riding behaviors

The agility of e-bikes plays a significant role in the maneuverability of riders. Beyond speed, e-bikes provide greater freedom and flexibility due to their smaller size and lighter weight compared to motor vehicles. Their agility enables riders to easily cut into traffic, change speed, and adjust direction in carriageways. "E-bikes occupy everywhere, including non-motorized lanes, sidewalks, and carriageways. They frequently weave among other vehicles." (ON1). Riders, particularly food delivery riders, often squeeze into small gaps between motor vehicles and find ways to navigate through traffic. Additionally, e-bikes can accelerate quickly, often making them the first to cross intersections when traffic lights turn green. "E-bikes are always the first ones to rush out, even before the lights have fully turned green. And when the lights are about to turn red in a few seconds, e-bikes prefer to speed up and cross the intersection rather than wait for another cycle." (ON1).

Not wearing helmets is one of the contributing factors leading to fatal injuries, according to TP1. The separation of the helmet from the e-bike rider and the uncomfortable body experience of wearing the helmet leads to reluctance in using a helmet while riding. The authors observed that many on-road riders did not wear helmets. Some riders carried helmets on their e-bikes but would only wear them when they noticed a police officer nearby. "It is not comfortable to wear a helmet. Too hot in the summer." stated by both TP1 and RE5. Although TP1 noted that riders are becoming increasingly aware of the importance and protective function of helmets, many still consider wearing them inconvenient and troublesome. Existing research further corroborates that the quality of safety equipment, particularly helmets and tires, significantly influences the severity of e-bike accidents [53].

Research findings indicate that specific e-bike riding patterns significantly contribute to both vehicle deterioration and accident risks. A prevalent issue among users is the tendency to maintain excessively high speeds followed by abrupt braking when approaching traffic signals or obstacles. This riding behavior not only compromises safety but also accelerates the degradation of critical components, particularly brake pads and tires. Furthermore, the throttle mechanism is susceptible to burnout caused by current overload during rapid acceleration or deceleration cycles. A common manifestation of this technical failure occurs when an e-bike fails to move despite adequate power supply, typically indicating throttle burnout.

- Infrastructure and riding behaviors

A lack of infrastructure, such as dedicated lanes for e-bikes, was frequently mentioned by TP1, e-bike riders, and drivers. TP1 highlighted that the absence of non-motorized lanes is a significant factor contributing to traffic conflicts caused by riders. "It is quite necessary to separate e-bikes and motor vehicles, especially trucks and buses" said TP1.

According to the interviews, riders generally prefer having separated non-motorized lanes. Some drivers also suggested that e-bikes should travel on the rightmost side of carriageways or on sidewalks instead of occupying carriageways. However, observations revealed that some riders, particularly food delivery riders, rushed into carriageways in areas where road fences separated the lanes. A possible reason for this behavior is the narrowness of the non-motorized lanes (1 m wide), which constrained riders and made overtaking difficult. This issue was also noted in a previous study [42]. Narrow non-motorized lanes can lead to congestion among non-motorized vehicles. Additionally, some riders occupied carriageways even when there were sufficiently wide non-motorized lanes available. This is because the riders can ride faster in the motor ways.

- The conflicts between e-bikes and other road users

Urban transportation involves the coexistence of various road users within the same road system. To a certain extent, e-bike riders are newcomers to Guangzhou's current transportation system, and their large numbers have posed significant challenges to both traffic management and other road users. Since road users interact with one another, the presence of diverse types of road users often leads to increased complexity and disorder.

E-bikes and motor vehicles were all crowded in the carriageways, which was observed at both OP1 and OP2. "Many two-wheeled vehicles and motor vehicles share the streets. The traffic appears chaotic due to the differences in their speed and the space they occupy. E-bikes are everywhere in the traffic. Sometimes, drivers shout at riders for their sudden cut-ins." (ON1). "The rightmost motorized-vehicle lane is occupied by food delivery e-bikes. The deliverers were waiting for orders in front of the shopping mall." (ON2). E-bikes traveling on carriageways often exceeded the speed limit of 25 km/h, further increasing the risk of accidents.

This agility creates challenges for other road users in predicting and responding to the movements of e-bikes. E-bikes always cut into motor traffic very quickly, forcing drivers to perform emergency braking to avoid collisions. A novice driver shared their concerns: "I've experienced many risky movements from e-bikes while driving. I feel nervous when e-bikes are riding around my car, and I'm always afraid of their sudden cut-ins." (RD1). At intersections, drivers must pay extra attention to e-bikes before moving when the traffic lights turn green. "Motor vehicles have to wait for e-bikes to go first at intersections because e-bikes always change lanes and occupy carriageways after taking off." (ON1). Additionally, drivers and passengers must ensure no e-bike is approaching before opening car doors. One respondent shared, "I had a collision once—not while driving, but when I opened the car door and got hit by a rushing e-bike." (RD3).

Additionally, risky and rule-violating riding behaviors contribute to conflicts and chaos within the traffic system. One respondent stated, "I always have to wait for e-bikes to go first. But there are so many of them that motor vehicles often get stuck on the road. Sometimes we don't even have enough time to pass the green light because the e-bikes block the way." (RD3). Both RD5 and RD6 shared experiences of encountering risky situations involving riders who rode in front of or beside their buses, which is particularly dangerous due to the blind spots of large vehicles. RD6 recounted, "Once, there was a rider squeezing between my bus and another bus. I honestly think he wasn't afraid of death.".

In the interviews, both drivers and non-drivers expressed frustration about the chaos caused by e-bikes. "Guangzhou traffic is a mess now. I miss the days when there weren't so many e-bikes." (RB1). During peak hours with heavy traffic, the chaos makes it difficult for road users to make accurate judgments or safely maneuver e-bikes, as the small distances between road users exacerbate the situation. Other road users also reported feeling pressure. "I feel unsafe cycling on the road with e-bikes. Sometimes I have to cycle on the sidewalks just to avoid them." (RB2).

4.2.3. Individual Riders and Riding Behaviors

The individual riders' embodied conditions and trip purposes have influence on riders' behaviors. Although e-bikes are electrically powered and reduce the physical demands of cycling, they impose significant cognitive, emotional, and sensory requirements on riders. Yet, riders often lack sufficient awareness, and, to some extent, they do not take their embodied capacities to ride properly very seriously. Since e-bikes were prohibited for a long time in Guangzhou, education and regulations regarding e-bikes remain incomplete. And for some experienced riders, they are inclined to take risks due to a "not me" mentality, even when they are aware of the dangers.

The desire to travel quickly and conveniently are the main reasons for not following the rules. Yet, this long-term unsafe riding behavior in turn reinforces improper behaviors, and some e-bike riders acknowledge their violation behaviors but remain unconcerned, as their previous risky behaviors have not yet resulted in injuries [93]. This finding is consistent with a study conducted in Tianjin, China. TP1 emphasized the need for traffic safety education: "It is better to educate people about e-bike traffic safety from a young age. Promoting such knowledge in daily life is very important". We contend that for certain e-bike riders, deeply ingrained riding habits developed through extensive experience may significantly diminish the effectiveness of conventional safety education programs.

Riders' trip purposes have great influence on the choice of a trip and riding behaviors [49]. For instance, riders who use e-bikes to pick up and drop off children tend to prioritize safety, and they drive slowly. "There are several riders who have a child on the back seat. They do not ride fast, always stay focused on their surroundings, and avoid occupying carriageways. They are careful to steer clear of drivers and other riders." (ON1).

In addition, some riders are fully aware of the risks associated with violations and intend to ride safely, but their actual behaviors are often influenced by external factors. This is particularly evident among food delivery riders, who are task-based workers relying on e-bikes for their livelihood. In 2023, there were total 12,000 e-bike accidents involving food delivery riders in China; there were 120,000 recorded violation cases involving food delivery riders in Guangzhou [94]. Observations revealed that the primary risky behaviors of food delivery riders include speeding, running red lights, occupying carriageways, riding in the wrong direction, and using mobile phones. These findings align with studies on food delivery riders in Beijing and Tianjin [95]. One observer noted, "Food delivery riders make up a large portion of all riders. They are easy to identify, as they all have large boxes on the back of their e-bikes. They ride quickly in carriageways, searching for empty spaces to accelerate. Some even ride alongside large vehicles and buses, while frequently checking their mobile phones." (ON2).

Most of the interviewed food delivery riders admitted to violating traffic rules to avoid fines for late deliveries, even though they were fully aware of the risks. As task-based laborers, the opportunity cost of obeying traffic rules is high for them. The primary concerns of food delivery riders are completing delivery tasks, meeting time demands, and ensuring convenience while riding, as they are under the control of app-based algorithms [95]. It is often impossible for them to complete the tasks assigned by these app algorithms without

violating traffic rules. One Meituan food delivery rider stated, "I was hit by another food delivery rider once. I just let it go because both of us were in a hurry to deliver in time. This happens a lot for us." (FD12). Pupu delivery riders explained that, "The slogan of Pupu is to delivery grocery to home within 30 min. To meet this goal, we even have to run from the warehouse to our e-bikes." (FD15 & 16). Furthermore, the competition in the food delivery industry is becoming increasingly intense, and delivery times are getting tighter. "Within the same amount of time, we have to complete more orders than before to earn the same amount of money." (FD14).

Food delivery riders ride at high speeds, even on rainy days and extremely-hot days. E-bike accidents involving food delivery riders are more frequent on rainy days due to limited visibility and slippery roads, particularly during turns [96]. On extremely-hot days, their riding behaviors are influenced by heat exposure [97].

The high reliance on mobile phones is also a significant factor for food delivery riders, as they must frequently communicate with customers and check locations. This issue was also highlighted in a study conducted in Xuzhou and Nanjing, China [60]. Using mobile phones, whether hands-free or handheld, distracts riders from their surroundings and slows their reaction times in emergencies. Even texting while stopped at a red light can be dangerous [42]. In terms of wearing helmets, most food delivery riders comply with this rule, as it is mandated by their companies.

4.3. Regulations and Regulation Enforcement

Overall, traffic policies have been relatively slow in response to e-bike mobility [98]. From 2004 to 2021, Guangzhou policy frameworks predominantly adopted restrictive measures towards e-bikes, primarily focusing on prohibition. Despite the substantial growth in e-bike usage patterns across Guangzhou during this period, it was not until December 2021 that regulatory measures addressing the facilitation and management of e-bike mobility were formally implemented. TP1 emphasized that the low cost of violating traffic rules is a significant contributing factor. Enforcing traffic rules for e-bike riders is challenging for several reasons. (1) Not all e-bikes are registered. For instance, while Guangzhou has over 6 million e-bikes, only about 5 million are licensed [76]. (2) Technologies for monitoring e-bikes are not yet fully integrated into the traffic surveillance system. Even when violations are detected, the most common outcome is a verbal warning. Consequently, riders have little incentive to comply with traffic rules, as they perceive minimal consequences for violations.

5. Discussion

Study 1 identified the components of infrastructure, individual riders, other road users, and weather conditions through quantitative analysis. Study 2 identified the on-road riding behaviors and analyzed how infrastructure, other road users, e-bike technology, and individual riders interacted with riding behaviors. Furthermore, this study argues that regulations and law enforcement influence riding behaviors. Based on Study 1 and Study 2, we propose an e-bike safe system that elucidates how e-bike accidents occur (Figure 3) in the context of Guangzhou.

The e-bike safe system consists of infrastructure, other road users, the materiality of e-bikes, individual riders, and riding behaviors. The model posits that e-bike accidents are precipitated by systemic dysfunctions. The failure of individual components culminates in the dysfunction of the system, thereby leading to accidents. Additionally, the alteration of one component influences other components, which may, in turn, provide feedback to the original component. These components do not have a one-way impact on each other;

rather, they interact mutually. Weather and management practices are externalities that influence the safe system.

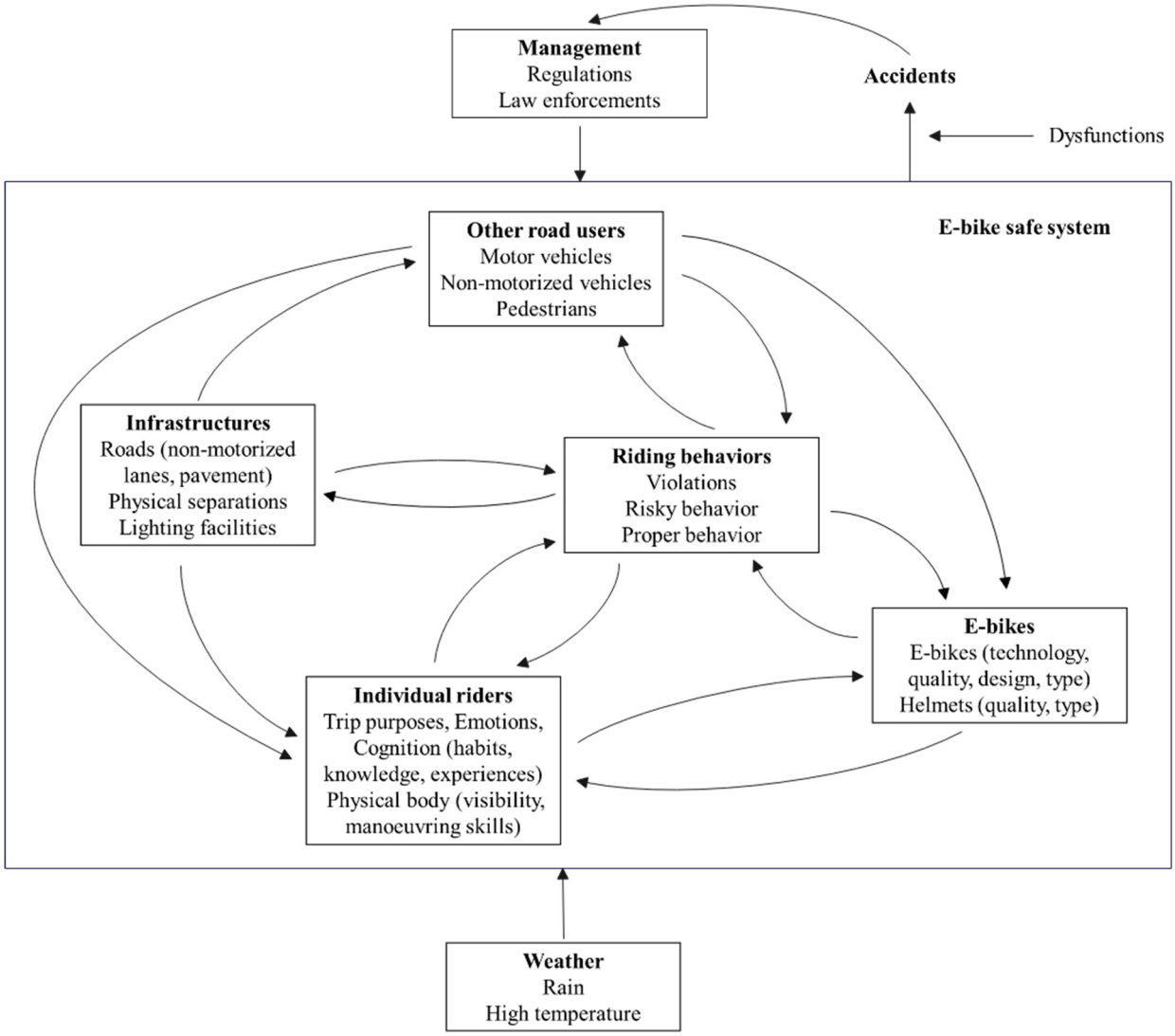


Figure 3. E-bike safe system.

Similar to safe systems designed for motor vehicles and bicycles, this safe system indicates that riders may make mistakes during riding, yet these mistakes are often influenced by various components of the system, and the responsibilities for accidents are shared.

Infrastructure also constitutes a fundamental component of the e-bike safe system, as in motor vehicle and bicycle safe systems [20,24]. Infrastructure encompasses three key elements: road conditions, physical segregation between non-motorized and motorized lanes, and dedicated e-bike facilities. The absence of dedicated non-motorized lanes and facilities has long been a pressing issue in China [32,40]. This is particularly evident in Guangzhou, where early urban planning failed to incorporate non-motorized lanes [98], a deficiency that continues to pose significant challenges to this day [99]. The implementation of exclusive e-bike lanes plays a crucial role in minimizing vehicular conflicts and enhancing traffic flow efficiency for all road users. Complementary facilities, particularly lighting systems, significantly contribute to safety by improving rider visibility and overall road safety conditions. While existing research predominantly emphasizes the unidirectional impact of infrastructure on riding behaviors, a reciprocal relationship exists wherein riding behaviors can substantially influence infrastructure conditions, potentially leading to safety

incidents. For instance, improper riding behaviors may result in infrastructure damage, such as breaking protective barriers, which in turn can create hazardous conditions that contribute to accident occurrence.

E-bike technology and material composition represent critical components within the safe system. Interestingly, while the material properties of e-bikes have been extensively examined in design research, they have rarely been integrated into transportation safety studies. Our analytical model reveals complex interactions between e-bikes and their riders' behaviors. E-bikes provide enhanced mobility characteristics, including greater flexibility, increased speed, and improved maneuverability. While e-bikes have expanded mobility access for diverse age groups, including seniors and younger riders, they simultaneously demand heightened kinesthetic control, physical coordination, and sustained attention. On the other hand, riding behaviors significantly influence e-bike conditions through mechanisms such as brake degradation and component wear. Safety equipment, particularly helmets, plays a crucial role in mitigating accident severity by substantially reducing the risk of fatal injuries. However, helmet usage presents practical challenges, especially during warmer seasons when discomfort may deter consistent use. Furthermore, safety concerns are exacerbated by the prevalent practice of illegal modifications aimed at increasing speed capabilities, which compromises both vehicle integrity and road safety.

Riding behaviors constitute a pivotal element within the e-bike safe system framework. Distinct from motor vehicle safe systems, speed regulation alone does not adequately address e-bike safety concerns. The inherent vulnerability of e-bike riders, coupled with limited physical protection, renders them susceptible to severe injuries even in low-speed collisions. Various traffic violations and risky behaviors, including red-light running, unauthorized use of carriageways, and erratic lane changes, significantly contribute to accident severity. These behaviors demonstrate complex interactions with other system components [100]. The absence of dedicated infrastructure may compel riders to encroach upon motorized lanes, thereby increasing the risk of conflicts and accidents. Apart from other components that may lead to violations, rider behaviors can also influence the performance and safety of other components. For instance, different riding patterns can affect e-bike conditions, potentially creating accident-prone situations. Risky riding behaviors may also increase psychological pressure and tension among other road users, who must remain constantly vigilant and highly attentive to guard against the sudden appearance of e-bikes. Furthermore, the physiological adaptation to specific riding behaviors creates behavioral inertia, wherein cognitive awareness of risks often fails to translate into behavioral modification, presenting a substantial challenge for safety interventions.

Individual rider characteristics, encompassing trip purposes, physical attributes, knowledge bases, and established riding habits, significantly influence safety outcomes through their dynamic interactions with both riding behaviors and e-bike materiality. Beyond the direct impact of weather and lighting on physical condition and control ability, the accumulation of knowledge, experiential learning, and technical competencies over time fundamentally shapes riding patterns and safety outcomes. Trip purpose variability manifests in distinct riding patterns, with child-transporting riders typically demonstrating greater caution compared to delivery riders, whose economic dependence on timely deliveries may incentivize riskier behaviors.

Regulatory frameworks and enforcement mechanisms represent critical institutional components that impact on the e-bike safe system. The development of a specialized management system tailored to e-bike safety requirements is imperative, with particular emphasis on enhanced enforcement of riding behavior regulations. While weather conditions and temporal factors constitute external variables beyond direct transportation sector control, our model reveals their substantial influence on both system components and their

interactions. This finding underscores the necessity for future research to investigate the resilience capacity of e-bike safe systems in adapting to these environmental variables. Weather and time are uncontrollable factors. As a result, both riders and drivers should exercise heightened caution during rainy conditions and at nighttime.

6. Conclusions

The escalating prevalence of e-bike accidents has presented substantial challenges to contemporary transportation systems. The proposed safe system approach for e-bike demonstrates distinct characteristics from both traditional bicycle and motor vehicle safe systems, particularly in its emphasis on all risky riding behaviors as components due to the vulnerabilities of e-bike riders, rather than focusing predominantly on speed regulation, which aligns with the bicycle safe system. Additionally, compared to traditional bicycles, the materiality of e-bikes themselves is a crucial component. The inherent characteristics of e-bikes are also an integral part of the safety system. Furthermore, our framework identifies the human body as a distinct critical component, recognizing the distinction between embodiment and behavioral patterns.

This study extends beyond component identification to examine the complex interactions among system elements, revealing both short-term and long-term effects that significantly influence safety outcomes. While individual rider errors contribute to accidents, the causation also lies in systemic dysfunctions resulting from component interactions. This systemic perspective suggests that e-bike safety interventions in Guangzhou should transcend accident-based single-component solutions, necessitating comprehensive strategies that particularly address three critical areas: e-bike infrastructure development, riders' social relations, and behavioral modification programs.

The objective of the safe system approach is to systematically mitigate traffic-related accidents while enhancing overall road safety through comprehensive, multi-layered control. This study develops a conceptual framework for assisting local authorities in designing and implementing systemic safety interventions in the future management of e-bikes, contextualized within Guangzhou's specific urban environment. Therefore, we recommend integrating the e-bike safe system into future management strategies, with a specific focus on two critical enhancements: (1) systematic integration of e-bike mobility with the contemporary transportation system, with particular emphasis on improving the specialized infrastructures and (2) implementing targeted interventions focusing on rider-centric and associated systemic components, with particular emphasis on establishing compulsory safety education curricula and strengthening comprehensive law enforcement mechanisms.

A comprehensive improvement of infrastructure for e-bikes is essential, including the addition of non-motorized lanes, signage, left-turn waiting a reas, and lighting. Providing isolated spaces for riders to separate them from other road users is crucial. For newly planned areas, providing spacious and dedicated non-motorized vehicle lanes is essential, whereas in downtown Guangzhou, the current carriageways do not adequately accommodate the demands of private cars and public transport. Thus, in such regions, a viable solution is to slightly reduce the width of each motorized vehicle lane to create non-motorized lanes on the sides. Additionally, when the non-motorized vehicle lanes are particularly narrow, refrain from adding physical barriers, as this may discourage riders from using them. The design of non-motorized lanes must ensure path connectivity so that riders can continuously use these lanes without interruption. Left-turn waiting areas are also required to prevent conflicts between left-turning e-bikes and motor vehicles [40]. For traffic facilities, it is important to ensure adequate lighting during nighttime and in rainy days.

Education on formal traffic rules and proper riding behaviors can enhance riders' understanding of safety and social responsibilities. Practical training and examinations can improve the riding skills of novices [12]. Programs are suggested to be tailored to different rider groups based on their trip purposes. This targeted approach ensures that diverse groups, such as commuters, delivery riders, and recreational riders, receive appropriate training and support to promote safer riding practices. For instance, regular road safety education sessions could be conducted for students in schools. Furthermore, it is imperative to enhance the dissemination of road safety knowledge and intensify public awareness campaigns regarding road behavior safety.

Implementing licensing systems and video surveillance to monitor e-bikes is recommended to support traffic police in their supervisory duties [40]. First, it is essential to ensure that all e-bikes are properly registered, and to update the license plate recognition algorithms for e-bikes. Secondly, it is crucial to ensure the proper deployment of surveillance cameras. It is imperative to strictly prohibit e-bikes from entering urban expressways, highways, and other roads with high vehicle speed limits. It is also important to increase the penalties for violations and ensure their strict enforcement. In terms of the violation behaviors of food delivery riders, it is essential to regulate platform companies to reduce the pressures on food delivery riders. Currently, food delivery companies pay workers based on their efficiency. New workers often lack adequate training. Therefore, regulations should be established to protect the rights and well-being of delivery riders.

In addition to strengthening law enforcement regarding riding behaviors, implementing comprehensive quality control measures for e-bikes is equally essential. This includes establishing stringent regulations to prohibit illegal modifications of e-bikes, which pose significant safety risks. Furthermore, the introduction of a mandatory annual inspection system would ensure the ongoing maintenance of e-bike quality standards and operational safety.

Given Guangzhou's geographical location, special attention should be paid during extreme weather conditions, such as typhoons and heavy rain. Issuing preemptive warnings to advise people against going outdoors based on weather forecasts is crucial. It is also important to enhance the design of e-bikes by incorporating more slip-resistant tires. Additionally, close attention should be paid to the materials used for road surfaces when constructing new roads.

Furthermore, establishing a comprehensive indicator system for components within the e-bike safe system framework is essential for assessing how its integration into local management practices can enhance e-bike safety performance.

The present study has several limitations and suggests directions for future research. First, the qualitative component did not include individuals who had experienced severe incidents. Second, the study did not examine the effects of individual attributes (e.g., age, gender, and riding experience) and individual psychological factors on travel behaviors. Future research should address these limitations. This comprehensive approach will provide a more holistic intervention to e-bike accidents.

Author Contributions: Conceptualization, B.J. and J.L.; methodology, B.J.; software, B.J. and Q.W.; validation, B.J. and Q.W.; formal analysis, B.J.; investigation, B.J.; resources, B.J. and J.L.; data curation, B.J. and Q.W.; writing—original draft preparation, B.J.; writing—review and editing, B.J.; visualization, B.J.; supervision, J.L.; project administration, J.L.; funding acquisition, J.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Science and Technology Planning Project of Guangdong Province, grant number 2023B1212060029.

Data Availability Statement: Data are not available due to a confidentiality policy.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

E-bike	Electric bike
BN	Bayesian network
SRS	Supplemental Restraint System

Appendix A

Appendix A.1

Table A1. Code of interviewees.

Riders Who Make Living by E-Bikes			Residents		
Number	**Gender**	**Job Duties**	**Number**	**Gender**	**Road Users**
FD1	Male	Meituan food deliverer	RD1	Female	Private car driver
FD2	Male	Meituan food deliverer	RD2	Male	Private car driver
FD3	Male	Meituan food deliverer	RD3	Male	Private car driver
FD4	Male	Meituan food deliverer	RD4	Male	Didi * driver
FD5	Male	Meituan food deliverer	RD5	Male	Bus driver
FD6	Male	Meituan food deliverer	RD6	Male	Bus driver
FD7	Male	Meituan food deliverer	RD7	Male	Didi driver
FD8	Male	Meituan food deliverer	RD8	Male	Taxi driver
FD9	Female	Campus food deliverer	RB1	Male	Bicyclist
FD10	Male	Meituan food deliverer	RB2	Female	Bicyclist
FD11	Male	Meituan food deliverer	RP1	Male	Pedestrian
FD12	Male	Meituan food deliverer	RP2	Female	Pedestrian
FD13	Male	Meituan food deliverer	RE1	Male	E-biker
FD14	Male	Meituan food deliverer	RE2	Male	E-biker
FD15	Male	Pupu food deliverer	RE3	Male	E-biker
FD16	Male	Pupu food deliverer	RE4	Male	E-biker
FD17	Male	Pupu food deliverer	RE5	Female	E-biker
FD18	Male	Pupu food deliverer	RE6	Female	E-biker

* Didi: Chinese online car-hailing service company.

Appendix A.2 Interview Outline

The outlines of the interview (including but not limited to):

Researcher: We represent a research team from the School of Intelligent Systems Engineering at Sun Yat-Sen University, specializing in the investigation of safety challenges associated with e-bike usage. Before commencing this session, we would like to outline several important protocol details: First, this interview will be recorded in its entirety for research purposes. Second, all collected data will be used exclusively for academic research, with no commercial applications. Third, we will implement strict confidentiality measures, ensuring that all personal identifiers are anonymized in any subsequent publications or reports. The estimated duration for this interview is approximately 20–30 min. May we proceed with your consent?

1. Could you tell us how long have you been riding e-bikes? If so, when did you begin? How often do you use and for what purpose?
2. Do you think e-bike safety is an important issue that we should do something about?
3. Have you experienced any accidents? If so, can you tell me the process of how the accident actually happened? It will be helpful if you tell me the details, for instance, the traffic situation, the riding process. And have you tried to avoid accidents, and how did you try?

4. Have you had risky experiences, not accidents but only risky experiences? If so, can you tell me some of the risky experiences you have had? It will be helpful if you tell me the details.
5. What are the major factors you think are significant related to accidents or risk situations? Such as infrastructure? The situation of e-bikes? Traffic?
6. We are aware that many people say violations and improper riding behaviors are the most important factors leading to accidents, including not wearing helmet. What do you think? Have you ever done so? Why? Do you think it is difficult to ride safely, such as slowing down, or wearing a helmet? Have you been troubled by other riders' riding behaviors?
7. What do you think are the differences of e-bike riders' roles in accidents or risky situations? For instance, is there any difference between delivery riders and residents?
8. Are physical fitness, knowledge, and riding habits important? Why?
9. Do you think the condition of e-bikes and helmets plays an important role in accidents? Why? Can you give me a few examples?
10. Do you think that riders can also have an impact on the situation of e-bikes? Or infrastructure? Does riding behavior influence the situation of e-bikes?
11. What you think how other road users' roles in e-bike accidents and why?
12. How important do you think infrastructure is in e-bike accidents and why?
13. If you give suggestions to the government, what should be included in the regulations? For instance, regulating riding behaviors. Do you think it is necessary to consider other aspects?

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