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ASSESSING RISK FACTORS FOR E-SCOOTER SAFETY: A WEIGHTED RISK MODEL BASED ON EXISTING LITERATURE

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Abstract

Cities globally are facing safety issues related to the rapid growth of e-scooters as a mode of micromobility. This paper proposes a systematic weighted risk assessment framework for evaluating and prioritizing e-scooter safety risk factors based on a structured review of 19 peer-reviewed studies published from 2020 to 2024. These studies were retrieved from Scopus, Web of Science, and Google Scholar databases based on specific inclusion criteria. Four risk factor domains were identified: vehicle, rider, infrastructure, and environment. The risk factor weighting scores were allocated from 1 to 10 based on four specific weighting criteria: severity of impact, frequency of occurrence, cross-study consistency, and dependency. Sensitivity analysis was conducted on the assigned weight factors to evaluate the internal validity and robustness of the proposed weighting framework. The top-ranked risk factors based on their weights were alcohol impairment (9), speeding (8), poor road conditions (8), lack of dedicated lanes for micromobility (8), and helmet non-compliance (8). Rider behavior and infrastructure issues dominated the risk factor ranking. This ranking was consistent for all the sensitivity analyses performed. The proposed framework provides a transparent model for synthesizing evidence from various sources to guide data-informed decision-making for urban policy and infrastructure planning.

Keywords: micromobility safety, E-scooter risk assessment, weighted risk mode

1 Introduction

New challenges have arisen for transportation safety management with the rapid adoption of e-scooters in city transit networks and with the increasing number of e-scooter accidents. French police data shows that between 2019 and 2022 a total of 4,118 collisions occurs by the micromobility riders like e-scooters [1]. Based on the existing literatures, the main factors causing accidents include alcohol consumption, lack of experience, poor infrastructure design, and unstable e-scooters. For instance, studies in Germany found that the majority cause of e-scooter accidents was because of alcohol consumption [2]. Records of 268 e-scooter accidents by the German emergency department show that 58% e-scooter accident injuries were head or facial injuries for the riders with alcohol consumption being common for those involved [3]. Worldwide alcohol consumption is involved in most of the fatal e-scooter accidents [4]. Another risk factor is risky rider behaviors, as it was found by a naturalistic study of 500 vehicle-e-scooter accidents that rider inexperience and unpredictable movements were the main cause of accidents [7]. Collision risks increase when e-scooter riders combine walking and riding [4].

Infrastructure design impacts accident rates significantly, due to the scarcity of dedicated micromobility lanes e-scooter riders break traffic laws and use incorrect lanes which is the primary cause of accidents severe injuries are caused by frequent e-scooters crashes on cobblestone streets and slippery surfaces [3]. Also, studies indicate e-scooter accidents related to road hindrances and surface irregularities can be reduced by the maintenance of road surfaces and dedicated micromobility lanes [1, 13]. Furthermore, proper urban design and developed infrastructure safety measures being prioritized in transportation systems help to lower e-scooter and micromobility usage safety risks [14].
The e-scooter's safety also heavily depends on their structure and design, when having accidents unique injury patterns were experienced by the e-scooter riders based on crash-test simulation research with the existence of a higher center of gravity than cyclists and pedestrians during collisions [13]. The severity of crashes resulting in fatal outcomes increases due to higher vehicle speeds combined with limited maneuverability based on German crash statistics [2]. Hence higher crash rates and more severe injuries are results of vehicle speed and maneuverability combined with rider behavior [12]. Only limited research frameworks have been developed that prioritize the risk factors in an integrated comparative framework. This research aims to contribute to this field by proposing a clear and reproducible weighted risk model that incorporates empirical research into an integrated decision-support framework. Unlike narrative reviews of current research in this field, this model proposes to quantify severity, frequency, consistency, and dependency into a standardized scoring framework to allow comparative prioritization of e-scooter safety risks.

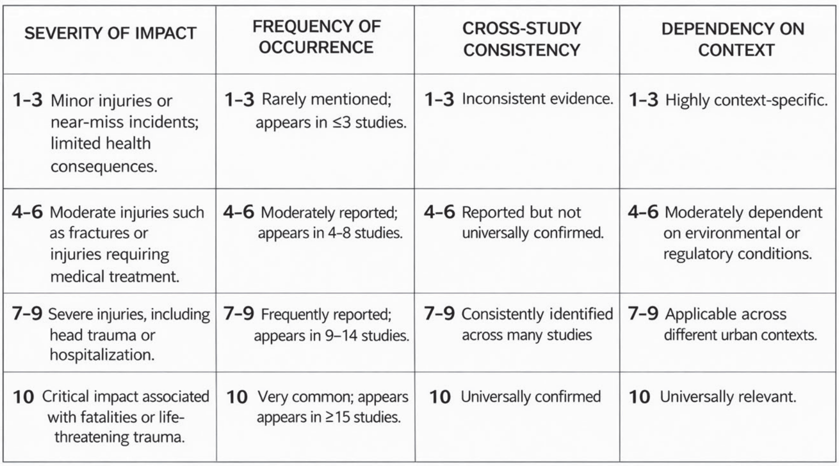
2 Methodology

A structured qualitative framework was applied to assess the relative importance of e-scooter safety risks through four stages: systematic literature review, risk identification, weight assignment, and validation, as illustrated in figure 1.

Figure 1 Step-by-step research chart for the weighted risk model methodology

The literature related to e-scooters has been identified using appropriate keywords such as "e-scooter safety, " "micromobility risk factors, " "e-scooter injuries, " and "helmet use in e-scooters." Relevant literature has been identified through a series of sources such as peer-reviewed journals, conference proceedings, and reports published between 2020 and 2024 through databases such as Scopus, Web of Science, and Google Scholar. A total of 19 studies have been considered to cover a wide range of geographic locations and methodologies to identify e-scooter accidents and related risk factors, where the risk factors can be classified into four categories: vehicle design factors such as visibility, illumination, stability, braking system, and speed capacity; rider factors such as speeding, alcohol use, and helmet non-use; infrastructure factors such as road conditions, lack of lanes, and lack of appropriate signages; environmental factors such as visibility at night and weather conditions.
The risk factors were evaluated and weighed using four qualitative measures: the severity of the impact, the frequency of occurrence, consistency across studies, and context dependency.

The risk factors were weighted with the use of a score of 1-10, with scores of 1-3 indicating low impact with limited evidence, scores of 4-6 indicating moderate impact that depends on the conditions, scores of 7-9 indicating high impact that frequently occurs with the risk of severe injuries, and score 10 indicating critical risk factors that are frequently linked with severe injuries. The adopted 1–10 weighting scale is conceptually aligned with established risk assessment approaches such as Failure Mode and Effects Analysis (FMEA). To support transparent scoring, a rubric was developed based on evidence from the 19 analyzed studies as shown in figure 2. The final weights for the risk factors were obtained from the integration of the four measures. The severity of each risk was based on the injury outcome, frequency was based on the citation rate and reported prevalence, consistency was based on the uniformity of findings, and dependency was based on the universality of the risk factors. The weighted values were derived based on the above parameters The robustness of the model was obtained from the sensitivity analysis, whereby the weights were varied by ±10% and ±20%. The result indicated stability in the risk factors' weights, although there are still limitations in the paper based on the qualitative nature of the risk weighting, variability in research findings, and contextual factors, which may limit the generalization of the findings.



SEVERITY OF IMPACT	FREQUENCY OF OCCURRENCE	CROSS-STUDY CONSISTENCY	DEPENDENCY ON CONTEXT
1-3 Minor injuries or near-miss incidents; limited health consequences.	**1-3** Rarely mentioned; appears in ≤3 studies.	**1-3** Inconsistent evidence.	**1-3** Highly context-specific.
4-6 Moderate injuries such as fractures or injuries requiring medical treatment.	**4-6** Moderately reported; appears in 4-8 studies.	**4-6** Reported but not universally confirmed.	**4-6** Moderately dependent on environmental or regulatory conditions.
7-9 Severe injuries, including head trauma or hospitalization.	**7-9** Frequently reported; appears in 9–14 studies.	**7-9** Consistently identified across many studies	**7-9** Applicable across different urban contexts.
10 Critical impact associated with fatalities or life-threatening trauma.	**10** Very common; appears appears in ≥15 studies.	**10** Universally confirmed	**10** Universally relevant.

Figure 2 Risk evaluation rubric used to assign weights to e-scooter safety factors (1–10 scale)

3 Results

The weighting procedure was applied to assess the relative importance of selected e-scooter safety risk factors based on the four evaluation criteria: severity of impact, frequency of occurrence, cross-study consistency, and context dependency, using the defined 1–10 scoring scale. Examples of how weighting scores are calculated for selected e-scooter risk factors, based on their evaluation across the four criteria, are presented in table 1. Rather than reporting individual study outcomes, the results synthesize common evidence trends identified in the literature to justify the assigned scores and final weights of the risk factors. The weighting reflects the combined influence of the four criteria, where factors associated with higher injury severity, frequent occurrence, strong agreement across studies, and broader applicability receive higher final scores. Based on this approach, the evaluated risk factors are categorized and discussed in the following subsections.

Table 1 Example scoring of selected e-scooter risk factors

Risk Factor	Severity	Frequency	Consistency	Dependency	Final Weight
Alcohol impairment	10	9	9	8	9
Speeding	9	8	8	8	8
Helmet non-use	9	8	8	7	8
Poor road surface	8	8	8	7	8
No dedicated lanes	8	8	7	7	8
Vehicle stability	8	7	7	7	8
Night visibility	6	7	7	7	7

3.1 Vehicle design

Stability issues (weight: 8): Frequent and severe accidents are caused by the instability of e-scooters. Many research papers indicate that rider balance maintenance is restricted by the elevated center of gravity combined with a narrow deck and upright standing posture especially on uneven or slippery surfaces [2, 5, 13]. Serious injuries or near-miss events occur when unstable e-scooters cause riders to lose control [7, 10, 17]. Instability increases when riders drive with one hand [11]. Stability is an essential safety component of e-scooters which is challenged by uneven or inclined surfaces often cause directional collisions and falls [1, 8, 12].
Braking systems (weight: 7): The inadequate braking mechanisms in e-scooters increase the collision risk in urban areas, also increases the odds of both near-miss incidents and devastating accidents [7, 13, 17]. Loss of control caused by the failure of braking systems in urban environments presents significant dangers [1, 5]. The braking performance of e-scooters worsens on damp or uneven roads causing a braking distance increase and a higher chance of crashes [2, 10, 12].
Visibility and lighting (weight: 6): The e-scooter riders face decreased visibility to vehicles and other traffic participants during nighttime riding which accounts for 45.8% of injuries [5, 7, 17]. Nighttime riding is riskier with a higher chance of serious injuries and fatalities since most e-scooter crashes happen during poor light conditions at night [4, 8]. The combination of insufficient lighting together with environmental factors like afternoon glare or shadows leads to decreased visibility causing higher crash risks [10, 11]. Improved visibility through better lighting solutions and reflective clothing is crucial to mitigate the higher crash rate of e-scooters compared to bicycles during nighttime conditions [1, 2].
Speed capabilities (weight: 8): Greater speeds achieved by e-scooters lead to more severe injuries and deadly collisions, the risk of severe injuries would increase 50% for e-scooter riders especially motorcyclists traveling above 25 km/h [3, 5]. Roads with speed limits above 40 mph or 50 km/h led to higher chances of major collision, usually high-speed zones play a vital role in injury severity assessments [1, 18]. Vehicle crashes become more serious and fatal when drivers exceed safe speed limits [2, 11]. Quick actions on speed management systems are essential for better e-scooter safety as the differences in vehicle speeds at intersections lead to more severe accidents [4, 9].

3.2 Rider behavior

Alcohol impairment (weight: 9): Studies show that 20 to 33 percent of people involved in e-scooter crashes were under the influence of alcohol which enhances the risk of head and facial [3, 6, 11]. Alcohol impaired riders tend to ride in groups while engaging in doing dangerous maneuvers such as speeding and abrupt swerving increasing the severity of collisions [1, 2, 5]. Drunk male motorcycle riders experience a higher incidence of severe collisions and traumatic brain injuries [10, 17]. Up to 41% of deaths from e-scooter accidents are because of alcohol indicating that micro-mobility transportation requires quick safety interventions to reduce impairment risks related to alcohol [4, 18].
Speeding (weight: 8): The severity of e-scooter crashes significantly increases by speeding, with severe injuries and fatalities directly correlating with higher speeds, speeding is a common behavior of e-scooter riders, leading to greater crash severity and high-risk encounters with vehicles [2, 9]. Speeding has critical role in crash outcomes, severe injuries due to speeding are four times more likely to happen on roads with speed limits higher than 50 km/h [1, 12]. Additionally to enhance e-scooter safety effective speed management is needed especially at intersections where speed mismatches at intersections further exacerbate crash risks [4, 5].
Lack of helmet use (weight: 8): Existing studies show that unfortunately only 1-3 percent of e-scooter riders wear helmets while helmets reduce head injury occurrences by 50% [3, 6, 19]. There are higher chances of crashes causing traumatic brain injuries and severe head injuries with the insufficient helmet usage rate during crashes [5, 18]. Even though studies confirm helmets help reduce severe injuries current enforcement of mandatory helmet rules falls short, with helmet usage rate being minimal more rigorous regulatory enforcement is required alongside educational efforts to protect riders and diminish injury severity reveals an immediate requirement [1, 10].
Reckless maneuvering (weight: 7): Riders engaging in reckless behaviors like sudden swerving and riding side-by-side on sidewalks as a part of reckless riding maneuvers causes frequent e-scooter crashes in cities, actions such as sudden lane changes and kerb jumping have a great role in creating near-miss occurrences and crashes [7, 11, 17]. Studies show that dangerous actions are performed frequently by e-scooter riders increasing the risks of collision especially when riding on unpaved trails and sidewalks [2, 10]. It is demonstrated by studies that risky maneuvers such as crossing roadways are performed more by e-scooter riders than cyclists causing the collision risks to increase [1, 5].

3.3 Infrastructure

Poor road surfaces (weight: 8): The e-scooter crash chances increase based on the road conditions marked by uneven pavement and potholes along with slippery surfaces also increasing injury severity, research indicates that 40% of loss-of-control incidents and 79% of falls are due to uneven or dangerous road conditions [2, 3]. Fewer injuries occur on bike lanes than those occurring on unpaved surfaces or poorly maintained roads [10, 11]. In urban settings the road surfaces which are wet, oily, or covered in snow, increase the danger of serious injuries [1, 12]. Damp or uneven roads worsen the braking performance of e-scooters, creating higher chance of crashes [2, 10, 12]. The bad condition of road surfaces generate instability leading to falls and collisions of e-scooters [4, 5].
Lack of dedicated lanes (weight: 8): The lack of exclusive micromobility lanes raises the potential for accidents among e-scooter users. Research demonstrates that urban areas with separate lanes for scooters see a 30% reduction in car-scooter crashes while mixed traffic environments raise collision rates notably in densely populated cities [1, 2].

Bike lane usage leads to decreased injury risks compared to sidewalks and motor roads which lack dedicated lanes where collision chances rise [10, 17]. Micro-mobility users face higher accident rates when sharing roads with vehicles, especially when there is no dedicated infrastructure, research results indicate that exclusive lanes are essential to improve e-scooter safety and minimize interactions with vehicles and pedestrians [5, 8].
Traffic signals and signs (weight: 7): Poorly marked traffic signals and lack of signage at junctions and busy urban areas are major contributors to e-scooter crashes. Research findings indicate that signage which creates uncertainty leads to confusion resulting in crashes that often end in injuries [2, 10, 17]. Micromobility users experience increased accident risk when they turn or change direction at intersections where traffic signals are inadequate or poorly managed [1, 8]. Signalized junctions operate effectively to minimize hazards, yet they can lead to more severe crashes if traffic signals are improperly controlled or marked, the clear visibility of traffic signs enhances rider safety while reducing user confusion [5, 12].

3.4 Environmental factors

Weather conditions (weight: 6): Rain creates slippery surfaces reduce braking efficiency of e-scooters, also the braking distance extends by 35% on wet road surfaces increasing the likelihood of accidents [2, 5] Rainy and snowy weather conditions lead to loss of control and falls increasing the chances of severe injuries [8, 12]. Adverse weather conditions causing poor visibility notably at nighttime also increase the likelihood of e-scooter crashes [3, 4].
Poor visibility at night (weight: 7): Up to 45.8% of e-scooter crash injuries occur at nighttime riding due to poor visibility at nighttime [6, 9]. In areas with insufficient lighting low-light conditions reduce the visibility of e-scooter riders to other vehicles, increasing the risks of collision [5, 8]. During nighttime the Personal Mobility Devices (PMD) crash frequency is at 26.9% which is higher than the 20.5% rate for bicycle crashes showing the crucial importance of lighting and visibility for protection of riders [1]. In order to reduce the likelihood of e-scooter crashes at night indicates the need for better lighting and reflective clothing as the statistic show that 82% of e-scooter fatalities happen at night [4]. The weighting score for all the risk factors are summed in table 2.

Table 2 Shows the risk factor weightening results

Category	Risk Factor	Weight
Vehicle design	Stability issues	8
Vehicle design	Braking systems	7
Vehicle design	Visibility and lighting	6
Vehicle design	Speed capabilities	8
Rider behavior	Alcohol impairment	9
Rider behavior	Speeding	8
Rider behavior	Lack of helmet use	8
Rider behavior	Reckless maneuvering	7
Infrastructure	Poor road surfaces	8
Infrastructure	Lack of dedicated lanes	8
Infrastructure	Traffic signals and signs	7
Environmental factors	Weather conditions	6
Environmental factors	Poor visibility at night	7

4 Sensitivity analysis and robustness of the weighting framework

Sensitivity analysis was conducted on the assigned weight factors to evaluate the internal validity and robustness of the proposed weighting framework. while holding all remaining weights constant Each individual weight was systematically perturbed by ±10% and ±20%. Composite risk scores were recalculated after each perturbation scenario, and the relative ranking was reassessed for all identified risk factors. High degree of ranking stability was observed. The risk factors being top five retained their relative positions across all perturbation scenarios, which includes poor infrastructure conditions, low visibility, lack of protective equipment, excessive speed, and alcohol impairment. Only among lower-ranked factors minor rank changes were observed. The rank stability of each risk factor under all perturbation levels are illustrated in figure 2.

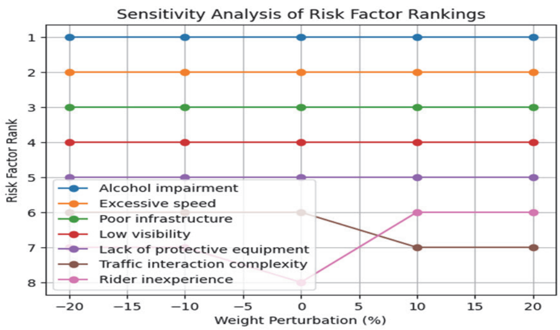


Figure 3 Sensitivity analysis of risk factor ranking

5 Conclusion

This study proposes a weighted qualitative framework for assessing critical risk factors for e-scooter crash severity, comprising four domains: rider behavior, vehicle design, infrastructure, and environment. The proposed framework was developed using a structured synthesis of 19 peer-reviewed articles. The results suggest that rider behavior and infrastructure are the most critical factors in determining crash severity. Of all the factors, alcohol impairment was found to be the most critical risk factor, having a weight value of 9. This indicates that alcohol impairment is strongly associated with severe injuries and fatalities. Other critical risk factors for e-scooter crashes are speeding and helmet non-use, both having weight values of 8. Deficiencies in infrastructure, including poor road conditions and lack of dedicated micromobility lanes, also contribute significantly to accident likelihood, having weight values of 8 each.

Vehicle design factors, including vehicle speed and stability, also contribute to e-scooter crashes and are assigned a weight value of 8. Other risk factors, including braking performance, traffic control conditions, reckless riding, and reduced visibility at night, are also significant and assigned weight values ranging from 6 to 7. The proposed framework was validated using sensitivity tests for weight value variations ranging from +10% and -20%. The results suggest that for both tests, the relative order of risk factors remains unchanged, thus validating the proposed framework. Therefore, this study proposes that authorities should focus on stricter alcohol-related riding regulations and safety helmet use and implement strategies for managing speeding. In parallel, authorities should also focus on upgrading road conditions and establishing dedicated micromobility lanes to reduce infrastructure-related risks.

Overall, this study proposes that the proposed framework for assessing safety risks for micromobility is transparent and reproducible and thus could be used for decision-making in urban planning. Future studies should focus on using actual crash data and large sample sizes to further validate this proposed framework for assessing safety risks for micromobility.

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