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Case Study on the Traffic Collision Patterns of E-Scooter Riders

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Abstract

In recent years, nonmotorized transportation and micromobility have become increasingly popular in urban areas, and bike sharing and e-scooter usage are more affordable and accessible than ever before. However, users of these modes face several significant challenges, including risky riding behavior and the danger of being involved in collisions or near collisions with other motorists. Because of a lack of relevant data sets, it is difficult to comprehend the underlying causes of e-scooter collisions. This study collected narrative descriptions of 24 e-scooter collisions that occurred in Texas in 2021. The perceptual cycle model (PCM) was applied to these narrative crash reports to analyze the causation patterns of the crash occurrences. The PCM mechanism was applied independently to fatal and injury collisions, and the results were then compared with Haddon's matrix to develop policy recommendations. The novel approach proposed in this study can be widely utilized by road safety professionals to understand the causal relationships behind other key road safety issues.

Keywords

e-scooter, safety, perceptual cycle model, crash

In recent years, the proliferation of e-scooter-sharing systems has ushered in a new era of urban mobility, with nonmotorized users playing an increasingly vital role in this. However, the safety of these users has become a growing concern considering the alarming number of e-scooter-related injury collisions reported worldwide. Despite the surge in e-scooter ridership, the lack of appropriate crash data has hindered efforts to determine the influence of the built environment and socioeconomic factors on e-scooter safety. Thus, the aim of this study is to examine the causation patterns of e-scooter collisions.

Traffic crashes are complex phenomena that have long been the subject of extensive research. E-scooters, because they are a vulnerable micromobility system with high speeds and limited protection, warrant particular attention in this regard. The intricate nature of urban infrastructure further emphasizes the importance of understanding the causal patterns of e-scooter-associated traffic crashes. Conventional crash data analysis techniques are insufficient for discerning the key contributing factors, given the nonlinear interactions that characterize dynamic and complex transportation systems. As such, this study employs the perceptual cycle model (PCM), a sociotechnical approach, and Haddon's matrix to unravel the causation patterns of e-scooter collisions.

As of 2021, Texas boasts 15 operational e-scooter systems, and the Texas Department of Transportation (TDOT) has updated its Crash Records Information System (CRIS) to include a new flag that can identify e-scooters involved in collisions. This study collects e-scooter crash data and police-reported crash narrative data from Texas in 2021 using this filter. It should be noted that e-scooter crash records were not previously

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included in crash databases, making it difficult to identify e-scooter-related collisions before 2021. Nonetheless, the 2021 CRIS database reveals a total of 24 crash records involving e-scooters, and this study applies the PCM mechanism to the crash narrative reports to identify the causal patterns associated with e-scooter collisions. Finally, the study compares its findings with the conventional Haddon's matrix results to offer novel insights into the e-scooter crash phenomenon.

Literature Review

This study conducted a brief literature review that highlighted two topics: (a) e-scooter safety-related studies; and (b) transportation studies on the PCM.

E-Scooter Safety Studies

Most earlier studies have utilized data from emergency department visits to characterize the intricate nature and prevalence of fatalities and injury severity associated with e-scooter collisions (*1–4*). Two other critical data sources used in the related literature are the National Electronic Injury Surveillance System (*5*, *6*) and news articles (*7*). Very few studies concentrate exclusively on traditional police-reported crash information to determine the actual crash mechanisms of e-scooters (*8*, *9*). The potential reasons for this could be limited data availability (*7*) and difficulty in identifying e-scooter crashes (*8*). The primary focus of studies on e-scooter safety is on the risk factors related to e-scooter crashes, and these can be specified and derived from crash reports produced by the police.

It has been well documented that young e-scooter riders are more likely to be involved in collisions than older age groups (*7*) because of the emerging popularity of this travel mode among younger people (*10*, *11*). Studies have reported that the highest share of e-scooter fatalities and injuries are found among riders aged 18 to 40 (*12*, *13*). Males are often associated with risky e-scooter riding behavior (*4*, *8*) and, therefore, they predominate in the samples of injured e-scooter riders (*4*, *14*). However, it is important to mention that describing the e-scooter riders as exhibiting risky behavior is often a biased statement. In many cases, roadways have not been designed with sufficient facilities for e-scooters or other nonmotorist movements. One possible reason for the increased probability of injury when riding e-scooters is traveling at high speeds on the road compared with sidewalks (*15*). Multiple studies have highlighted the low rate of helmet usage among e-scooter riders (*16*, *17*), because this significantly increases the risk of head injuries (*18*). It should be noted that there is no compulsory law on helmet usage for e-scooter users in the U.S.A. With regard to impaired riding, a few studies have reported a high rate of alcohol or drug involvement (*19*, *20*), whereas others found an insignificant association between impairment and crashes that resulted in injuries (*4*). Police investigation officers often face difficulties in determining the degree of intoxication during a crash because of the time delay after a collision (*9*), which could explain the inconsistent findings in the literature.

Crashes involving e-scooters that result in injury are more common during the summer because of favorable weather conditions and increased tourism (*8*). The rate of e-scooter usage is at its peak during weekends (*21*), and as a result, most collisions occur on these days (*14*). With regard to the overall time distribution of e-scooter crashes, the afternoon and evening (noon–9:00 pm) are the most vulnerable hours (*8*, *22*). However, fatal and injury crashes are found to increase after 7:00 pm and hold a significant share until 5:00 am (*9*). This pattern indicates the significance of visibility in e-scooter crashes, because most serious injuries happen at night. The findings are found to be consistent in relation to weather, because most of the e-scooter fatalities have been observed to take place in adverse weather conditions (*9*). Cicchino et al. (*4*) reported that poor surface types, such as uneven pavements and potholes, could contribute significantly to e-scooter crash incidence. Additionally, Shah et al. (*8*) inferred that enhancing intersection design for slow-moving vehicles on the basis of geolocation information for e-scooter collisions could significantly reduce the frequency of impacts.

Several studies have highlighted the factors contributing to e-scooter crashes and also the safety concerns in relation to roadway factors, motor vehicles, pedestrians, and other road users. Roadway conditions, lack of sufficient space, and improper braking have been identified as contributors to e-scooter crashes involving obstacles such as drains, potholes, and curbs (*23*). A high percentage of collisions involving motor vehicles and e-scooters have been found to result in e-scooter riders sustaining serious injuries or becoming fatalities (*14*). The number of crashes increases when riders travel straight ahead, turn right, or approach to enter crosswalks (*8*). The interaction between pedestrians and e-scooter riders is highlighted as a major safety concern (*24*) because most e-scooter users travel on sidewalks (*25*). However, further research is needed to understand the vulnerability of other road users when e-scooter riders are in front of them (*26*).

PCM Studies

Sociotechnical approaches such as the PCM are gaining popularity among transportation safety researchers. In 1976, Neisser (*27*) proposed that the human thought process and interactions with the outside world are inextricably linked and mutually inform one another in a cyclical relationship (*28–31*). Developing an "in context" understanding of this interaction necessitates considering both the operator and the environment.

Banks et al. (*32*) investigated the circumstances surrounding a fatal crash involving a Tesla car in May 2016 using schema theory and the PCM. According to the analysis, the crash was caused by an error in the design of the car's autopilot feature. Scott-Parker et al. (*33*) investigated the need for situation awareness skills in relation to young novice ambulance drivers, using a hierarchical task analysis and a PCM. The findings revealed that insufficient of these skills has a negative impact on safety and that complex environmental information alters the driver's "world" schema, influencing their actions. Revell et al. (*34*) used the PCM to investigate how drivers adapt to changing relationships with their vehicles by conducting an on-road study in a semi-autonomous vehicle and using the "think aloud" technique. Another study found evidence for the existence of a "counter cycle" (*29*). Damman and Steen (*35*) studied the sociotechnical processes that structure ports' efforts to become zero-emission energy hubs using the multilevel perspective (MLP), and found that the scope for new solutions for individual ports is influenced by geographical factors and institutional work interactions.

Debnath et al. (*36*) analyzed pedestrians' underlying cognitive processes and their interactions with other road users using the PCM. The factors that affected decision-making in relation to various road segments were identified. Several environmental obstacles (i.e., street vendors, lack of shade, trash blocking the walkway, deteriorating pavement condition) hindered the use of the sidewalk and contributed to riskier road behavior. Wu et al. (*37*) employed sociotechnical transition theory and the MLP technique to illustrate the interaction between niche, regime, and landscape and to predict future trajectories for the transition to new energy vehicles. The early development period (2001–2011), the take-off phase (2012–2020), the acceleration phase (2021–2035), and the final spring phase (2036-later) were recognized. Ceylan et al. (*38*) utilized a systems theoretic accident model and process (STAMP) model to investigate a ship accident that occurred in confined waters. It was demonstrated that complex system accidents are system-based, dynamic, and complex events. McKerral and Pammer (*39*) employed a preexisting system based on the PCM to discover elements contributing to the development of driving skills. They discovered that specialists and experienced drivers update their schemas of the driving task differently, although they use the same amount of effort. In addition, there were significant variations in gaze content. Duarte et al. (*40*) created a technique to assist local governments in expanding public participation and enhancing residents' commitment to the city. They also studied and contrasted a set of initiatives used by municipalities to promote citizens' engagement. Using linear regression, support vector machine, and neural networks, Tawfeek (*41*) attempted to model unassisted drivers' speed at the yellow light onset to improve applications for connected and autonomous vehicles at signalized crossings and optimize drivers' comfort. The neural network model was determined to be the best model, and the results of the investigation suggested that the speed at the commencement of the yellow light may be predicted using behavioral data and drivers' perceptual abilities. Hamim et al. (*42*) studied a level crossing event in Bangladesh utilizing a mixed methods approach comprising AcciMap, a combined STAMP–CAST (causal analysis using systems theory) technique, and one cognitive approach, the PCM. Each method provided unique insights into the situation, enabling the identification of several contributing variables.

Although Haddon's matrix has been extensively studied, previous research has not explored its association with the PCM in the context of crash narrative reports, and although the PCM has been adopted in transportation safety research, its application to e-scooter collisions remains unexplored. To fill the gap, this study aims to investigate causal patterns of e-scooter collisions and link them with Haddon's matrix using the PCM. By utilizing both approaches, the study makes a unique contribution to the field and can serve as a starting point for future research on the causes of e-scooter crashes.

Methodology

The PCM

The PCM proposes a relationship between the world, schema, and actions, as shown in Figure 1. According to Neisser (*27*), this relationship involves both top-down (TD) and bottom-up (BU) processing. TD processing occurs when a schema is activated, and specific information is anticipated. BU processing, in which actions are taken to find information that fits within the constraints of the current schema, follows. If what is observed conflicts with expectations based on an existing schema, either the schema needs to be changed or an alternative schema must be chosen. For a more in-depth explanation of the conceptual background of the PCM, we recommend consulting Neisser (*27*).

The purpose of this paper is to highlight the advantages of the PCM as a framework for analyzing e-scooter collisions. Additionally, it aims to demonstrate how generalized suggestions for safety improvement can be created, drawing inspiration from the three components of the PCM (schema, world, and action) and acknowledging their interdependence.

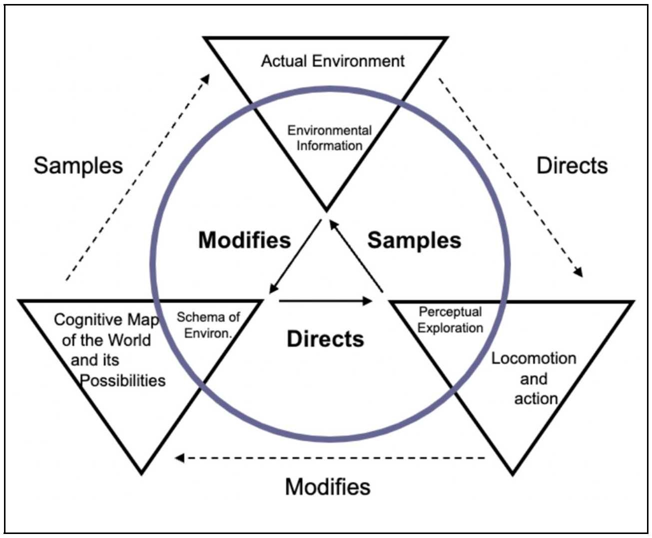

Figure 1. Schematics of the perceptual cycle model (PCM).
Note: Environ. = Environment.

The PCM is a sociotechnical approach that allows for a comprehensive and nuanced analysis of complex systems such as transportation systems. It considers both the technical and social aspects of a system, making it very suitable for understanding the intricate nature of e-scooter collisions. On the other hand, Haddon's matrix is a widely used framework that provides a systematic approach for studying events that cause injuries, including traffic collisions. It helps in identifying the factors that contribute to collisions and their effects, and it enables the development of countermeasures to prevent or mitigate injuries. By comparing the findings of the PCM with those of Haddon's matrix, this study aims to offer a novel perspective on the e-scooter crash phenomenon and provide insights for effective safety interventions.

Data Collection and Analysis

This study gathered data on e-scooter collisions in 2021 from CRIS, which is maintained by TDOT. The study then used the e-scooter filter to identify 24 relevant collisions. CRIS is widely recognized as a reliable source of traffic crash data and is frequently utilized by TDOT and other research agencies. The data were subjected to a rigorous review process to ensure accuracy, and this study used the final clean 2021 CRIS data set for the analysis. Although the study took great care to include all relevant collisions, it is possible that some incidents may not have been tagged or reported to the police. However, no relevant information on misclassification is available in the CRIS database.

Figure 2*a* shows that 58% of the 24 collisions occurred at 30 mph (14 collisions), 21% occurred at 25 mph (5 collisions), 13% occurred at 35 mph (3 collisions), and 8% occurred at 40 mph (2 collisions). This distribution is expected because most of the e-scooters operate on roadways with speed limits that range from 15 to 30 mph (*4*). With regard to lighting conditions, 42% of collisions occurred in daylight conditions, which is inconsistent with Shah et al. (*8*). This could be because the riders feel more comfortable using e-scooters in good weather and daylight conditions (*14*). Of the collisions, 13% occurred in the dark but with no lights, and 4% occurred in other conditions (Figure 2*b*). In relation to location, 46% occurred at intersections, 25% were related to intersections, 17% were

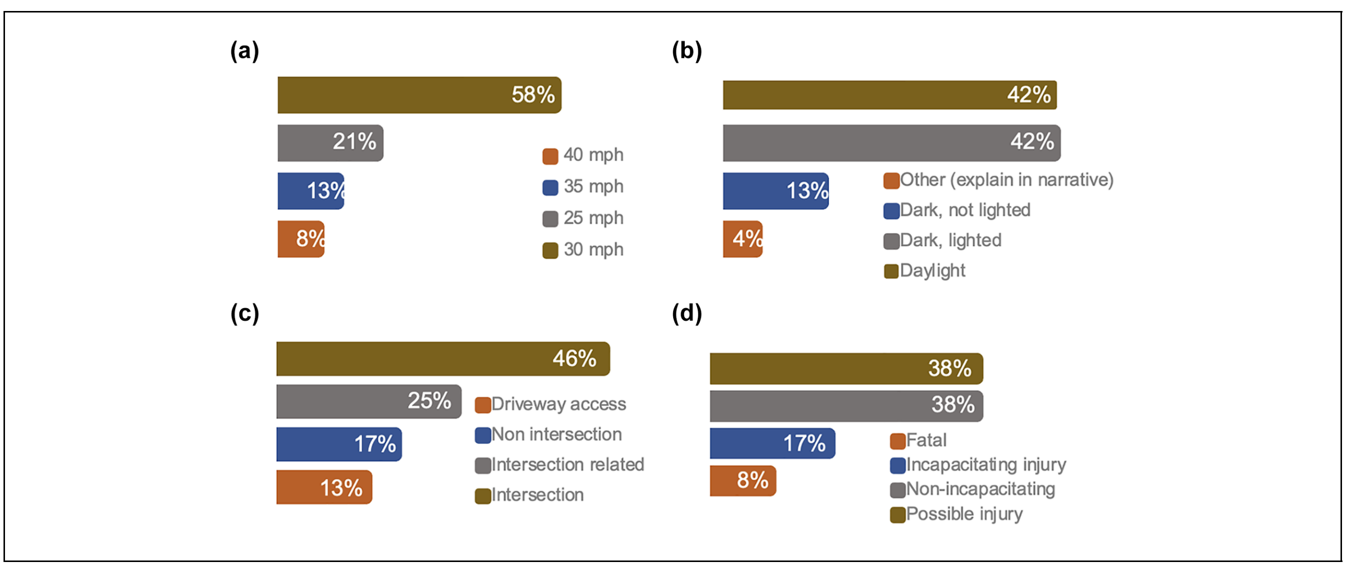

Figure 2. Distribution of key factors: (*a*) crash speed limit, (*b*) lighting condition, (*c*) location, and (*d*) severity type.

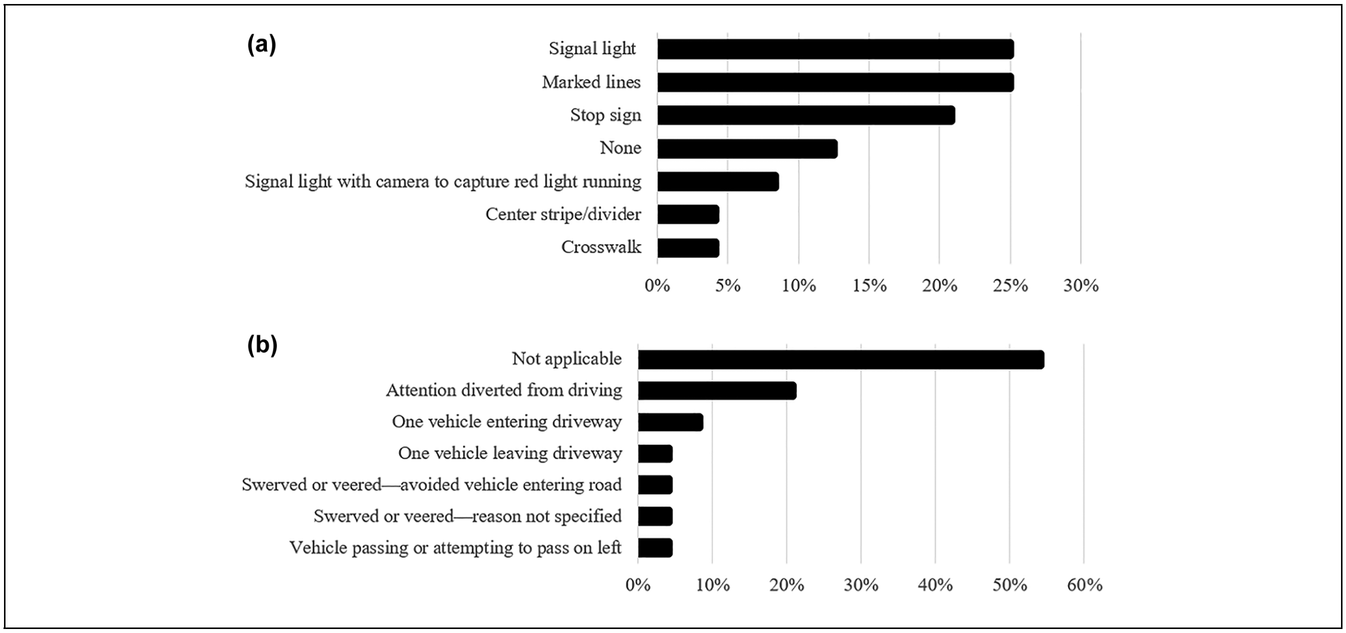

Figure 3. Traffic control device and hazardous action: (*a*) traffic control device, and (*b*) hazardous action.

not at intersections, and 13% occurred where there was driveway access (Figure 2*c*). Because of the complex road environment, young e-scooter riders often face problems when turning right at intersections or managing speed when entering the road from sidewalks (*8*), which increases the risk of collision with motor vehicles (*4*). In relation to crash severity, the distribution follows the usual pattern seen here: possible injuries and nonincapacitating injuries occurred in 38% of the collisions; incapacitating injuries occurred in 17% of the collisions; and fatal injuries occurred in 8% of the collisions (Figure 2*d*).

Figure 3*a* presents a breakdown of the types of traffic control devices present when e-scooter collisions occurred. Among the 24 collisions analyzed, signal lights were implicated in six incidents, whereas marked lanes played a part in six collisions. Stop signs were a factor in five of the collisions, and signal lights with cameras to capture drivers running a red light were implicated in two incidents. One crash involved center stripe/dividers, and crosswalks were a factor in another of the collisions. Notably, traffic control devices did not play a part in three of the collisions. Figure 3*b* details the hazardous actions that led to the e-scooter collisions. In five of the collisions, the driver's attention was diverted from the road, highlighting the dangers of distracted driving. In two of the collisions, a vehicle was either entering or leaving a driveway. Additionally, two collisions involved a vehicle attempting to pass on the left, whereas the reasons for swerving or veering were not specified in two other collisions. These findings emphasize the importance of addressing distracted driving and other hazardous actions to improve e-scooter safety on the roadways.

Results and Discussion

PCM Framework for Fatal (K) Crash Narratives

The intricate mechanisms of the PCM in two fatal e-scooter collisions (K1 and K2) are outlined in Figure 4 and Table 1. The first collision scenario, K1, involved a stop-controlled intersection with one straight and one left-turn lane. The driver, who failed to detect the rider, collided with the e-scooter when attempting a turn. The rider, who was under the influence of alcohol with a blood alcohol concentration (BAC) of 0.19, suffered fatal injuries. In the second fatal collision, K2, both the driver and rider were traveling straight in a segment location with marked lanes. However, the rider, who was traveling against the traffic, collided with a vehicle, and the impact caused the rider to be ejected onto the side of the highway. The driver, who was found to be intoxicated with a BAC of 0.20, survived the collision. Notably, impairment (either in the driver or the rider) was identified as the primary contributing factor in both fatal collisions. These findings emphasize the importance of addressing the issue of driver-impaired e-scooter operation and the need for effective interventions to improve e-scooter safety.

PCM Framework for Severe Injury (A) Crash Narratives

Figure 5 and Table 2 illustrate the PCM mechanisms in four serious injury collisions (A1–4). In all collisions, the vehicle was traveling straight, with typical "environmental information" identified. Three of these collisions occurred at signalized intersections (A1, A3, and A4) with signal

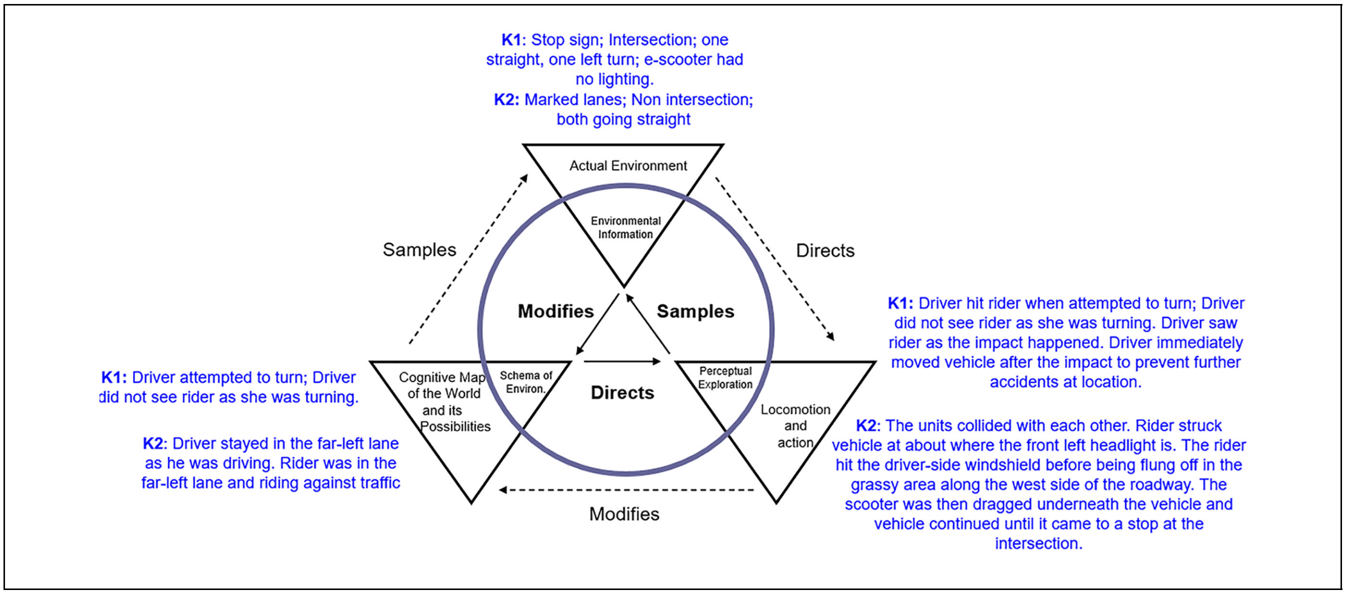

Figure 4. Perceptual cycle model (PCM) for fatal collisions.
Note: Environ. = environment.

Table 1. PCM Mechanism for Fatal Collisions

ID	World	Schema	Action	Aftermath
K1	Stop sign; intersection; one straight, one left turn; e-scooter had no lights.	Driver attempted to turn; driver did not see rider as she was turning.	Driver hit rider when attempted to turn; driver saw rider as the impact happened; driver immediately moved vehicle after the impact to prevent further collisions at location.	Driver did not provide details on the crash occurrence; rider was transported to hospital where he was pronounced deceased; rider had a BAC of 0.19.
K2	Marked lanes; not an intersection; both going straight.	Driver stayed in the far-left lane as he was driving; rider was in the far-left lane and riding against the traffic.	The units collided with each other; rider struck vehicle approximately where the front left headlight is; rider hit the driver-side windshield before being flung off in the grassy area along the west side of the roadway; the scooter was then dragged underneath the vehicle and vehicle continued until it came to a stop at the intersection.	Rider succumbed to his injuries at the scene and the driver was arrested for DUI; driver had a BAC of 0.20.

Note: PCM = perpetual cycle model; DUI = driving under the influence; BAC = blood alcohol concentration.

lights on. In two of the crash scenarios (A1 and A3), the driver was distracted from driving, which is a potential cause of the vehicle running a red light. The A4 crash scenario is associated with rider wrong way driving (WWD). As a result of this, a collision occurred between the two vehicles, causing the rider to sustain serious injuries (broken right femur and facial fractures). The remaining crash (A2) occurred at a segment and was driveway related. The main reason for the crash identified in this scenario was rider failure to yield the right of way to oncoming traffic.

PCM Framework for Moderate Injury (B) Crash Narratives

Table 3 lists the PCM mechanisms in nine moderate injury collisions (B1–B9). Seven occurred at intersections (stop-controlled: B2, B9; signalized: B4, B5, B6, B7, B8), whereas the remaining two took place at segments (B1) or had driveway access (B3). The primary contributors to the first two collisions (B1, B2) were speeding, reckless driving, and running a stop sign, and the driver was at fault in both incidents, which were also hit-and-run. The

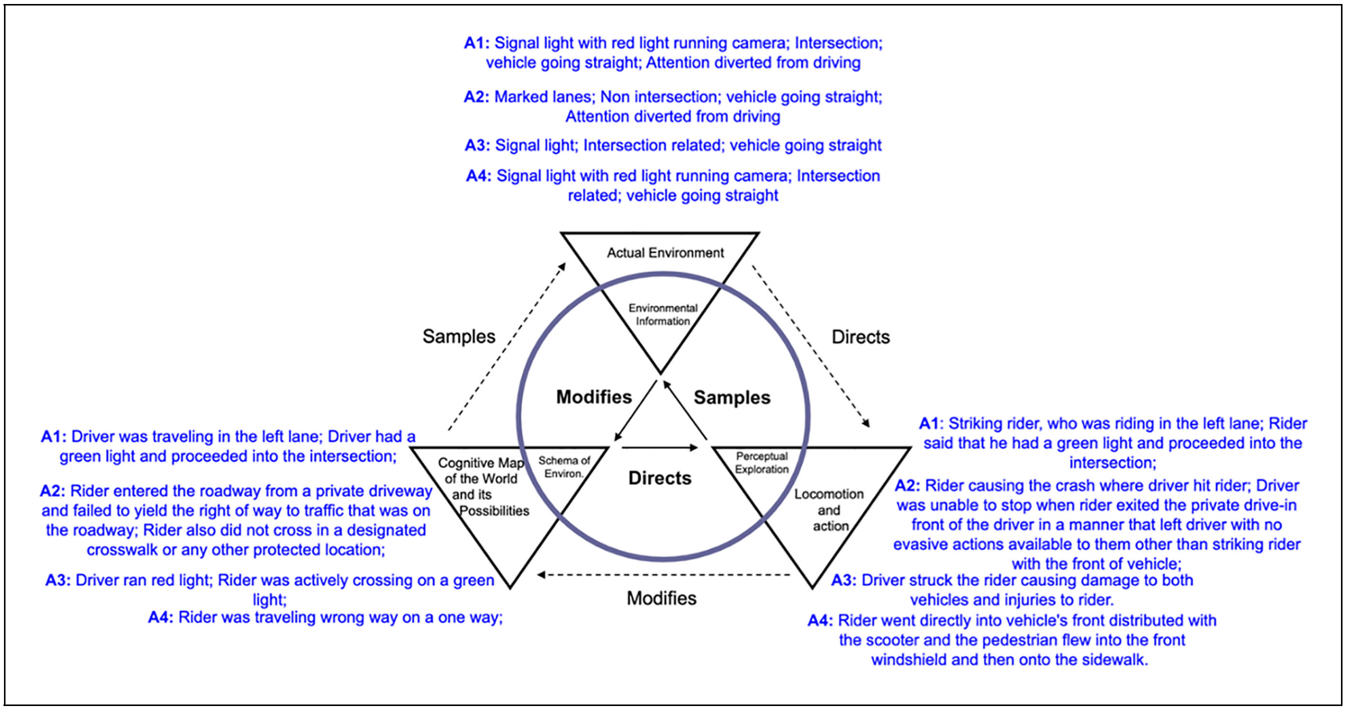

Figure 5. Perceptual cycle model (PCM) for severe injury crashes.

Table 2. PCM Mechanism for Severe Injury Collisions

ID	World	Schema	Action	Aftermath
A1	Signal light with camera to capture drivers running a red light; intersection; vehicle going straight; attention diverted from driving.	Driver was traveling southbound in the left lane; driver stated seeing a green light and proceeded into the intersection; the rider, who was traveling eastbound, also stated seeing a green light and proceeded into the intersection.	Driver struck the rider in the intersection.	Witness said that driver ran red light; no information with regard to injuries.
A2	Marked lanes; not an intersection; vehicle going straight; attention diverted from driving.	Rider entered the roadway from a private driveway and failed to yield the right of way to traffic that was on the roadway; rider also did not cross in a designated crosswalk or any other protected location.	Rider caused the crash in which driver hit rider; driver was unable to stop when rider exited the private drive in front of the driver in a manner that left driver with no evasive actions available to them other than striking rider with the front of vehicle.	Rider was transported for medical treatment, but was not cited at fault because his injuries meant there was no opportunity or ability to interview him.
A3	Signal light; intersection related; vehicle going straight.	Rider was traveling eastbound and ran a red light at an intersection; driver was traveling northbound.	Driver struck the rider causing damage to both vehicles and injuries to rider.	Citation issued to the driver; rider was transported to hospital.
A4	Signal light with camera to capture drivers running a red light; intersection related; vehicle going straight.	Rider was traveling the wrong way in a one-way segment.	Rider collided directly with the vehicle's front and hit the front windshield before landing on the sidewalk.	Rider had a broken right femur and facial fractures.

Note: PCM = perpetual cycle model.

Table 3. PCM Mechanism for Moderate Injury Collisions

ID	World	Schema	Action	Aftermath
B1	No TCD; not an intersection; both going straight; swerved or veered for reason not specified.	Driver was traveling at a high speed and was driving erratically; rider was traveling on the dirt shoulder.	Driver failed to drive in single lane and swerved off the roadway onto the dirt shoulder, striking the rider.	Driver failed to stop; rider was transported to hospital with apparent minor injuries; witness reported driver's erratic behavior and followed driver to where the hit-and-run vehicle was recovered.
B2	Stop sign; intersection related; other.	Rider was riding his electric scooter with his parents; rider was crossing the roadway and driver ran the stop sign.	Driver struck rider, knocking him off his scooter, and then left.	No information.
B3	Center stripe/divider; driveway access; vehicle turning right; one vehicle leaving driveway.	Driver was exiting parking lot to turn.	Driver proceeded forward at 1 mph and collided with rider.	No information.
B4	Signal light; intersection; vehicle going straight.	Rider was moving down the hill at a high speed yelling to another that she could not stop.	Rider collided with a vehicle.	Rider was injured on her left arm, elbow, and leg, but after evaluation by EMS on site was not transported to hospital; examination of the e-scooter revealed that the brakes were not working; e-scooter caused minor damage to the passenger rear of the vehicle; the vehicle was driven from the scene.
B5	Signal light; intersection related; one straight, one left turn.	Rider was riding an e-scooter in the cycle lane; rider began to cross the intersection with a green light, and she merged slightly to the right into the crosswalk; the car approached from her left.	Driver struck rider, causing her to fall off her e-scooter; the signal light was yellow as driver made the left-hand turn; driver hit his brakes and the rider fell off her scooter; driver stated that he believed he did not make contact with rider.	Rider was transported for medical treatment; rider had abrasions on her left shoulder; witness stated that he heard tires screech from rider applying brakes before he heard the metal scooter sliding against the concrete.
B6	Signal light; intersection; angle—both going straight.	Driver had a solid green light to cross over; rider was crossing over the intersection in a diagonal line from the southwest corner to the northeast corner.	Driver struck rider in the intersection; driver could not provide any details with regard to the accident and had possibly been drinking beforehand.	No information.
B7	Marked lanes; intersection; vehicle turning left; attention diverted from driving.	Driver was driving westbound; rider was coming through the intersection in an eastbound direction.	Driver failed to see rider and made contact in the intersection.	No information.
B8	Signal light; intersection; vehicle turning left.	Driver had a blinking yellow arrow when the vehicle proceeded through the intersection; rider was traveling across and had a green light; rider did not have headlights on or a lit headlamp on his helmet, and there were no streetlights, so the intersection was dark at the time of the collision.	Driver struck rider in the intersection; rider had right of way.	Police failed to determine who was at fault for this accident because both drivers committed traffic offenses.

(continued)

Table 3. (continued)

ID	World	Schema	Action	Aftermath
B9	Stop sign; intersection; one straight, one left turn; vehicle passing or attempting to pass on left.	Rider was attempting to turn; rider stated that there was no stop sign (there *was* a stop sign); rider went on the left side of vehicle, slowed down when he reached the intersection but did not stop, and then proceeded into the intersection; at the same time, driver started to make the left turn; the street was not illuminated by a street lamp; the intersection was dark at the time the crash occurred.	Rider collided with vehicle.	Driver stopped to ask why rider ran into his vehicle but did not exchange insurance information and then left the scene.

Note: PCM = perpetual cycle model; TCD = traffic control device; EMS = emergency medical services.

analysis of collisions at signalized intersection revealed various contributing factors such as mechanical failure of the e-scooter (e.g., brakes not working), at-fault riders (misjudgment of crossing, not following the signal timing, keeping headlamp off), and at-fault drivers (alcohol involvement, distraction, failure to see). In the case of crash B9, rider failure to see the stop sign because of poor visibility on the roadway, possibly caused by challenging environmental conditions such as lack of street lighting, led to human error and a collision.

PCM Framework for Minor Injury (C) Crash Narratives

Table 4 provides a comprehensive account of the PCM mechanisms in nine minor injury collisions (C1–C9). Of the nine collisions, six took place at intersections, with stop-controlled intersections accounting for two (C2, C8), a signalized intersection accounting for one (C1), and three unspecified types of intersections accounting for the remainder (C5, C7, C9). Two collisions occurred at a driveway access point (C4, C6), whereas the last one occurred at a segment (C3). Notably, in most of these collisions, both the rider and driver were traveling straight. Additionally, three major contributing factors were identified: driver failure to yield the right of way in two collisions (C2, C4); rider failure to yield the right of way in three collisions (C3, C6, C7); and traffic rule violation in two collisions (C1, C8).

The investigation of collisions at a stop-controlled intersections revealed various scenarios leading to collisions. Among these, crash scenario C1 was attributed to "driver distraction," causing a red light violation. Other collisions were linked to the failure of drivers or riders to yield the right of way, resulting in collisions at stop-controlled intersections (C2, C4, C6, and C8) or rear-end collisions (C3). One of the collisions (C8) also occurred because of challenging environmental conditions, that is, dense fog resulting in poor visibility. Additionally, one crash (C5) was caused by a rider suddenly appearing on the crosswalk. Although the emergency services (EMS) were only contacted for two collisions, and the rider was transported to hospital in only one crash, there is a lack of information with regard to the aftermath of four collisions (C5, C6, C7, and C9).

The major findings of the PCM analysis for the different injury types are listed below:

- In fatal collisions, a predominant factor appears to be intoxication, whether it be the rider or the driver.
- In serious injury collisions, a significant issue is riders failing to yield or riding in the wrong direction, combined with rider distraction. Additionally, driver distraction seems to play a large role.
- With regard to the moderate injury collisions, several of these appear to involve the rider crossing at an intersection. As far as collisions not at an intersection are concerned, either speeding or driveway access was involved. Additionally, there were two hit-and-run collisions.
- In minor injury collisions, it was observed that when the driver was at fault, the primary cause was running a red light or a stop sign. Conversely, when the rider was at fault, it was mainly because of failing to yield to the driver. Although it is true that some e-scooter collisions may occur because of rider failure to yield, it is important to note that the circumstances surrounding such incidents can be complex and multifaceted. For example, in many urban locations, e-scooters are used as a mode of transportation in highly congested areas with heavy vehicular traffic. In such situations,

Table 4. PCM Mechanism for Minor Injury Collisions

ID	World	Schema	Action	Aftermath
C1	Signal light; intersection; vehicle going straight; attention diverted from driving.	Driver was traveling northbound and ran a red light; rider was traveling eastbound.	Driver struck rider.	EMS on the scene; rider refused to be transported to hospital.
C2	Stop sign; intersection; vehicle going straight; swerved or veered to avoid vehicle entering road.	Driver failed to yield right of way at a stop sign.	Caused rider to swerve and fall off his e-scooter.	Driver fled the scene.
C3	None; not an intersection; angle—both going straight.	Rider failed to yield right of way.	E-scooter's front tire struck vehicle's back right tire.	No damage to either e-scooter or vehicle; rider complained about pain in her leg and was taken to medical center by EMS.
C4	None; driveway access; vehicle turning right; one vehicle entering driveway.	Driver attempted to turn right into a private driveway to an apartment complex when the rider was traveling the wrong way in the cycle lane; driver failed to yield right of way.	Rider collided with vehicle's passenger side mirror and fell off the scooter.	Rider was transported to a hospital with a potential right upper arm fracture.
C5	Crosswalk; intersection related; angle—both going straight.	Driver looked in both directions twice before moving forward to enter the intersection; driver advised rider appeared out of nowhere.	Driver immediately braked but could not prevent the collision; driver was still in the buffer zone; rider was using a rideshare rental scooter; rider saw driver had stopped and entered the crosswalk; rider was still on the scooter when he was struck.	No information.
C6	Marked lanes; driveway access; one straight, one right turn; one vehicle entering driveway.	Driver was preparing to turn into a parking lot; rider was riding an e-scooter on the sidewalk; as driver began to turn in to the parking lot, rider failed to yield the right of way to driver.	Rider collided with vehicle.	No information.
C7	Marked lanes; intersection related; angle—both going straight	Driver was traveling in the lane; rider was traveling on the sidewalk; driver failed to yield right of way to vehicle.	Rider failed to yield right of way to vehicle and collided with it.	No information.
C8	Two-way stop sign; intersection; vehicle going straight; attention diverted from driving; the weather that morning was poor, with dense and low fog and wet roadways, and visibility was limited.	Rider ran the stop sign.	Rider crashed into the driver's vehicle, causing damage; driver tried to help rider by calling 911.	Driver stated that rider said he was not okay but did not want her to do anything about it; driver stated that she was not injured and declined EMS; rider walked several yards up the road where EMS were able to make contact with him; EMS checked him and stated that his injuries were not life threatening; rider had a hurt arm and bumped his head; rider was transported to MC for his possible injury.
C9	Marked lanes; intersection; vehicle going straight.	Driver was traveling westbound in the outer right lane; rider rode onto the roadway.	Driver tried to avoid the rider and struck the rider's scooter slightly, causing the rider to fall.	No information.

Note: PCM = perpetual cycle model; EMS = emergency medical services; MC = medical center.

Table 5. Haddon's Matrix for E-scooter Crashes

Scenario	Human	Vehicle (e-scooter)	Roadway/physical environment	Socioeconomic
Pre-crash	Alcohol involvement (driver or rider), speeding, reckless driving, driver distraction, rider WWD	Headlamp off	Dark, no streetlight condition, dense fog	Speeding behavior, red light running, DUI
Crash	Failure to yield the right of way (driver or rider), running a red light or stop sign	Brakes not working	Lack of crosswalk at intersection, lack of designated travel lane, hill area	Helmet usage, provision of headlamp on helmet
Post-crash	Hit-and-run, high BAC	Lack of protection system	Driveway access point, parking lot	Police, EMS, 911, transport to MC

Note: WWD = wrong way driving; DUI = driving under the influence; BAC = blood alcohol concentration; EMS = emergency medical services; MC = medical center.

riders may face challenges in maneuvering through the traffic and making safe turns, especially if there are inadequate dedicated lanes or infrastructure for e-scooters. Moreover, the lack of proper signage or guidance for e-scooter riders can also contribute to accidents, because riders may not be aware of the proper right of way or other rules of the road. Additionally, external factors such as weather conditions or poor road conditions can make it challenging for riders to yield safely. In such cases, it is important to assess the specific circumstances of the incident and determine whether the rider had a reasonable opportunity to yield and avoid the crash. By examining all factors that may have contributed to the accident, it may be possible to identify areas for improvement to prevent similar incidents in the future.

Haddon's Matrix

Another objective of this research was to construct Haddon's matrix to capture the results obtained from the PCM model. Haddon's matrix was developed by Haddon and Kelley (*43*), and is a logical framework for analyzing motor vehicle-related injuries using fundamental public health concepts. The matrix consists of four columns and three rows. The four columns refer to the "interacting factors" that contribute to the injury process: human; vehicle; roadway/physical environment; and socioeconomic. The three rows represent the phases of the crash event: pre-crash; crash; and post-crash. Haddon's matrix for the e-scooter collisions is shown in Table 5.

Human Factors

Several key factors contributing to human behavior before, during, and after a crash have been identified. In the pre-crash phase, the human element plays a significant role in factors such as "alcohol involvement," "speeding," "reckless driving," and "WWD." In the event of a collision between an e-scooter and a motor vehicle, factors such as "failure to yield the right of way," "running a red light," and "running a stop sign" were observed. Finally, after the crash event, "hit-and-run" and "high BAC" were identified as crucial factors that influenced the severity of the crash. By recognizing and addressing these human factors, safety professionals can work toward improving road safety and reducing the incidence of collisions.

Vehicle Factors

Several critical factors associated with vehicle (e-scooter) features were identified in the pre-crash, crash, and post-crash phases. In the pre-crash phase, it was found that keeping the headlamp off may contribute to accidents, although continuing to do so may be the result of human error or a defective device. During the crash event, factors such as malfunctioning brakes were identified. Furthermore, the lack of protection systems in e-scooters was recognized as a crucial factor in the post-crash phase. These findings highlight the importance of identifying and addressing vehicle-related factors to improve e-scooter safety.

Roadway/Physical Environment Factors

Several interesting factors associated with the roadway or surrounding physical characteristics were identified. For example, the absence of street lighting in conjunction with heavy fog contributed to a pre-crash event, whereas the lack of clearly designated crosswalks and travel lanes was identified as a contributing factor during the actual crash. Further examination revealed that the post-crash event was influenced by factors such as driveway access and parking lot design. These findings highlight the importance of considering all aspects of the built environment when designing and implementing traffic safety measures.

Socioeconomic Factors

Several socioeconomic factors were also identified. For example, the cultural mindset incites "speeding," "running a red light," and "driving under the influence (DUI)," and these factors play a critical role before the crash event. During a crash event, the factors that influence the severity of collisions are "helmet usage" and "provision of headlamp on helmet." Finally, the involvement of police, presence of the EMS, calling 911, and transport to the nearest hospital play an important role in the after-crash phase.

Recommendations for Crash Countermeasures Based on Haddon's Matrix

Haddon's matrix provides a comprehensive framework for understanding the different factors that contribute to injury severity in e-scooter collisions. By examining each cell of the matrix, specific interventions can be identified and then implemented to mitigate risks associated with e-scooter use. One notable finding is the impact of alcohol consumption on e-scooter safety, which was identified in the human pre-crash cell of the matrix. Research has confirmed the dangers of alcohol-related impairment when operating an e-scooter, highlighting the need for effective prevention strategies to address this risk factor (*44*). Regardless of previous riding experience on an e-scooter, alcohol consumption before e-scooter use is linked to an elevated risk of brain injury and hospital admission (*45*). Studies have shown that drink driving by both motor vehicle drivers and e-scooter riders can result in reduced cognitive function and decision-making ability, and slow reflexes, which can lead to severe collisions, endangering public safety. To improve e-scooter safety, education, and enforcement of laws against alcohol use for e-scooter riders as well as motor vehicle drivers must be a priority. Roadway features such as poor lighting, high driveway density, and a lack of crosswalks have been associated with e-scooter collisions. Improving roadway features, for example, installing lighting at segments, intersections, and crosswalks, as well as introducing other nonmotorist-friendly treatments, would be helpful in improving e-scooter safety. Special provisions should also be made for reducing e-scooter riding speed according to different roadway contexts, especially in areas where they are allowed to operate at high speeds, as in Texas. Finally, promoting the use of helmets among e-scooter riders will play an essential part in reducing the severity of collisions.

Mechanical failure is a key factor in traffic collisions, and this has been incorporated into Haddon's matrix as a critical component in the vehicle crash cell. To ensure safe driving, regular inspections of brake pads or brake shoes are essential, and any signs of wear and tear should be addressed immediately through replacement. In some cases, even if the brake pads or shoes appear to be in good condition, adjusting the brake cables may be necessary to enhance their responsiveness and reduce the risk of collisions related to mechanical failure.

Conclusions

E-scooters, especially shared e-scooters, have recently emerged as a convenient and adaptable mode of transportation for short trips in dozens of cities and on university campuses. E-bike and e-scooter riders' behavioral safety is a major concern for traffic safety as a whole. The purpose of this study was to understand the causation patterns of e-scooter-related traffic injuries by applying the PCM to crash narrative reports produced by the police. The study explored the PCM mechanisms in five injury groups to identify causal patterns for e-scooter injury types. Impairment was found to be the key cause of fatal e-scooter collisions, and the analysis of the role played by alcohol was based on the available data and information at hand. Although this study acknowledges the limitations imposed by the small number of fatal crashes, it is important to note that it aimed to explore and provide preliminary insights into the potential association between impairment and fatal e-scooter crashes. The study did not make any definitive claims about the causal relationship or draw absolute conclusions because of the constraints imposed by the data availability. With regard to collisions resulting in injury, some key contributors were driver distraction, speeding, rider failure to yield, and rider WWD. Vehicle factors (e.g., headlamp off) and road environment (e.g., dark conditions with no lights, lack of crossing areas, driveway density) were also identified as causal factors. The recommendations based on Haddon's matrix can help authorities in decision-making and improving micromobility safety. It is important to note that there is no clear legislation or information on safe riding in cities. In this sense, better infrastructure could lead to safer interactions. Finally, road safety education could emphasize the promotion of safer practices and interactions to improve how riders perceive their behavior.

This study makes two unique contributions to the literature. First, it proposed an analytic framework using the PCM for a less explored safety area, namely, e-scooter safety. The central idea of the method is to incorporate injury severity detailed in traffic crash narrative reports into comprehensive PCM scenarios and then perform the corresponding narrative data processing and analysis to understand the causal patterns. The proposed framework is applicable to other data sets that contain information about further road safety issues; therefore, it can be used to mitigate the negative consequences of traffic collisions generally. Second, this study linked Haddon's matrix with the PCM to develop policy implications and decision support mechanisms. There are only a handful of studies that have explored causal patterns by performing an in-depth exploration of the limited available data. For example, Henje et al. (*46*) utilized videos and conducted in-depth interviews with 13 powered wheelchair (PWC) users aged 20 to 66. This study determined the underlying causal factors of collisions and identified obstacles in relation to human, vehicle (PWC), and environmental involvement in accordance with Haddon's matrix. Based on the findings of the current study, it is recommended that a detailed crash typing mechanism (e.g., similar to the Pedestrian and Bicycle Crash Analysis Tool) for e-scooter collisions be produced, so that key contributing factors can be determined and policies in relation to e-scooter mobility updated according to the findings from the collision and incident data collected for a specific geographic region.

Although this study contributes to a greater understanding of e-scooter collisions, there are limitations that must be addressed in future research. First, the sample size used in this study was limited, and future studies should aim to increase this by including multiple years of e-scooter crash data for better interpretation. Second, although the PCM was applied to understand the causal patterns, more detailed sociotechnical applications such as AcciMap can be used to develop advanced protocols at the policy level. Finally, the manual exploration of contents required for PCM analysis can be time consuming, and the use of natural language processing can expedite the process when dealing with large databases. Future research should explore its application in PCM analysis.

Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: S. Das; data collection: S. Das; analysis and interpretation of results: S. Das, A. Hossain, M. Ashifur Rahman; draft manuscript preparation: S. Das, A. Hossain, M. Ashifur Rahman, A. Sheykhfard, B. Kutela. All authors reviewed the results and approved the final version of the manuscript.

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