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METHOD ARTICLE

REVISED A new method for evaluating the effectiveness of micro-mobility protective equipment

[version 2; peer review: 2 approved, 1 approved with reservations]

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Abstract

Micromobility is a form of transportation and an efficient urban mobility solution that can include human-powered or electric vehicles for short-distance travel such as traditional bicycles, e-bikes, and e-scooters. It refers to lightweight personal vehicles with a maximum speed of 45 km/h and a maximum weight of 350 kg. Effectively, micromobility safety represents one of the most critical concerns of vulnerable road users (VRUs) such as cyclists and employees of courier companies. Various measures and micromobility protective equipment (PE) have been used to enhance VRU safety and reduce traffic accidents involving VRUs. Therefore, evaluating the effectiveness of these PE such as high-visibility clothing and helmets is very important to ensure that they can successfully prevent or reduce the risk of accidents and injuries. In this paper, we present a data-driven approach for evaluating the effectiveness of micromobility PE. This novel method relies on data collected directly from micro-vehicles and their users by using various techniques, including a web-based questionnaire, micro-vehicle sensor kit, and micromobility hazards detector. Effectively, these data collection tools, services, and questionnaire have been developed and designed to be used for collecting real data as soon as the participants recruiting process is finalised. Therefore, synthetic data were generated and used to demonstrate that the proposed method is feasible and can work in practice. This data is solely used to show some examples of data analysis procedures and to demonstrate some results as a proof-of-concept for micromobility PE effectiveness evaluation. Hence, the all findings mentioned in this paper are not actual or empirical results but provided only for illustrative purposes to show the format of the expected results when real data is used.

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Any reports and responses or comments on the article can be found at the end of the article.

Keywords
micromobility, safety, vulnerable road users – VRUs, protective equipment – PE, effectiveness evaluation, sensor, hazard



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REVISED **Amendments from Version 1**

- The abstract is revised and paraphrased
- The results of the study are recasted as a proof-of-concept demonstration (not empirical findings)
- A section is added to explain the metrics used to evaluate the effectiveness of protective equipment
- The method used by authors to provide the initial manually created dataset
- The tables in Figure 2 are linked by repeating "User" field in all tables
- The web-based questionnaire designed for data collection is provided
- A section (Discussion) is added to interpret the paper contribution and outline next research steps

Any further responses from the reviewers can be found at the end of the article

1. Introduction

Micromobility is a transport mode that refers to small, low-speed, lightweight personal vehicles. This may include both human- and electric-powered vehicles such as bicycles and e-scooters. Essentially, users of transport modes such as cyclists and e-scooter riders are less protected in crash and accident situations. Like all other vulnerable road users (VRUs), such as pedestrians and motorcyclists, micromobility users require extra care from other road users (e.g., drivers). The risks of crashes or injuries for cyclists are significantly higher than for drivers; therefore, cycling is considered an unsafe mode of travel (Lawson *et al.*, 2013). Additionally, between 2008 and 2019, an average of 2200 fatalities occurred among bike riders in the European Union (EU) (Deck *et al.*, 2019). Therefore, various measures and protective equipment (PE), including helmets, high-visibility clothing, and lights, can be used to improve the safety of micromobility users (Høye *et al.*, 2020). However, PE should provide protection from injury and facilitate ease of movement, without causing fatigue or discomfort (de Rome, 2006).

The reason for crashes between cyclists and vehicles is the failure of drivers to detect cyclists in time to avoid accidents (Costa *et al.*, 2017). The poor visibility (or conspicuity) of VRUs to other drivers is one of the main reasons for accidents involving VRUs (Rogé *et al.*, 2019). Therefore, motorcycles can increase visibility to other road users by keeping their lights on during the day. Additionally, the probability of collision between cyclists and motorized vehicles can be reduced if cyclists wear high visibility (e.g., light or white colored) clothing in daylight conditions. Therefore, using visibility aids, such as reflective vests and lights, may improve the detection and recognition distance and the ability of drivers to detect pedestrians and cyclists (Costa *et al.*, 2017). In addition, helmet users are more likely to use accident prevention equipment, such as lights and high-visibility clothing, under poor visibility conditions (Hollingworth *et al.*, 2015).

Traumatic brain injury (TBI) is the main cause of mortality after bicycle-related injuries, and it represents three-quarters of deaths and two-thirds of hospital visits in the US (Joseph *et al.*, 2017). Effectively, there has been an ongoing debate regarding how to prevent head injuries of cyclists in collisions (i.e., with motor vehicles) and whether cycling helmets are efficient in preventing head injuries or reducing the severity of experienced injury (Bambach *et al.*, 2013). It has been found that using helmets by motorcyclists may reduce head and neck severe injuries by 69% and deaths by 42% (Morgado *et al.*, 2017). It has been also reported that the effectiveness of helmets are 48%–71% in preventing head injuries (Axelsson & Stigson, 2019). Therefore, the interactions between cyclists, vehicles, and the environment in the three phases of an accident (pre-event, event, and post-event) can be investigated to develop effective approaches to reduce injuries to cyclists. Principally, bicycle helmets reduce the risk of significant head injury and death in the "event" of a cyclist collision. On the other hand, "pre-event" equipment such as bicycle lights and high-visibility (reflective or fluorescent) clothing may reduce the risk of collision in conditions of reduced visibility (McGuire & Smith, 2000).

The percentage of adult cyclists who are using helmets in Norway has increased from 32% in 2006 to 56% in 2015 (Høye *et al.*, 2020). Additionally, many governments have introduced legislation regarding the mandatory use of PE, such as helmets on public roads, to reduce micromobility-related injuries and mortality (Bambach *et al.*, 2013; Joseph *et al.*, 2017). For instance, in France, helmets have been mandatory for 40 years and gloves have been mandatory since 2016 for motorized 2-wheeler riders (Wu *et al.*, 2019). However, in Sweden, bicycle helmets have been mandatory since 2005 for children under the age of 15 years (Axelsson & Stigson, 2019). Therefore, PE aims to enhance VRU safety, promote sustainable micromobility, and reduce traffic accidents involving VRUs. Additionally, evaluating the effectiveness of micromobility PE is very important because it provides the necessary insight to determine whether the PE is achieving its intended purpose.

Section two of this paper discusses and critically analyzes previous studies, highlighting gaps in the research topic. The proposed approach for evaluating the effectiveness of micromobility PE is described and detailed in section three including data collection methods, data processing, and analysis techniques used in this research. Additionally, the implementation of this approach and the presentation of potential results are provided in section four. Then, a discussion on the implications of the provided contribution and next steps is outlined in section five. Finally, the conclusions are presented in section six.

2. Background and related work

Several studies have been conducted to investigate the impact of micromobility PE on accidents and injuries. This includes the effectiveness evaluation of some micromobility PE, such as helmets and high-visibility clothing. One study investigated

the differences between cyclists who wear helmets and those who do not and evaluated injury prevention measures adopted by cyclists in Oxford, United Kingdom (McGuire & Smith, 2000). This study was based on an observational survey of cyclists passing a pre-identified point and recorded four measures of injury prevention: use of front or rear lights, high-visibility clothing, and bicycle helmets. Only 3.6% of cyclists were observed to use all four measures, while 34.9% of cyclists used none of them. It was also found that collision prevention measures are more likely to be used by bicycle helmet users under reduced lighting conditions. The relationship between safety measures and pediatric polytrauma severity in road traffic injury was analyzed through a retrospective observational study (Morgado *et al.*, 2017). This study used hospital data on polytraumatized pediatric patients who were hospitalized after road traffic accidents. It has been found that head injury associated with death in two-wheel vehicle riders is correlated with the absence of PE, such as helmets. In another study, an online questionnaire was used to collect information about cyclists' cycling behavior and cycling accident-related injuries (Hollingworth *et al.*, 2015). It has been found that accidents are associated with the use of various safety equipment, and helmet use is related to lower chances of being required for an overnight stay in the hospital. In another study, regression analysis of traumatic brain injury (TBI) data from bicycle-related accidents was employed to evaluate the association of helmet use with the severity of TBI and facial fractures (Joseph *et al.*, 2017). Helmets have been found to reduce the incidence of TBIs in bicycle-related accidents because bicycle helmets protect cyclists from severe head injuries and can save their lives.

The effectiveness of bicycle helmets in preventing head injuries among cyclists involved in crashes has been examined, and the impact of risky cycling behaviors among helmeted and unhelmeted cyclists has been assessed (Bambach *et al.*, 2013). This study analyzed relevant police reports on road crashes, hospital admissions, and mortality data. It has been found that the chances of sustaining a head injury increased by 1.98–3.89 times for cyclists who were not wearing a helmet, while helmet use was associated with a reduced risk of head injury by up to 74%. In another study, an advanced methodology was proposed for evaluating bicycle helmets by considering the risk of tissue-level brain injury, realistic impact conditions, and head kinematic parameters (Deck *et al.*, 2019). This study provides a means of comparing the protective capabilities of helmets using a dedicated rating system. In another study, the impact of using helmets by children bicyclists on injury and accident characteristics was evaluated using emergency care center data regarding children admitted due to bicycle crash injuries (Axelsson & Stigson, 2019). It has been found that the effectiveness of bicycle helmets was 61% in reducing all head injuries and 45% in reducing facial injuries.

The relationship between crash involvement and cyclists' safety-equipment use was also investigated (Høye *et al.*, 2020). It focused on the road behaviors of cyclists and attempted to explore scenarios such as using safety equipment (i.e., bicycle lights, high-visibility clothing, and helmets) that lead to risky (and reckless) or safer behaviors. The surveys showed that the regular use of safety equipment is negatively related to certain types of high-risk behaviors (e.g., listening to music while cycling) and collision involvement. In most bicycle–car collisions, drivers fail to detect cyclists in time to avoid collisions because of the poor visibility of cyclists. Therefore, a study based on a simulated car driving task was conducted to investigate whether wearing a yellow jacket by cyclists enhances the visibility of motorists during daylight hours (Rogé *et al.*, 2019). Motorists performed a VRU (i.e., cyclist and pedestrian) detection task in a car-driving simulator. Motorists can detect cyclists wearing high-visibility jackets at a greater distance. In another study, the impact of reflective tape application to a bicycle (i.e., to the rear frame and pedal cranks) on bicyclist conspicuity enhancement was evaluated (Costa *et al.*, 2017). This was done by comparing the bicyclist detection distance in four conditions (control, rear red reflector, high-visibility jacket, and reflective tape). As a result, it was concluded that bicyclist conspicuity and safety at night can be significantly improved by applying reflective tape to the rear bicycle frame.

A retrospective observational study using injury and postal survey data was conducted to assess the effectiveness of motorcyclist protective clothing, including trousers, jackets, knee-high or ankle boots, back protection, and gloves (Wu *et al.*, 2019). As a result of using Poisson regression to estimate the impact of these protective clothing on injury risk, it has been concluded that these PE can protect users from injuries such as lacerations and abrasions, but not from serious injuries such as fractures, sprains, or dislocations. In another study, a prospective cohort study using an online questionnaire was conducted to quantify bikers' attitudes towards various factors that might contribute to their choice to use PE (Pratt *et al.*, 2019). This study analyzed the correlations between these factors and the actual use of PE to assess their relative importance. Results indicated that more than 50% of bikers experienced an injury that required at least one week of work, and the injury severity was well correlated with choice of PE use. Another prospective cohort study was conducted to understand the impact of wearing protective clothing during crashes on the subsequent health conditions and quality of life of motorcyclists (de Rome *et al.*, 2012). Medical records, interview data, and mailed survey data were used for this study. As a result, there were substantial relationships between post-crash health, well-being, and the use of protective clothing. Motorcyclists wearing jackets (and pants) spent less time in the hospital and had less pain immediately post-crash than those who did not wear the PE. In another study, a cross-sectional analytic study was conducted to quantify the association between the usage of motorcycle clothing and injury in crashes (De Rome *et al.*, 2011). Participants were recruited through motorcycle repair services and hospitals and data were collected through interviews. As a result, protective clothing used by motorcyclists was related to a reduced risk (and severity) of injury after a crash. Motorcyclists wearing PE (jackets, pants, or gloves) were considerably less likely to be admitted to the hospital after a

crash. Moreover, the risk of injury to the upper body, hands, wrists, legs, feet, and ankles was substantially reduced when a body armor was used.

Most studies related to micromobility safety and PE efficiency address the benefits and advantages of these PE in preventing accidents and reducing crash injuries. Nevertheless, these investigations are limited and focus on specific types of PE, such as helmets and high-visibility clothing. Typically, retrospective and prospective observational studies, surveys, and interviews are used as a methodology in these studies. Police traffic accident reports and data, hospital admission data, medical records, injury data, and questionnaire data were used as input data.

This study proposes a new method to assess the effectiveness of micromobility PE and investigate how these PE can improve micromobility safety. Therefore, the outcomes of evaluating the effectiveness of such PE may play a considerable role in reducing traffic accidents involving VRUs, enhancing VRU safety, and promoting sustainable micromobility. This study evaluates the effectiveness of 1) micromobility PE used to reduce the chance of a micro-vehicle crash (or to prevent accidents) and 2) micromobility PE used to reduce the chance of personal injury (or to prevent injuries as a result of accidents). Therefore, this evaluation will give micromobility users insight into the effectiveness of PE and will encourage them to wear and use PE constantly while travelling. In this study, PE that can be used to prevent or reduce the risk of accidents or crash involvement is called PE-preventive (e.g., reflective accessories). However, PE, which can be used to prevent or reduce the effects and risks of injuries as a result of accidents, is called PE-protective (e.g., helmet).

3. Proposed method

Evaluating the effectiveness of micromobility PE can significantly enhance the safety of micromobility and VRUs. Therefore, the effectiveness of different categories and types of PE, including PE-preventive and PE-protective, can be analyzed and estimated. Assessing the effectiveness of PE will provide VRUs with a comprehensive understanding of the merits of each PE category, and will help users select and use the most appropriate PE. Therefore, this study introduces a novel methodology for assessing the effectiveness of various types of micromobility PE according to the road and traffic conditions, features of the PE, and characteristics of VRUs. Effectively, the proposed data-driven approach correlates metrics related to the surroundings of micro-vehicles with the characteristics and features of PE used by micromobility users. This approach employs several procedures and techniques of data collection and analysis to assess the effectiveness of various types of PE.

As mentioned above, most of the previously proposed approaches use historical medical and injury data, hospital admission records, and police traffic accident reports to evaluate the PE efficiency. However, the proposed method is more advanced and relies on near real-time data collected directly from micro-vehicles and users to immediately evaluate the effectiveness of micromobility PE after finalizing the data collection process. Figure 1 shows the flow diagram for this approach, which depicts the main procedures and steps starting from the data collection process and ending with the effectiveness evaluation of micromobility protective equipment.

3.1 Data collection

This study introduces a data-driven approach for evaluating the effectiveness of various types of micromobility PE. This approach relies mainly on collecting different types of data from several sources. Two main techniques were used to collect the required data. The first technique involves the use of a micro-vehicle sensor kit that can be mounted on a micro-vehicle to collect micro-level data about micromobility, user behavior, environmental and traffic conditions. However, the second technique involves the deployment of a web-based survey (i.e., questionnaire) to collect data from micromobility users about their behavior on the road, experienced accidents, sustained injuries, the PE they are using, and the characteristics of these PE.

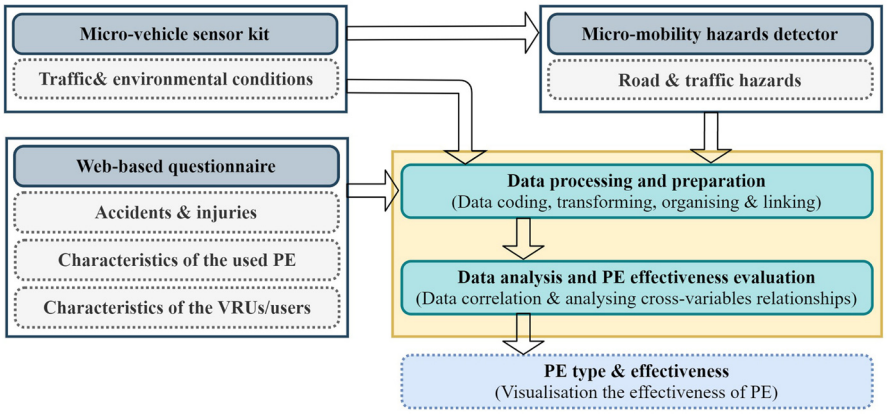

Figure 1. The proposed approach for evaluating the effectiveness of micromobility protective equipment.

3.1.1 Micro-vehicle sensor kit and micromobility hazard detector data

Various types of sensing systems can be mounted on micro-vehicles to collect safety-related data, including experienced vibration events, proximity to surrounding objects, and speed changes (Ma *et al.*, 2021). In addition, these systems monitor the status of micro-vehicles, identify riders' behavior, and detect riding styles (Han *et al.*, 2022). The proposed method utilizes a micro-vehicle sensor kit and data-driven approach to detect hazards (Almohammad *et al.*, 2025a). Therefore, this micro-vehicle sensor kit and micromobility hazard detector will be used to collect the first set of data required to evaluate the effectiveness of the micromobility PE. The micro-vehicle sensor kit integrates various devices and sensors such as accelerometers, gyroscopes, GPS receivers, grip sensors, environmental sensors, and depth cameras. However, the micromobility hazard detector uses the data collected by the micro-vehicle sensor kit to detect hazardous situations such as dangerous overtakes. It also identifies areas with specific infrastructure deficiencies (i.e., potholes) and a large number of vehicle conflicts (i.e., heavy traffic). However, other dangerous traffic situations, such as near misses experienced by micromobility users, can be detected by investigating and analyzing camera data and footage.

Effectively, the developed sensor kit consists of two parts; one represents the depth camera while the other represents all other sensors and devises enclosed within an appropriate case. The plan is to install one sensor kit on each micro-vehicle so data can be collected and used to develop and generate a number of machine learning (ML) models which are responsible for detecting various types and severities of hazards as part of the micromobility hazard detector. Initially, these installed sensor kits will be used to collect the sufficient data (e.g., 2000 records of 1-second data samples) required to train the ML models. The micromobility hazard detector will use this initial data collected to train and generate ML models to be used in the real time hazard detection process.

Accordingly, the output of the micromobility hazard detector is used as input data for the proposed approach to evaluate the effectiveness of PE. This input data includes the number of dangerous overtakes (and may be the severity of these incidents) experienced by micromobility users. Moreover, the proposed approach may use the output of the micro-vehicle sensor kit as input data, including camera footage data, environmental and weather conditions.

It is expected that many micromobility users will be recruited to participate in the data collection process for the proposed approach. Therefore, many bicycles will be equipped with micro-vehicle sensor kits and used by the recruited users. However, no restrictions are applied on the routes to be followed or the travel time. Consequently, data collected by the micro-vehicle sensor kit will be uploaded to the cloud in real time; therefore, the micromobility hazard detector will be able to read this data and detect related hazards. Principally, data collected by the micro-vehicle sensor kit and the output of the micromobility hazard detector are linked with the responses of micromobility users to the web-based questionnaire.

3.1.2 Web-based questionnaire data

The second set of data required for the proposed approach was collected by capturing the responses of micromobility users to a web-based questionnaire. This questionnaire was designed and developed to collect various types of data from micromobility users. As mentioned before, the responses of micromobility users to this questionnaire should be linked to the data provided by the micro-vehicle sensor kit and micromobility hazard detector. Therefore, it is important to use a common data variable that can facilitate the process of linking these datasets together (the response of micromobility users to the questionnaire and the data provided by the micro-vehicle sensor kit and micromobility hazard detector). Micromobility users will be asked to answer ten multiple-choice questions in this questionnaire (a copy of this questionnaire is available in the Appendix file). Users' answers to these questions provide information on the following:

- The type of micromobility used including motorcycle, moped, bicycle, scooter, e-moped, e-motorcycle, e-bicycle, and e-scooter.
- The behavior of micromobility users including normal, aggressive, and dangerous behavior.
- The PE (PE-preventive) used including high-visibility clothing, front light, rear light, reflective accessories, mirrors, and bells.
- The PE (PE-protective) used including helmet, gloves, glasses, body armor, chest guard, back protector, elbow pads, knee pads, and foot protector.
- Accidents experienced by users including crashes, near misses, and falls.
- Sustained injuries by users including head, face, chest, back, arms, hands, legs, and foot injuries.
- The severity of sustained injury including minor, moderate, and serious injury.
- The cause of experienced accident such as users are not using accident prevention tools, users are invisible to other road users, and other road users are invisible to the user.
- The performance of PE-preventive such as high-visibility clothing is supportive and useful, while the mirror is not.
- The performance of the PE protective used such as helmets and gloves are effective.

Effectively, micromobility users can respond to this questionnaire and answer questions either before they start their test rides or at the end of their trip.

3.2 Data processing and preparation

In the data collection stage, the collected data related to a micromobility user include the user's response to the web-based questionnaire, the user's micro-vehicle sensor kit data, and the hazards experienced by the user, such as the number of dangerous overtakes per time unit (output of the micromobility hazard detector). Effectively, the responses of micromobility users to some of the questionnaire questions may require coding or transformation, such as identifying the general behavior of users depending on the behaviors and actions of these users when they use micro-vehicles. However, the readings of environmental sensors, such as temperature and humidity, may be translated into weather condition features, such as good, fair, or poor. Additionally, camera footage can be viewed and manually analyzed to detect and identify the number of near misses per time unit experienced by users during their test rides.

The data processing and preparation stage starts after all the required data are collected from the different data sources, including the responses of all micromobility users and the related data from the micro-vehicle sensor kit and micromobility hazard detector. All collected data will be linked, organized, and combined in one dataset. Therefore, each row in this dataset includes all the collected data for one micromobility user. Figure 2 represents an example of this dataset and shows that each data entry (i.e., shaded row) includes the answers of one micromobility user to the questionnaire, weather conditions, number of near misses and dangerous overtakes per time unit.

3.3 Data analysis and PE effectiveness evaluation

Evaluating the effectiveness of micromobility PE aims to improve the safety of micromobility and VRUs. This evaluation may enhance the awareness of VRUs and users about the benefits of using PE and encourage them to wear and use PE constantly while they are travelling. Therefore, all response data to the questionnaire, micro-vehicle sensor kit data, and micromobility hazard detector data will be analyzed after they have been processed and prepared to assess the efficacy of each PE.

3.3.1 Data correlation metrics

A correlation metric is a statistical measure that can be used to understand the strength and direction of the relationship between two or more variables in data. Therefore, quantifying this relationship is vital for decision-making regarding the effectiveness of different PE. Hence, correlating the metrics related to the surroundings of micro-vehicles with the characteristics and features of micromobility users and the use of PE is crucial in the data analysis process for exploring the relationships among the data variables listed in Figure 2.

Effectively, the correlations among the collected data variables can be measured to understand the relationships among these variables and how they affect each other. In general, the type of relationship among data variables can be linear, nonlinear, or categorical. The phi coefficient (ϕ) can measure the strength of association between two dichotomous variables or variables that have only two possible outcomes such as yes/no or true/false. It is a special case of the Pearson correlation coefficient used for these binary variables, ranging from -1 to +1. A value of 0 indicates no relationship, while ±1 indicates a perfect correlation (positive or negative). Therefore, the relationship can be interpreted depending on the phi coefficient value: values between 0 and 0.19 refers to very weak relationship, values between 0.2 and 0.29 refers to weak relationship, values between 0.3 and 0.49 refers to moderate relationship, values between 0.5 and 0.69 refers to strong

User	PE-preventive						PE-protective									Accidents
	HV Cothing	Front Light	Rear Light	Reflective Accessories	Mirror	Bell	Helmet	Gloves	Glasses	Body Armour	Chest Guard	Back Protector	Elbow Pads	Knee Pads	Foot Protector	
user_1	Yes	Yes	Yes	Yes	No	No	Yes	Yes	No	No	No	No	No	No	No	Crash
user_2	Yes	Yes	No	No	No	No	No	Yes	Yes	No	No	No	No	No	No	Near_miss
user_3	No	Yes	Yes	Yes	No	Yes	No	No	No	No	No	No	No	No	No	Near_miss

User	PE-preventive Performance						PE-protective Performance									Micromobility Type
	HV Cothing	Front Light	Rear Light	Reflective Accessories	Mirror	Bell	Helmet	Gloves	Glasses	Body Armour	Chest Guard	Back Protector	Elbow Pads	Knee Pads	Foot Protector	
user_1	No	No	No	No	No	No	Yes	Yes	No	No	No	No	No	No	No	Motorcycle
user_2	Yes	Yes	No	No	No	No	No	No	No	No	No	No	No	No	No	Moped
user_3	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	Bicycle

User	Injuries								Accident Cause			Injury Severity	User Behaviour	Sensor Kit		Hazards Detector
	Head	Face	Chest	Back	Arms	Hands	Legs	Feet	I'm Not Using PE-prev	I'm Invisible to Others	Others Invisible			Weather Condition	Near Misses	Dangerous Overtaking
user_1	No	No	Yes	Yes	No	No	Yes	Yes	No	No	No	Moderate	Normal	Fair	0	1
user_2	No	No	No	No	No	No	No	No	No	Yes	No	Minor	Normal	Good	1	1
user_3	No	No	No	No	No	No	No	No	No	No	No	Moderate	Normal	Good	2	0

Figure 2. An example of the collected data after processing and preparation.

relationship, values between 0.7 and 1 refers to very strong relationship. The phi coefficient is calculated from a 2x2 contingency table:

$$\phi = \frac{TP\ x\ TN - FP\ x\ FN}{\sqrt{(TP+FP)(TP+FN)(TN+FP)(TN+FN)}}$$

Where: TP: True Positive, TN: True Negative, FP: Fase Positive, FN: False Negative.

Therefore, some questions in the designed questionnaire may be used to identify the relationships that need to be measured. For instance, the question of "how effective is high-visibility clothing in preventing or reducing accidents?" can be answered by analyzing and quantifying the relationship between this PE usage and accidents experienced such as near misses. In the data analysis and metrics correlation process, the statistics related to each data variable must be calculated and organized in an independent table to estimate the relationships among the relevant variables and draw meaningful conclusions. To answer this question, Figure 3 shows an example of the generated tables containing the statistics of different variables. For instance, the figure shows that phi correlation coefficient between the usage of this PE and no accident variable is -0.137 while it is -0.107 between the usage of this PE and near miss incidents. This means that there is very weak negative relationship between the usage of this PE and accidents. Therefore, wearing this PE can reduce the experienced near misses and enhance the safety of micromobility users. Additionally, the remaining relationships between the usage of different PE types and other data variables such as accidents and injuries can be investigated and discussed in a similar manner.

4. Experiments and results

The proposed approach for evaluating the effectiveness of micromobility PE requires various types of data to be collected using different techniques. Effectively, the data collection process is key and represents the most challenging aspect of the proposed approach. Because the proposed approach relies on correlation metrics and statistics, implementation of the proposed data collection plan requires a substantial number of micromobility users (i.e., cyclists or e-scooter riders) to be recruited, and each user should be provided with micro-vehicle equipped with a sensor kit. However, the proposed data collection plan has not yet been implemented to collect real input data. Therefore, there are no real data that can be used to evaluate and test the proposed approach for evaluating the effectiveness of micromobility PE.

Simulations and algorithms can be used to create synthetic or artificial data that mirrors real data. Therefore, these synthetic data can be used to replace or expand real-world data. Synthetic data were generated to test the proposed approach and demonstrate the different steps and procedures involved in this approach. Therefore, these synthetic data is used to provide a proof-of-concept demonstration of the proposed approach and provisionally evaluate the effectiveness of these PE by conducting laboratory experiments. However, these synthetic data were created to represent the final format of the collected data before the data analysis and PE effectiveness evaluation step, and after the data processing and preparation step (Figure 2).

To generate the synthetic data, a sample dataset was manually created, and each entry in this dataset represented all the data types expected from all data sources (i.e., questionnaire, micro-vehicle sensor kit, and micromobility hazard detector). Most potential values for the different data variables were considered in this sample dataset, such as types of micromobility, types of user behavior, types of accidents experienced, and sustained injuries. Effectively, the authors of this paper have pretended as micromobility users, filled in the designed questionnaire and answered all the questions many times to provide the manually created dataset. Additionally, associated sensor kit and micromobility hazard detector data in this dataset were randomly generated. However, the size of this manually generated sample dataset is still limited (i.e., 48 entries) and insufficient to extract significant conclusions. Generally, some techniques can be used to learn from real data and generate synthetic data with high fidelity. One example of these techniques is the Conditional Tabular Generative Adversarial Network (CTGAN), which is a collection of deep-learning-based synthetic data generators for single-table data (Ince *et al.*, 2024). Therefore, CTGAN was adopted and used to expand the manually created dataset (i.e., a total of 498 entries). As a result, the format of the synthetic data generated is similar to that shown in Figure 2 but includes data for 498 users.

Having generated the required data in a format similar to that of processed and prepared data, these data are now ready to be analyzed to evaluate the effectiveness of PE. Therefore,

PE-preventive		hv_clothing		ref_accessory		front_light		rear_light	
		Yes	No	Yes	No	Yes	No	Yes	No
near miss	Yes	29	70	42	57	37	62	34	65
	No	169	230	185	214	172	227	129	270
Correlation(ϕ)		-0.107		-0.032		-0.05		0.017	
no accident	Yes	76	157	102	131	78	155	84	149
	No	122	143	125	140	131	134	79	186
Correlation(ϕ)		-0.137		-0.034		-0.16		0.066	

Figure 3. Examples of generated tables to measure the effectiveness of PE.

the data analysis procedures and techniques described in Section 3.3 can be followed and applied to assess the effectiveness of different micromobility PE. Essentially, the statistics related to different data variables are calculated and organized in tables to estimate the relationships (i.e., phi coefficient correlation) between these variables and extract the results. Figure 4 shows an example of these tables to quantify the relationship between the use of micromobility PE and the injuries sustained by these micromobility users. For instance, it can be concluded from these tables (extracted from the synthetic data) that there is a very weak negative relationship between the usage of some PE (i.e., helmet, gloves, elbow pads, and body armour) and related injury. Therefore, micromobility users who are usually wearing helmets can significantly reduce the chance of head injury. These results are not empirical findings based on real data but examples of data analysis process and a proof-of-concept demonstration for the proposed approach.

Effectively, a wide range of relationships among the data variables has been identified. Additionally, a static Microsoft Excel-based dashboard was implemented and used as a basic visualization and presentation tool for these relationships (Figure 5). Therefore, all the generated tables and associated charts were incorporated in this dashboard to make the relationships among the data variables easily understandable. The left side of the dashboard shows the measured relationships between the PE used from one side and the other data variables from the other side. However, the right side of this dashboard shows the selected relationship (in this example, between the used PE and the sustained injury type) in terms of the associated charts and the interpretation of this relationship. This dashboard enables micromobility users (or other stakeholders) to select which relationship to display, understand the meaning of this relationship, and recognize the effectiveness of each PE.

5.Discussion and future work

Using micromobility protective equipment represents one of the fundamental measures that enhance the safety of micromobility and VRUs. However, most research addressing PE efficiency as part of micromobility safety investigate the pros of some PE in mitigating the consequences of accidents and minimising the severity of related injuries. Additionally, these investigations are limited to specific types of PE and based on historical data including accident reports, medical records, and injury data. Therefore, this study proposes an innovative and near real-time approach to evaluate the effectiveness of micromobility PE based on a customised and dedicated data collection method designed for this purpose. Additionally, one of the main contributions and advantages of this approach is evaluating the effectiveness of both preventive and protective PE. Effectively, this PE effectiveness evaluation approach will give micromobility users insight into the practicality of different PE and will encourage the VRUs to adopt and use PE regularly when they travel. However, governments and authorities may use the proposed approach, collect the required fata, and undertake practical implementation to gain some conclusions and introduce relevant recommendations or legislations about micromobility PE.

In this study, a novel approach for evaluating the effectiveness of micromobility PE has been proposed. Additionally, all data collection techniques (i.e., questionnaire) and tools (i.e., sensor kit and hazard detector) have been designed and developed. At this stage, the proposed approach has been demonstrated and the effectiveness of micromobility PE has been evaluated by using only artificial or synthetic data rather than real data. Therefore, all provided example results on PE effectiveness represent a proof-of-concept demonstration not empirical findings. As a next step, the proposed data collection method and techniques will be used to collect real input data to the proposed approach. Many recruited micromobility users can share one sensor kit (i.e., one user per day) due to the limited number of available kits. Then, real data collected by the sensor kit will be used to train the ML models responsible to detect micromobility hazards. Additionally, the recruited users will be contacted to asked to complete the designed questionnaire. Therefore, this real data will be used to validate the proposed approach for evaluating the effectiveness of micromobility PE.

PE-protective		helmet	
		Yes	No
head injury	Yes	28	28
	No	72	38
Correlation(ϕ)		-0.15	

PE-protective		gloves	
		Yes	No
hands injury	Yes	21	25
	No	79	41
Correlation(ϕ)		-0.18	

PE-protective		elbow pads	
		Yes	No
arm injury	Yes	15	34
	No	57	60
Correlation(ϕ)		-0.17	

PE-protective		glasses	
		Yes	No
face injury	Yes	18	36
	No	29	83
Correlation(ϕ)		0.077	

PE-protective		knee pads	
		Yes	No
leg injury	Yes	19	25
	No	45	77
Correlation(ϕ)		0.057	

PE-protective		body Armor	
		Yes	No
back injury	Yes	13	54
	No	30	69
Correlation(ϕ)		-0.12	

Figure 4. An example of generated tables to measure the effectiveness of different protective equipment.

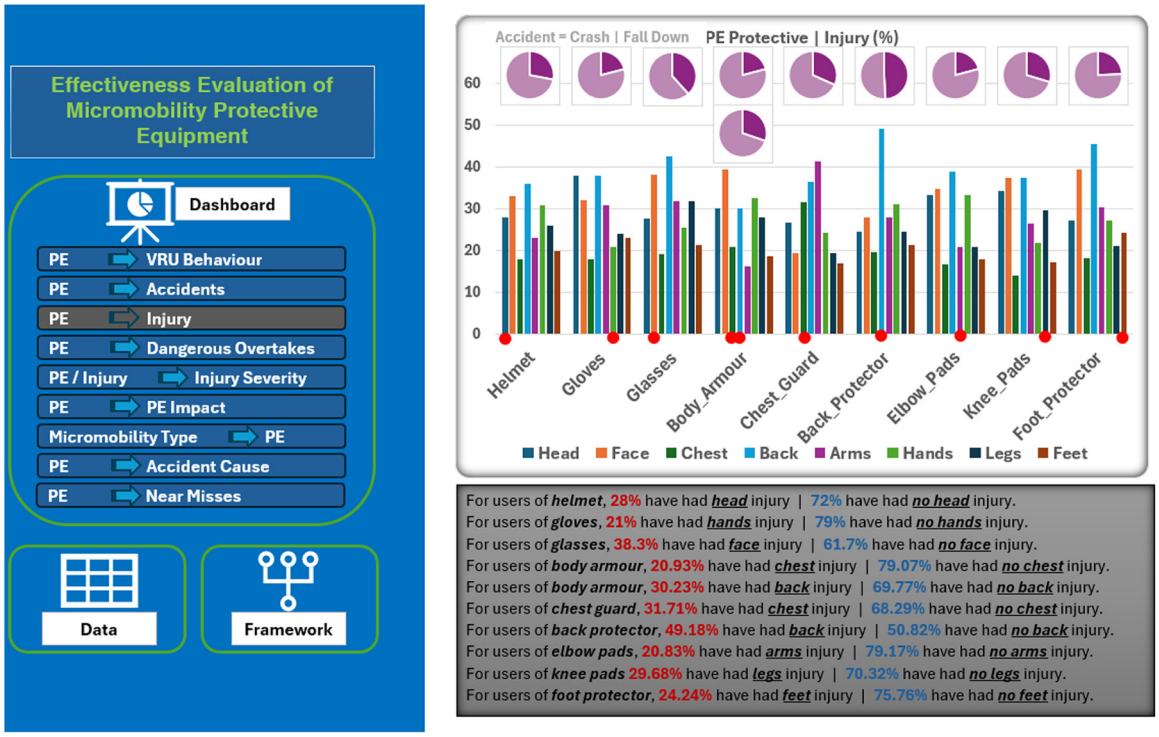

Figure 5. A screenshot for the Microsoft Excel-based dashboard designed to show the effectiveness of protective equipment.

6. Conclusion

The safety of micromobility users, such as cyclists and e-scooter riders, is an important factor in adopting this mode of transportation. Therefore, micromobility users may use or wear various types of PE, including helmets, high-visibility clothing, and lights, to improve their safety. In this paper, we presented a novel data-driven approach for evaluating the effectiveness of micromobility PE, including PE-preventive (i.e., light and reflectors) and PE-protective (i.e., helmets and gloves). Mainly, the aim of our approach is to provide micromobility users and other stakeholders with insights about the benefits and usefulness of PE and whether each PE achieves its objectives. The approach is mainly based on collecting data from micromobility users, micro-vehicle sensor kit, and micromobility hazard detector. Therefore, a questionnaire has been designed and tools have been developed (i.e., sensor kit mountable on micro-vehicles and hazard detector service) for this purpose. In this approach, the collected data needs to be processed and analyzed before measuring the relationships (phi coefficient correlation) among the data variables. Effectively, synthetic data is used instead of real data to demonstrate the proposed approach and provide some example results as a proof-of-concept. Therefore, the correlations between these synthetic data variables were calculated and visualized (by the developed dashboard) to show the effectiveness of various PE. Additionally, a roadmap for validating the proposed approach is provided to put the data collection plan into practice and collect real input data, implement data analysis and correlation, and provide actual results and conclusions.

6. Ethics and consent

Ethical approval and consent were not required.

7. Data availability

The data for all the experiments presented in the paper are available via accessible links on the Zenodo platform:

- Manually created data, and each entry in this dataset represented all the data types expected from all data sources (i.e., questionnaire, micro-vehicle sensor kit, and micromobility hazard detector), https://doi.org/10.5281/zenodo.17529854 (Almohammad *et al.*, 2025b)
- Synthetic data generated by using Conditional Tabular Generative Adversarial Network (CTGAN) to expand the manually created data, https://doi.org/10.5281/zenodo.17529873 (Almohammad *et al.*, 2025c)
- The web-based questionnaire designed to be used for collecting data from micromobility users, https://doi.org/10.5281/zenodo.17542606 (Almohammad *et al.*, 2025d)

Data are available under the terms of the Creative Commons Attribution 4.0 International license (CC-BY 4.0).

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Open Peer Review

Current Peer Review Status: ✔ ✔ ?

Version 2

Reviewer Report 05 January 2026

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Azzuhana Roslan
Malaysian Institute of Road Safety Research (MIROS), Kajang, Malaysia

The article presents a novel data-driven framework for evaluating the effectiveness of micro mobility protective equipment (PE), integrating three key data sources: a micro-vehicle sensor kit, a micro mobility hazard detector, and a web-based questionnaire.

The method is designed to overcome limitations of existing studies that rely heavily on retrospective hospital or police data and typically focus on only one category of protective equipment. By combining near real-time sensor information on riding conditions and hazards with self-reported user behaviour and PE usage, the proposed approach enables simultaneous evaluation of both preventive PE (e.g. lights, reflective accessories) and protective PE (e.g. helmets, gloves, body armour). The workflow is logically structured from data collection to processing and preparation, and finally to statistical analysis using phi-coefficient correlation metrics, making the technical description sound and internally consistent.

The rationale for developing the new method is clearly articulated, highlighting the fragmented nature of previous research and the need for a holistic, context-aware evaluation of PE effectiveness. The paper also provides sufficient operational details to allow replication, including specifications of the sensor kit components, an explanation of the hazard-detection process, a full questionnaire, and open access to the synthetic datasets and manually created seed data used in the proof-of-concept. These elements allow other researchers to reproduce the demonstration stage of the method and to understand how different data streams are integrated and analysed.

However, although all datasets used in the paper are publicly available, the study relies entirely on synthetic data. As such, reproducibility is only partial and limited to the demonstration environment, and the absence of real-world data restricts the empirical validation of the method. To address this, the authors should include a dedicated real-world validation protocol specifying minimum sample sizes, deployment duration, sensor calibration and data quality procedures, as well as a clear data schema for operational use. In addition, the conclusions, while appropriately cautious, would be strengthened by defining explicit performance benchmarks and decision thresholds (for example, what correlation levels would be considered meaningful in practice) and

by providing a worked template showing how real-world results would be interpreted. With these additions, the article would move from a strong proof-of-concept to a fully operational and scientifically robust methodology suitable for wider adoption.

Is the rationale for developing the new method (or application) clearly explained?
Yes

Is the description of the method technically sound?
Yes

Are sufficient details provided to allow replication of the method development and its use by others?
Yes

If any results are presented, are all the source data underlying the results available to ensure full reproducibility?
Partly

Are the conclusions about the method and its performance adequately supported by the findings presented in the article?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Road safety and traffic injury prevention; micromobility and active mobility planning; evaluation of protective equipment and user behaviour; transport safety data analytics; urban mobility systems and policy; application of sensor-based and questionnaire-based methods for transport safety assessment.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Reviewer Report 23 December 2025

https://doi.org/10.21956/openreseurope.23656.r64019

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George Yannis
National Technical University of Athens, Athens, Greece
Virginia Petraki
National Technical University of Athens Ship Design Lab, Zografou, Attica, Greece

Thank you for sending the revised manuscript. All of my comments have been fully addressed, and I have no further comments. The manuscript is now suitable for indexing.

Competing Interests: No competing interests were disclosed.

We confirm that we have read this submission and believe that we have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Reviewer Report 24 November 2025

https://doi.org/10.21956/openreseurope.23656.r64018

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Mariano Gallo
Università del Sannio, Benevento, Italy

In my opinion, now the paper can be indexed

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Transportation engineering

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Version 1

Reviewer Report 09 October 2025

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Your Report:

This paper is a method article and aims to present a novel approach for evaluating the effectiveness of micromobility protective equipment. The paper is well organized with an interesting objective; however, several key issues should be tackled before the paper is accepted for indexing.

- First, the current dataset is entirely synthetic, built from a manually curated dataset and expanded via CTGAN; no real data have yet been collected. As a methods article, this is acceptable for demonstration, but any empirical claims about PE effectiveness must be removed or recast as illustrative only, with an explicit validation plan for real deployments. Recast all results as a proof-of-concept demonstration, not as empirical findings on PE effectiveness. Avoid language implying real-world effects (e.g., “helmets significantly reduce head/face injury” drawn from synthetic tables).
- Please add a dedicated section that specifies exactly how you will test the effectiveness of the PE metrics once real data is available. The current statement that “a correlation metric can be used…” is too generic; name the specific metrics/models, units, and decision rules. This addition will make the manuscript actionable as a methods article by presenting exactly what metrics to compute, which statistical tests, and how much data is needed (based on literature) to credibly evaluate PE effectiveness.
- Please add a short paragraph that transparently describes how the initial, manually created dataset was built before CTGAN expansion.
- Figure 2 is difficult to read; if a single consolidated table isn’t feasible, keep the three sub-tables but make the linkage explicit (e.g., repeat the user_id).
- Please include in an Appendix the exact questionnaire (full item wording, response options/scales) and cite any validated scales used. This will improve reproducibility and help readers interpret variables and coding choices.
- It is recommended to add a subsection that states exactly what technology you will install on each micro-vehicle, how it will be installed and operated, and for how long.
- Please add a Discussion Section to interpret the contribution in context, relate it to prior work, articulate practical and policy implications, and outline a concrete validation roadmap and future research.

Is the rationale for developing the new method (or application) clearly explained?

Partly

Is the description of the method technically sound?

Partly

Are sufficient details provided to allow replication of the method development and its use by others?

Partly

If any results are presented, are all the source data underlying the results available to ensure full reproducibility?

Partly

Are the conclusions about the method and its performance adequately supported by the findings presented in the article?
Yes

Competing Interests: No competing interests were disclosed.

We confirm that we have read this submission and believe that we have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however we have significant reservations, as outlined above.

Author Response 06 Nov 2025

Adel Almohammad

Thank you for giving us the opportunity to submit a revised version of our manuscript to Open Research Europe. We appreciate the time and effort that you have dedicated to providing your valuable feedback on our manuscript. We are grateful to the reviewers for their insightful comments on our paper. We have been able to incorporate changes to reflect most of the suggestions provided by the reviewers. We have highlighted the following changes within the manuscript - The results of the study are recasted as a proof-of-concept demonstration (not empirical findings)
- A section is added to explain the metrics used to evaluate the effectiveness of protective equipment
- The method used by authors to provide the initial manually created dataset
- The tables in Figure 2 are linked by repeating "User" field in all tables
- The web-based questionnaire designed for data collection is provided
- A section (Discussion) is added to interpret the paper contribution and outline next research steps

Competing Interests: No competing interests were disclosed.

Reviewer Report 25 September 2025

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?

Mariano Gallo
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[2] Università del Sannio, Benevento, Italy

The paper proposes a new methodology for assessing the effects of protective equipment for micromobility users. The paper is well written and the content is interesting. In the abstract, there is a sentence that, in my opinion, is unrealistic: 'Micromobility is one of the most important modes

of transportation in urban environments...'
It is more appropriate to say that it is a new and increasingly popular mode of transport, but to say that it is one of the most important is an excess. The idea proposed by the authors is interesting. The most critical point of the paper is the lack of real data, as highlighted by the authors. In practice, it is not possible to be certain that the method will produce accurate results. However, I believe that the paper can be indexed if the authors clarify this aspect in the abstract and show that the equipment to be used is available and the user survey has been designed. In this way, it can be demonstrated that this work is a useful piece of a larger, ongoing but appropriately designed research project.

Is the rationale for developing the new method (or application) clearly explained?
Yes

Is the description of the method technically sound?
Yes

Are sufficient details provided to allow replication of the method development and its use by others?
Yes

If any results are presented, are all the source data underlying the results available to ensure full reproducibility?
Partly

Are the conclusions about the method and its performance adequately supported by the findings presented in the article?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Transportation engineering

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 06 Nov 2025

Adel Almohammad

Thank you for giving us the opportunity to submit a revised version of our manuscript to Open Research Europe. We appreciate the time and effort that you have dedicated to providing your valuable feedback on our manuscript. We are grateful to the reviewers for their insightful comments on our paper. We have been able to incorporate changes to reflect most of the suggestions provided by the reviewers. We have highlighted the changes within the manuscript.

Competing Interests: No competing interests were disclosed.