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Original Research Paper

Developing a multi-method approach to identifying e-scooter hazard hotspots

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HIGHLIGHTS

- The safety of e-scooters as a new mode of transport is discussed.
- Multi-method approach to identifying hazardous locations.
- Large proportion of conflicts is caused by unorganized parking of e-scooters.
- Hotspots mainly located at large intersections involving several modes of transport.
- Further hotspots can be identified along dense urban roads.

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ABSTRACT

In recent years, e-scooters have been introduced in many European cities. In several places we have witnessed a rapid uptake of this new mode of transport mainly as a result of public sharing schemes. A number of incidents, injuries and even fatalities have given rise to questions regarding the safety of these vehicles. These questions are being researched mainly using official crash data and data specifying injuries and hospital treatment. Until now, the research has focused on investigating typical injury patterns and estimating risk levels. Very little is known about exactly where conflicts and crashes occur. Knowledge of hazard hotspots is crucial when investigating risk levels and improving safety for all road users.

Hence, this paper develops an approach to investigating locations with potentially dangerous interactions within the active mobility system in the city of Berlin. The approach consists of explorative expert interviews, an online poll, and quantitative analyses. For the latter we combine three datasets. First, we research crash hotspots using official data. Second, we use data based on acceleration sensors from cyclists' smartphones to find locations of sudden movements. Third, we use trip data from the operators of e-scooter sharing systems. The information gathered is used in a conclusive expert workshop to identify hazard hotspots.

Results show that many of the conflicts with pedestrians are caused by parked e-scooters. Second, e-scooter trips are concentrated in the inner city and along specific routes. In moving traffic, various data sources are used to identify hotspots at intersections and in areas between intersections.

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The present research lays the foundation for important further studies to investigate interactions at hotspots in detail by determining nine specific locations in the city of Berlin.

1. Introduction

From 2017 onward, lightweight electric standup scooters (e-scooters) emerged in US cities and later Europe (Fitt and Curl, 2020; McKenzie, 2020; Zhou et al., 2023). Soon after the launch of this new type of vehicle, shared e-scooters gained massive popularity and the number of users exceeded that of established bike sharing systems in several places (Hamann et al., 2019).

A growing number of transport related studies investigate usage patterns, environmental implications and the potential of e-scooters (Bozzi and Aguilera, 2021; Fitt and Curl, 2020; Jiao and Bai, 2020; Liu et al., 2019). The main focus is on safety concerns arising as a consequence of initial crashes (Lentzen et al., 2021). Since then, several medical studies dealing with conflicts, safety issues and injuries related to e-scooter usage have been published. In a joint medical approach, persons injured after crashes were examined in hospital to evaluate the main injury patterns (Namiri et al., 2020; Störmann et al., 2020; Trivedi et al., 2019; Uluk et al., 2020). Some studies focus specifically on crashes between e-scooters and pedestrians, raising concerns about the safety of pedestrians following the introduction of e-scooters (Maiti et al., 2022; Sikka et al., 2019; Yang et al., 2020). These studies gather knowledge about typical injuries and compare such patterns to other modes of transport (English et al., 2020; Kobayashi et al., 2019; Uluk et al., 2020). Studies conclude a vast increase in injuries caused by crashes with the new vehicle type following its introduction (Alwani et al., 2020; Badeau et al., 2019; Uluk et al., 2020). This research provides valuable information for the healthcare system. It is not surprising that the number of injuries tends to increase when a new vehicle type is introduced. However, without knowledge of the number of trips made or miles driven by e-scooters, the resulting additional injuries and trends only tell half the story. Some authors take an approximation of e-scooter traffic (e.g., miles driven) into account when evaluating their risk level (Gebhardt et al., 2021) or compare the relative risk to other modes of transport (Santacreu et al., 2020). The conclusion is that the risk of crashes on e-scooters is higher than on bikes (Gebhardt et al., 2021). When including the risk not just for the driver but for all road users, it is smaller than the risk posed by cars or motorcycles (Santacreu et al., 2020).

Only a few studies investigate the exact locations of crashes (Cicchino et al., 2021; English et al., 2020). Thus, only sidewalks and road space (Cicchino et al., 2021), and the transition between sidewalk and roadway (Shah et al., 2021) are identified as the primary places for crashes without identifying exact locations. Accordingly, authors conclude that a high-quality bike infrastructure is crucial when aiming to prevent crashes and injuries involving e-scooter users (Arndt et al., 2020; Gössling, 2020; Gubman et al., 2019; Markvica et al., 2020; Santacreu et al., 2020). It is obvious that the introduction of e-scooters has led to a fundamental change in the use of the road infrastructure. Since e-scooters predominantly use the bike infrastructure, interactions with the active mobility system (walking and cycling) are particularly important.

Where the current state of research is concerned, there is a gap between the medical studies researching injuries after crashes and the transport-related studies dealing with potential, patterns and statistics across all risks. There is not yet sufficient knowledge about which specific locations in urban areas are potentially dangerous for e-scooter users. Knowing about hazard hotspots at this early stage in the evolution of a new mode of transport is crucial. This knowledge enables further research action to evaluate risk factors. It is important to know the location of hazard hotspots in order to evaluate how these hotspots are characterized from an infrastructural perspective and to identify which interactions between e-scooters and other traffic participants are critical. It also means that interventional safety considerations could be taken into account at potentially dangerous locations.

Hence, the objective of this study is to identify potentially dangerous locations in the city of Berlin, Germany. This is specifically relevant as the number of e-scooter crashes is increasing throughout Germany, but particularly in Berlin where 10% of all crashes in Germany happen. The number of e-scooter crashes in Berlin increased 2.5 times from 325 in 2020 to 819 in 2021 (Dpa, 2022). The number of severely injured increased even more steeply from 34 in 2020 to 96 in 2021. We propose an approach combining different methods and using various types of data. The approach consists of expert interviews as an explorative prestudy, an online poll of users and non-users, and subsequent quantitative analyses of various secondary datasets. We merge these datasets together and identify e-scooter hazard hotspots in a conclusive expert workshop with joint consideration of the data from various sources. Since e-scooters have only recently been introduced, the available official data on usage is limited. Hence, some of the analyses are based on data specific to bicycles. As single-track vehicles with a comparable speed and use of the same infrastructure, these vehicles appear most similar. This approximation has been used in earlier research (Gehrke et al., 2022) and is supported by recent findings (Leschik et al., 2022). Furthermore, the regulation of e-scooters in Germany is comparable to regulations for bike usage. This includes the mandatory use of bike lanes and bike infrastructure for riding, use of public spaces like sidewalks for parking, and the voluntary use of helmets. In contrast to bikes, e-scooters are not allowed to drive faster than 25 km per hour (eKFV, 2019). This research lays the foundation for further analyses of the resulting locations and the interactions between traffic participants occurring at these hotspots.

2. Materials and methods

In this section, we describe the methodology used to identify e-scooter hazard hotspots. The approach is shown in Fig. 1. It contains different modules and combines qualitative and quantitative methods (Schreier and Odağ, 2020). First, expert interviews are conducted in an explorative prestudy to gain knowledge and to establish the basis for the quantitative estimations. Second, a public online poll of users and non-users is carried out. Third, a quantitative approach is performed based on three individual datasets to provide a longlist of potential locations. The first dataset is crashes recorded by the police (a). The second dataset is incidents recorded by a smartphone app (b). The third dataset is trip data of e-scooters generated by the sharing operator's API (c). Fourth, a qualitative expert workshop is held to merge the results and condense the findings to a shortlist of hazard hotspots.

2.1. *Expert interviews*

Qualitative, guided, semi-structured expert interviews (Reuber and Pfaffenbach, 2005; Strauss et al., 1994) were conducted to explore the state of knowledge in this early stage of a new mode of transport. A guideline was developed for this purpose. The guideline structure was based on the five topics of supply, utilization, regulations, conflicts and safety, and outlook, and included a total of 18 questions, some with additional subquestions. Between April and June, 2021, several experts were contacted and a total of 15 interviews were conducted. The 10 interview partners came from municipal offices dealing with micromobility in large German cities, such as the office of public order, department of city planning or transport and police. These city representatives are crucial when trying to understand the particularities in the uptake of e-scooters in cities and therefore account for most interviews. In addition, 1 researcher as well as associates of 4 operators were interviewed. They are considered as experts because their job is to deal with the challenges of micromobility in cities. Seven experts were Berlin-based and eight were located in other large German cities. The objective when selecting the experts was to obtain knowledge and experience from Berlin and other large German cities (e.g., Stuttgart, Cologne). We aimed to incorporate different perspectives by including different stakeholders for each city.

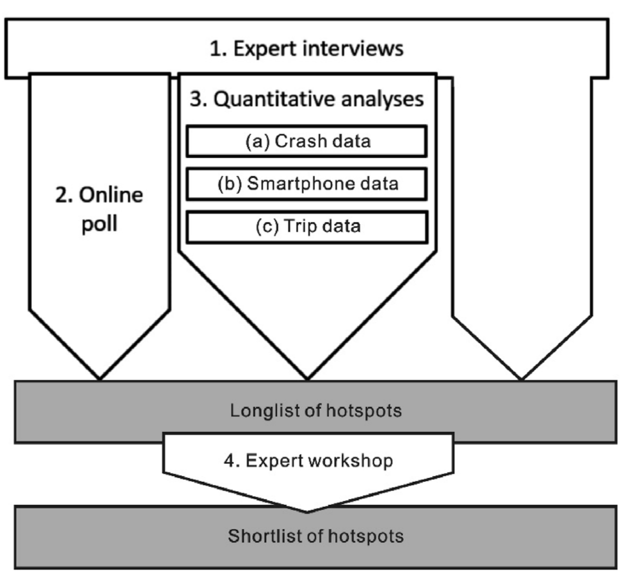

Fig. 1 – Methodological approach.

The total duration of the interviews was between 45 and 80 min. The topic of conflicts and safety was considered for the present research. The experts were asked if, from their point of view, conflicts occur between users of e-scooters and cyclists or pedestrians, how potential conflicts are characterized and what parameters are linked to conflicts. These open questions did not direct or bias the participants. In addition, experts were asked if they knew of specific hazard hotspots and how they were characterized. The interviews were transcribed and the information was organized in a matrix, enabling evaluation of the assessment based on individual parameters, such as group of experts, city of occupation or background. The analyses were performed manually following predefined categories.

2.2. *Online poll*

The results of an online poll were integrated into the methodological approach to include the experience and requirements of e-scooter users and other road users with regard to conflict situations. They refer to a Germany-wide online poll on the topic of e-scooters in road traffic. The poll was available online between mid-April and mid-June, 2021. Participation was open to any interested person, both e-scooter users and non-users. Participants were recruited mainly via social media and newsletters. In addition, collaboration with one operator of shared e-scooters established direct contact with users of e-scooters. During the survey period, a link to the poll was displayed in the app for the duration of one week after each trip. As a consequence of the wide distribution, the sample is self-selecting and not representative. Sample composition was not controlled to maximize sample size.

The questionnaire covered a wide range of questions. Content, wording and understanding of questions were checked in a pretest with a small number of private persons and experienced fellow researchers. First, the availability and frequency of use of several private and shared transport modes were queried. Based on this information, it was possible to filter e-scooter users and non-users. For the subgroup of e-scooter users, a large section dealt with usage of e-scooters in general as well as detailed information about the most recent trip with an e-scooter (e.g., use of shared or private e-scooter, trip duration, trip purpose, combined use with public transport, substituted mode, and reasons for use). Furthermore, all participants were asked about their general opinions on e-scooters in cities, conflict interactions experienced, and socio-demographic information. The main objective of the online poll was to collect information about e-scooter usage and conflicts between e-scooter users and other active modes of transport (walking and cycling). Hence, key questions referred to the conflicts experienced by e-scooter users, cyclists, and pedestrians. Many people use multiple modes of transport in their daily lives. Therefore, participants were asked to answer the questions about conflicts with e-scooters from different perspectives depending on their individual mobility behavior. Each participant was asked the questions about conflicts with e-scooters as a pedestrian. In addition, depending on their mode use indicated in the questionnaire, they were asked to answer the questions as e-scooter users and/or cyclists as well. Consequently, each participant answered the conflict questions 1 to 3 times in the loop from different perspectives, resulting in an overlap between the e-scooter user, cyclist, and pedestrian subgroups. As conflicts with other active modes of transport (walking and cycling) were the focus of the survey, the respondents' perspectives as car users were not included to avoid making the questionnaire longer.

To cover the wide range of conflicts, conflicts in the survey were not only understood as crashes, but also included situations where people almost collided or had to swerve or slow down. For cyclists and pedestrians, conflicts with parked e-scooters were included as well. Participants were first asked to indicate all types of conflicts they had experienced to date. The conflicts asked for ranged from serious conflicts (e.g., crashes, falls) to more minor conflicts (e.g., swerves, insults). In the next step, participants were asked to state, from their individual point of view, which of the conflicts they experienced was their most serious. Then, they were asked to describe this conflict alone in more detail, providing reasons, parties involved, and characteristics of the locations. The aforementioned questions in the dataset were analyzed using descriptive methods for this paper.

2.3. Quantitative analyses

Three datasets are used to investigate locations with potentially dangerous interactions in the city of Berlin. First, we use official crash data on bicycles for the past four years. Second, we use data based on acceleration sensors from cyclists' smartphones to find locations of sudden movements. Third, we use trip data from the operators of e-scooters.

2.3.1. Spatial clustering of crashes and incidents

Crashes and near miss incidents on bicycles were used to get an idea of potential hazardous spots for e-scooter users. This is because e-scooters were first introduced in Germany in 2019 and therefore there is only limited data available on e-scooter crashes. In line with Gehrke et al. (2022), bikes are a close relative to e-scooters regarding crash data on vulnerable road users and in addition, in Germany, e-scooters are obliged to use the same infrastructure as bikes (Gehrke et al., 2022). Thus, crash data on bikes appear to be the best proxy. Two types of data sources were taken into account to generate a representative overview for the city of Berlin. Crash data from municipal statistics (Hagedorn and Hoffmann, 2020) and information on "near miss incidents" (referred to hereafter as incidents) recorded in the bicycle tracking project SimRa (Bermbach, 2021).

The data on bicycle crashes (n = 10,196) were extracted from the official crash data (Hagedorn and Hoffmann, 2020) covering the years from 2016 to 2019. The crash data include information of the exact geolocation, time, severity, weather characteristics as well as crash type and transport modes involved.

The incident data (n = 13,453) were generated in a crowd-sourcing approach using smartphone sensors to identify critical situations in bicycle traffic (Karakaya et al., 2020). In this approach, the authors identify eight different types of incidents, including (1) close passing of cars, (2) someone pulling in or out, (3) near left or right hook, (4) someone approaching head on, (5) tailgating, (6) near-dooring, (7) dodging an obstacle, and (8) other (Karakaya et al., 2020). Exploration of the data shows that the majority of incidents belong to category (1). Close passing incidents define a nearly ubiquitous risk for cyclists and therefore occur across the whole road network. As a consequence, these incidents, which are not caused by specific dangerous local characteristics, outweigh other incident types in the clustering process and lead to inappropriate clusters in respect of crash risk. Hence, we dropped category (1) from the dataset for the following analysis.

From both data sources, crash clusters were calculated using the density-based spatial clustering of applications with noise (DBSCAN) algorithm (Ester et al., 1996). DBSCAN is a density-based algorithm that spatially groups together points with nearby neighbors based on the neighborhood of a given radius (eps) and a minimum number of objects in each cluster, leaving outliers (noise) unconnected. To generate meaningful and representative clusters, several combinations of tuning parameters were tested and visually evaluated (eps values between 20 and 120 at intervals of 10 and minimum number of points between 5 and 10). The evaluation process was based on the following criteria: first, points on network parts with different characteristics (such as intersections or network edges) should not be mixed within one cluster; second, each intersection should be represented by only one cluster; third, the clusters should represent real accumulations of crash points, leaving out intersections and network edges with only a few crashes. Based on this, crash and incident clusters were generated using an eps value of 50 m, whereas the incidents were calculated using a minimum number of 7 points and the crash clusters were generated using a minimum number of 5 points in each cluster.

Besides the crash data on bicycles, the official crash data of 2020 included crashes with e-scooters for the first time. They added up to a total of 327 cases which is too few to use them for clustering analysis. However, they enabled us to verify the calculated crash clusters with the data on e-scooter crashes by evaluating whether an e-scooter crash had happed within the relevant cluster.

2.3.2. Synthetic generation of e-scooter traffic volume

The e-scooter trip data used for analysis was obtained by regularly performing requests from the API of one e-scooter operator in Berlin. Each request resulted in a dataset containing a vehicle ID, the battery status, and the geolocation of each e-scooter currently available. By performing the request every 2–10 min, it is possible afterwards to calculate the movements of e-scooters. We used this method to calculate all movements of e-scooters observed between August 2019 and January 2021. As e-scooters are redistributed or charged from time to time, not every movement can be defined as a trip. We therefore developed a set of assumptions based on Reck et al. (2021) to define which movements are counted as a (user) trip (Reck et al., 2021). They consider factors such as distance, time and speed of vehicles and are defined as follows.

- Trip distance longer than 200 m and shorter than 15 km.
- Average speed faster than 3 km/h and slower than 20 km/h.
- Maximum trip duration of 90 min.
- Battery level after the trip has to be lower than before the trip.

The resulting dataset includes 879,191 trips with their respective start and end location as well as trip time and battery level.

We used the UrMo Accessibility Computer (Krajzewicz et al., 2017) to calculate the route of every trip through the Berlin road network in a shortest-path approach. This results in a representation of the complete distribution of trips in the city and the traffic volume per network edge. The road network used is based on OpenStreetMap and consists of all streets and paths that are marked as legally usable for bikes. We are aware that using shortest-path routing for trip generation implies uncertainties but we assume that this approach is accurate enough to give at least a rough estimation of e-scooter flows. The traffic volume per year of the routed trips is shown in Fig. 2. The color of each segment reflects the volume of trips and ranges from a light red with at least one trip to a dark red with up to 10,378 trips per year.

2.3.3. *Merging and selecting*

Subsequently, the traffic volume as well as the crash and incident cluster were combined to identify the hazard spots. In this process, the traffic volume of each trip intersecting with a cluster was added up in each cluster. In addition, the corresponding trips in each cluster are divided by the length of the network to generate more comparable results, more precisely the relative volume of e-scooter trips. Finally, a longlist of hazard spots is identified by selecting the clusters with the highest relative volume of e-scooter trips.

2.4. *Qualitative expert workshop*

Finally, a qualitative expert workshop was held in July, 2021. All methods described above were outlined and the corresponding results presented. Based on these selection criteria, all locations in the longlist were discussed and the experts condensed them into a shortlist consisting of nine locations. The group consisted of Berlin-based researchers dealing with micromobility. In summary, the selection criteria were: existence of crashes cluster (bicycle), existence of incidents cluster (bicycle), e-scooter crashes, absolute number of e-scooter trips in the cluster, number of e-scooter trips in the polygon relative to road length, significance of each group of road users/mode of transport (pedestrians, bicycles, motorized transport, public transport), number of tourists, infrastructural characteristics regarding the size of the road, and the existence and type of bike infrastructure as well as the size of intersections.

3. Results

3.1. *Expert interviews*

All 15 experts interviewed shared their thoughts on conflicts and potential hotspots. It was thus possible to identify key

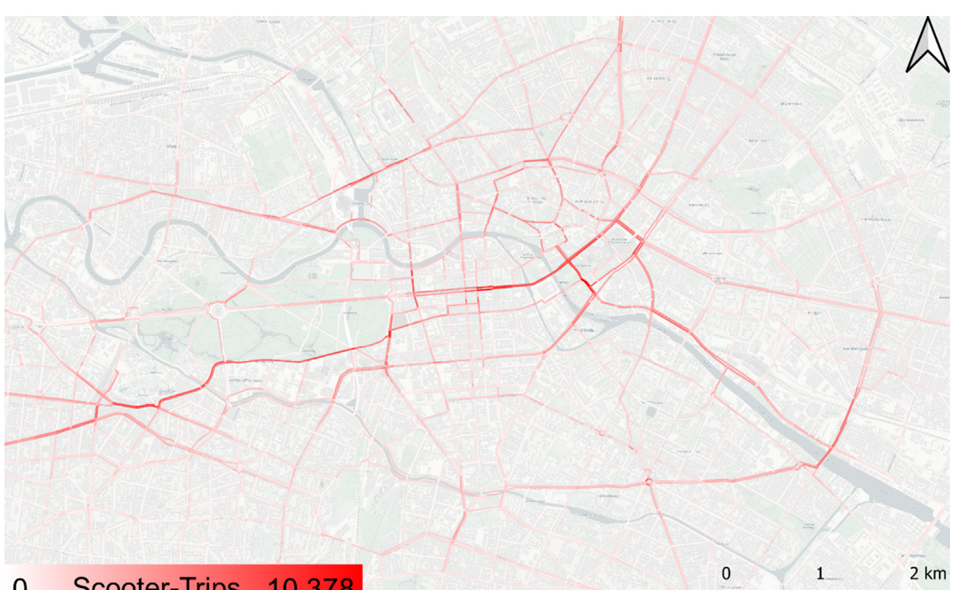

Fig. 2 – Routed e-scooter trips (background map: CartoDB).

statements which are described below. Of the 15 participants, 13 mentioned parked vehicles as a major source of conflicts with pedestrians. When looking at moving traffic, dense urban areas with several different modes of transport were particularly important. Tourist spots were repeatedly mentioned explicitly. According to 9 experts, many conflicts occurred when e-scooters and pedestrians (legally or illegally) shared the same road space; 8 experts stated that conflicts with e-scooters were not distributed any differently to those of other modes of transport. Thus, comparisons can be made with bicycle crashes. The relevant group specified that the main hotspots were traffic intersections, as conflicts occurred when turning or crossing. In contrast, a smaller group pointed out that, compared to bicycles, many conflicts did not occur at intersections but along the road. According to them, the reasons for this finding may be fast acceleration but relatively low maximum speed (20 km/h) compared to bicycles. This difference resulted in more interactions between bicycles and e-scooters apart from at intersections and traffic lights. Other explanations mentioned for the difference experienced are the improper use of e-scooters or the influence of alcohol. According to the experts, the bike infrastructure is crucially important to the risk and type of conflicts. A high-quality bike infrastructure could therefore reduce conflicts and improve safety. Table 1 provides an overview of the experts' assessment.

Regarding the quantitative analyses, the experts' assessment confirms that the approach focusing on data gathered from bicycles is promising. As a result, in addition to large intersections, special attention should be paid to potential hotspots along the road between such intersections.

3.2. *Online poll*

A total of 3834 people participated in the survey. The sample was characterized by a relatively balanced age distribution of the middle age groups (20–29: 18.7%; 30–39: 24.2%; 40–49: 18.4%; 50–59: 22.1%). The youngest and older age groups were less well represented (15–19: 3.3%; 60–69: 10.3%; ≥70: 3.0%). In comparison with the German population, young adults (20–39 years old) especially were particularly highly represented in the sample. There was a relatively strong gender bias in the sample with an overrepresentation of males over females (males: 59.2%; females: 39.4%; non-binary: 1.3%). Participants lived primarily in two-person households (40.2%) or one-person households (24.5%). However, one-person households were significantly underrepresented compared to the German average. They were predominantly employed (76.0%) and had a high level of education (university degree: 56.1%), both above the German average. About one third of participants were e-scooter users.

3406 participants answered the questions on conflicts. Of these, 89.2% reported that they had already experienced some kind of conflict with an e-scooter as an e-scooter user, a cyclist or a pedestrian. Figs. 3 and 4 show the type of conflicts experienced by e-scooter users, cyclists and pedestrians. Of the e-scooter users, one third had not yet experienced any conflict. The most frequent situations were those in which e-scooter users had to slow down or swerve due to other road users (multiple answers possible). Falls or near falls without the involvement of other people were comparatively common. Only e-scooter users had already collided with other road users. Among cyclists, a comparatively high proportion had not yet experienced any conflict situation with e-scooters. The most frequent conflict situations related to parked e-scooters (annoyed by incorrectly parked e-scooters, swerving due to a parked e-scooter). In addition, situations mentioned similarly by e-scooter users occurred quite often: swerving due to a moving e-scooter or driving slower. A quarter of cyclists had been annoyed by the behavior of a person on an e-scooter. Among pedestrians, only about one sixth of respondents stated that they had not experienced any conflict with e-scooters. Similarly to cyclists, parked e-scooters were seen as the main problem but to a much higher degree. Every sixth pedestrian had already tripped or fallen because of a parked e-scooter. Conflicts also frequently occurred with moving e-scooters. Almost half of pedestrians had to swerve due to a moving e-scooter or had been annoyed by their behavior. More than a quarter had nearly collided with a moving e-scooter, 4% had a collision.

The detailed analyses on the characteristics of the locations are based on 630 reported conflicts from the perspective of e-scooter users, 1407 from the perspective of cyclists, and 2690 from the perspective of pedestrians. The location of the most serious conflict experienced was queried in three categories: small-scale description of the conflict location (straight stretch, curve, intersection, narrow section, etc.), type of road (major road, minor road, bike lane, sidewalk, bus lane, etc.), and type of situation (when going straight, when turning, when overtaking, etc.) (Table 2). Nearly half the conflicts

Table 1 – Nine key statements mentioned by the experts.

Statement	Mentioned by expert
Parking as major cause	MR2, MR3, MR4, MR5, MR6, MR7, MR8, MR9, MR10, OP1, OP3, OP4, RE1
Dense urban areas with different modes of transport	MR2, MR4, MR7, MR8, OP2, RE1
Tourist spots	MR4, MR7, MR9, RE1
E-scooters and pedestrians using the same road space	MR2, MR4, MR5, MR7, MR8, MR9, OP1, OP4, RE1
Similarities to other modes (bike)	MR3, MR4, MR6, MR8, MR9, OP3, OP4, RE1
At intersections	MR3, MR4, MR6, MR8, RE1
Along the road	MR1, MR5, MR6
Improper use/alcohol	MR1, MR2, MR3, MR4, MR5, MR6, MR8, MR9, MR10, OP1, RE1
Importance of high-quality infrastructure	MR1, MR2, MR3, MR5, MR6, MR7, MR8, MR9, MR10, OP1, OP2, OP3, OP4, RE1

Note: MR = municipal representative; OP = operator; RE = researcher.

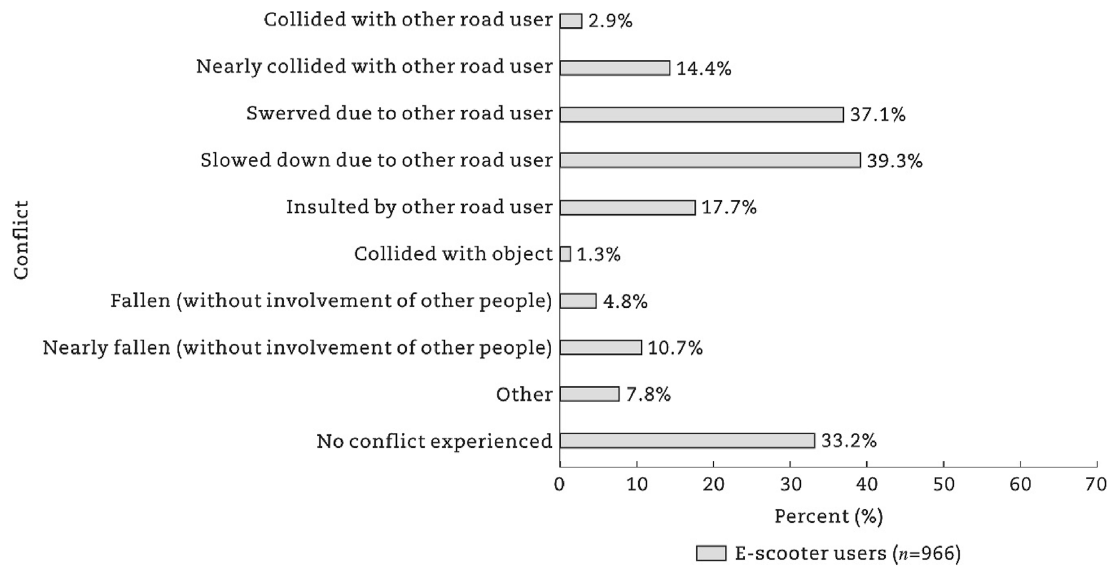

Fig. 3 – Conflicts experienced by e-scooter users (source: own survey).

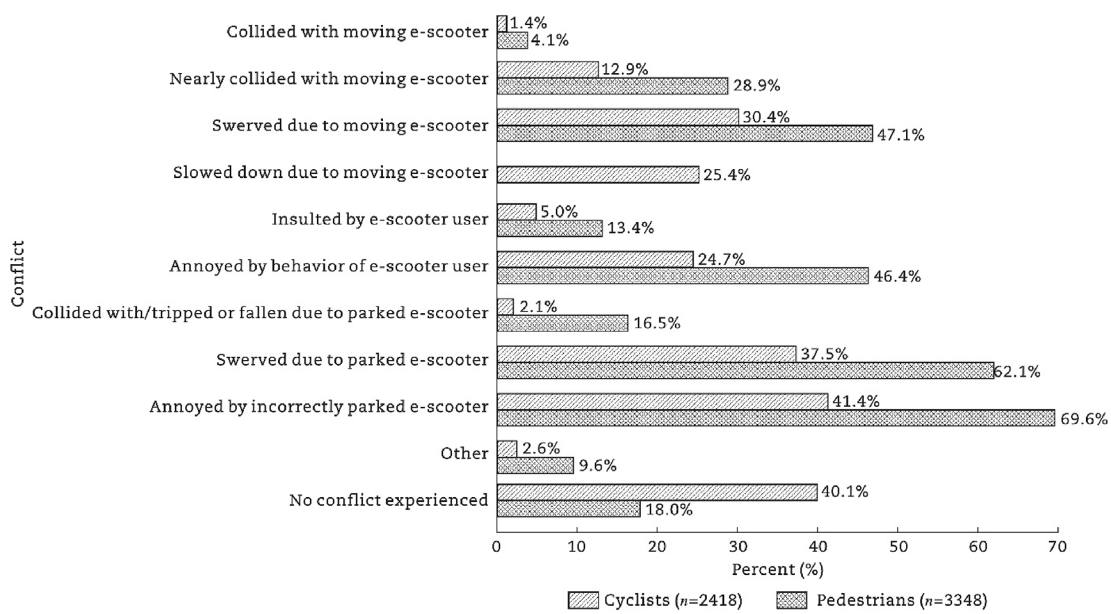

Fig. 4 – Conflicts with e-scooters experienced by cyclists and pedestrians (source: own survey).

between e-scooters and cyclists or pedestrians occurred on a straight stretch. Cyclists and pedestrians also experienced conflicts in narrow sections comparatively frequently (about one in five). In contrast, for e-scooter users, intersections were the second most frequent location of conflicts. Not surprisingly, pedestrians experienced conflicts with e-scooters mainly on the sidewalk, cyclists in the bike lane or in a bike lane on the bike path. The conflict locations among e-scooter riders were more differentiated: in the bike lane, on major roads, on minor roads, and in bike lanes on the roadway. In contrast, from the perspective of e-scooter users, conflicts on the sidewalk were rare. Consistent with the high proportion of conflicts on straight stretches, conflicts reported by e-scooter users or cyclists were often situations of simply going straight, or walking or standing in the case of pedestrians, respectively.

3.3. *Quantitative analyses*

The merged datasets developed in section 2.3.3 are used for identifying the e-scooter hazard spots. From both categories (crashes and incidents) the clusters were sorted according to the amount of e-scooter traffic volume normalized by the length of the network inside the cluster that is suitable for bikes/e-scooters. The top 20 (i.e., those clusters with the highest e-scooter traffic volume) were selected as a longlist. This longlist forms the basis for selecting the final hotspots in the subsequent expert workshop.

Table 2 – Location description of conflicts experienced (source: own survey).

Conflict experienced	e-scooter users ($n = 603$)	Cyclists ($n = 1407$)	Pedestrians ($n = 2690$)	All
Small-scale description				
Straight stretch (%)	49.5	54.9	44.6	48.3
Curve (%)	6.7	12.4	6.6	8.3
Intersection (%)	18.3	8.0	5.9	8.5
Roundabout (%)	1.7	0.6	0.4	0.7
Narrow section (%)	9.5	18.0	21.6	18.7
Traffic lights (%)	3.8	2.2	5.1	4.0
Crosswalk (%)	1.7	0.7	2.8	2.0
Driveway (%)	4.8	1.5	4.0	3.4
Public transport stop (%)	4.0	1.7	8.8	6.1
Number	475	865	1700	3040
Type of road				
Major road (%)	19.2	12.3	11.0	12.6
Minor road (%)	16.9	8.9	4.7	7.7
Traffic-calmed street (%)	6.2	3.8	2.4	3.3
Bike lane (%)	14.0	17.8	2.5	8.6
Bike path (%)	28.5	47.4	6.5	21.5
Bus lane (%)	1.2	0.4	0.0	0.3
Sidewalk (%)	8.5	6.1	61.9	38.0
Pedestrian area (%)	2.7	1.7	8.6	5.7
Park (%)	2.9	1.6	2.4	2.2
Number	485	953	1871	3309
Type of situation (%)				
Going straight (%)	59.5	70.7		66.7
Turning (%)	10.9	9.6		10.1
Overtaking (%)	12.7	12.1		12.3
Starting (%)	4.4	2.5		3.2
Slowing down (%)	5.4	0.8		2.5
Waiting (%)	4.6	1.4		2.6
Parking (%)	2.5	2.9		2.8
Crossing a road (%)			12.1	
Walking or standing (%)			80.5	
Getting on or off public transport (%)			7.4	
Number	479	853	1572	1332

3.4. *Shortlist of hazard hotspots*

We briefly describe below the resulting locations of interest. They are selected in an expert workshop based on the previous analyses as described in 2.4. All locations selected for shortlist are shown in Fig. 5, with crash clusters in red and incident clusters in yellow. All locations are located in the inner city of Berlin. As can be seen, crash and incident clusters coincide at two locations.

Below, a detailed overview of the relevant parameters in the shortlist is provided. The properties of each hotspot are described. It is indicated whether a crash or incident cluster for bicycles is located at the hotspot and if scooter crashes occurred. The total number of scooter trips in the cluster as well as the scooter trips per kilometer is also stated. In addition, the volume of pedestrians, bicycles, cars, public transport options, and tourists is assessed. Finally, the type of location is indicated. The numbers in parenthesis refer to Fig. 5.

(1) Unter den Linden/Brandenburger Tor Station

This location is identified as a crash cluster and incident cluster. It is specified as a square. There is also a large pedestrian area on one side. The area is characterized by many pedestrians and cyclists, quite a lot of them are tourists as this is the location of one of the city's most important tourist spots. There are 30,220 scooter trips and 57,145 trips per kilometer (see Fig. 6).

(2) Oberbaumbrücke/Mühlenstrasse

This location is specified as an incident cluster and as a large intersection. The area is characterized by the highest levels of cycling traffic in the city. In addition, there is a lot of motorized transport on both intersecting streets. There are 22,147 scooter trips and 28,092 trips per kilometer (see Fig. 7).

(3) Zoo/Hardenbergplatz

This location is identified as an incident cluster. It is specified as a high traffic area with a large intersection. It is characterized by many pedestrians, as it is one of the most important intermodal hubs in the city with many people changing between different means of transport. It is also a densely used urban center with all kinds of functions. In addition, there is a lot of car and bicycle traffic and many

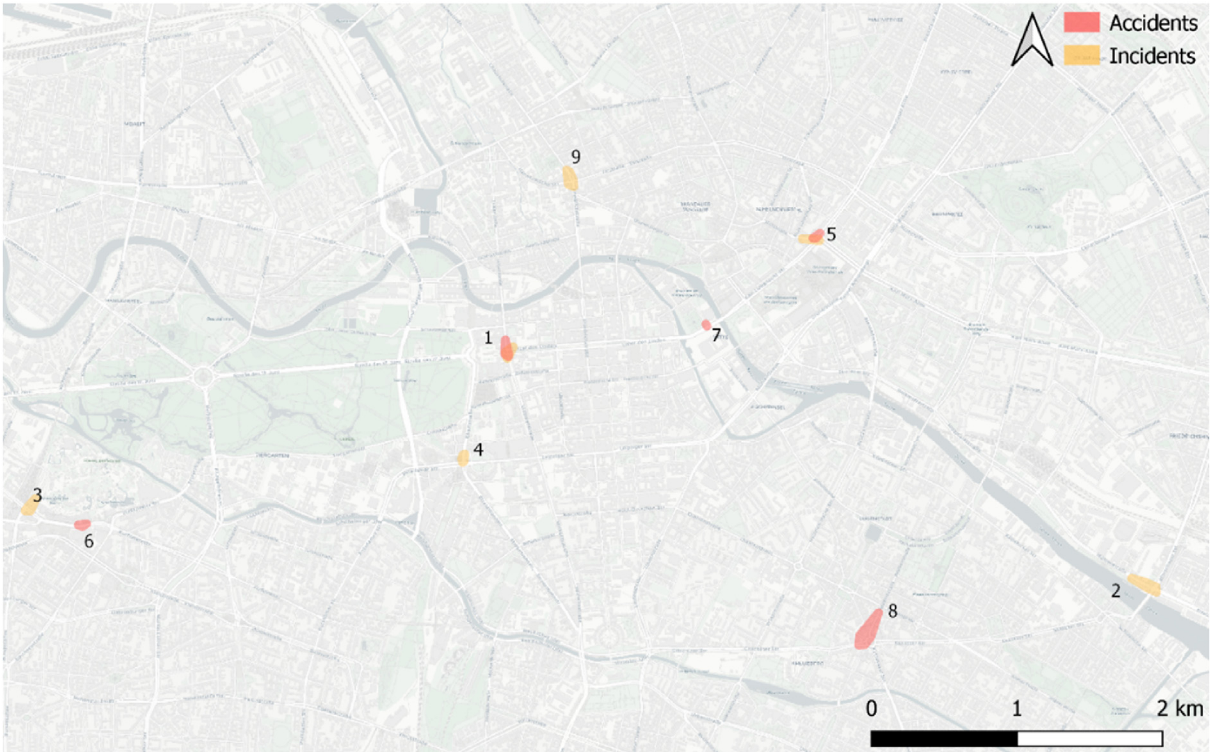

Fig. 5 – Locations of hazard hotspots in the city of Berlin (background map: CartoDB).

Fig. 6 – Arial view of unter den Linden/Brandenburger Tor Station (source geoportal Berlin/DOP20RGBI).

tourists. We found 18,913 scooter trips and 28,032 trips per kilometer (see Fig. 8).

(4) Potsdamer Platz

This location is identified as an incident cluster. It is specified as a large square with a large intersection, bus and bicycle lanes and public transport stations. This area is characterized by many pedestrians, cyclists and cars. There are 26,353 scooter trips and 36,158 scooter trips per kilometer (see Fig. 9).

(5) Alexanderplatz

This location is identified as a crash cluster and incident cluster. It is specified as large intersection with many pedestrians and cyclists (as there is a large pedestrian square with malls and public transport stations) as well as many cars. The area is characterized by a lot of public transport and can be described as a (public) transport hub. We found 26,654 scooter trips and 69,894 trips per kilometer in this cluster (see Fig. 10).

(6) Budapester Strasse

This location is identified as a crash cluster. It is located on the edge of the western city center with considerable volumes

Fig. 7 – Arial view of Oberbaumbrücke/Mühlenstrasse (source Geoportal Berlin/DOP20RGBI).

Fig. 8 – Arial view of Zoo/Hardenbergplatz (source Geoportal Berlin/DOP20RGBI).

Fig. 9 – Arial view of Potsdamer Platz (source Geoportal Berlin/DOP20RGBI).

Fig. 10 – Arial view of Alexanderplatz (source Geoportal Berlin/DOP20RGBI).

Fig. 11 – Arial view of Budapester Strasse (source Geoportal Berlin/DOP20RGBI).

of tourists/pedestrians, cyclists and cars. On this stretch we found 20,838 scooter trips and 80,660 trips per kilometer (see Fig. 11).

(7) Schlossplatz

This location is identified as a crash cluster. It is characterized by being the center of the "Museumsinsel" (Museum Island) which can be described as one of the tourist highlights. It is therefore specified as an area with many pedestrians, cyclists and cars as well as lots of tourists. We found 18,989 scooter trips and 81,338 trips per kilometer (see Fig. 12).

(8) Adalbertstrasse

This location is identified as a crash cluster. It is specified as a narrow section and crash accumulation line with a bus stop and crosswalk. It is a dense urban area with many different functions and a high population density. There are considerable volumes of cyclists, cars and pedestrians, but not so many tourists. 18,424 e-scooter trips and 13,247 trips per kilometer were counted (see Fig. 13).

(9) Oranienburger Tor

This location is identified as an incident cluster. It is characterized as a confusing intersection with tramway lines crossing and narrow sections. It includes cyclists, pedestrians,

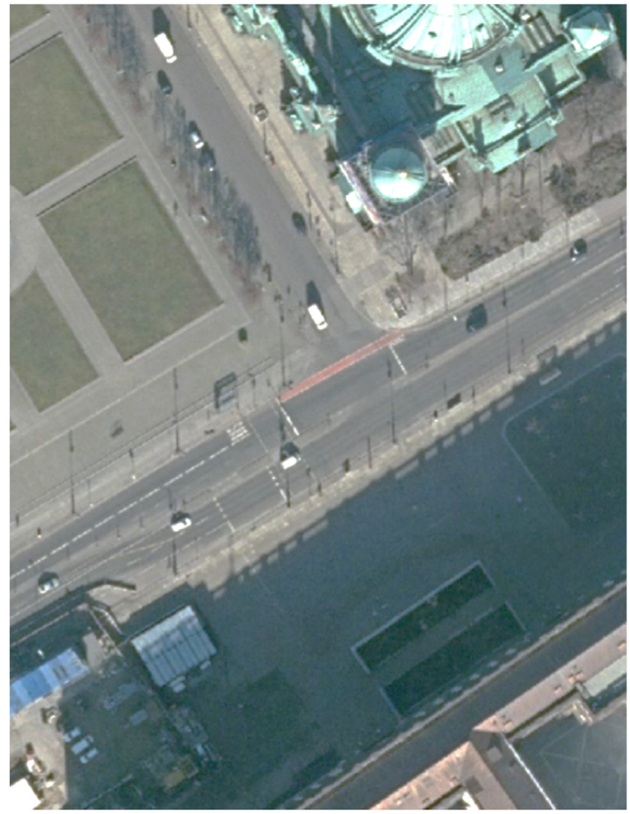

Fig. 12 – Arial view of Schlossplatz (source Geoportal Berlin/DOP20RGBI).

Fig. 13 – Arial view of Adalbertstrasse (source Geoportal Berlin/DOP20RGBI).

Fig. 14 – Arial view of Oranienburger Tor (source Geoportal Berlin/DOP20RGBI).

cars, public transport, and tourists. There are 16,173 scooter trips and 26,146 trips per kilometer (see Fig. 14).

4. Discussion

The present submission develops an approach to identifying e-scooter hazard hotspots based on data analysis and additional quantitative and qualitative surveys. Since e-scooters is a relatively new mode of transport, a lack of data and knowledge of specific hazard hotspots can be observed. We combine different methods and use data from various origins to generate a basis for discussion. As a result, bicycle crash data and data of bicycle incidents conducted in a crowdsourcing tracking project are spatially clustered. In many cases, the incidents spatially match the official crash statistics, particularly in regions with a high volume of crowdsourced trips. The crowdsourced dataset additionally includes some areas where there was no observable accumulation of officially reported crashes but which, based on the expert discussions, still represents dangerous locations. Generally, the result of the clustering demonstrates a high level of agreement with the expert evaluation. Adding the number of trips made by e-scooters for each cluster results in an illustration of the most hazardous spots for e-scooter riders in the city of Berlin.

One key finding of the online poll is that parked e-scooters are very important. Parked e-scooters caused the majority of conflicts with pedestrians as delivered by the online questionnaire. The majority of experts also mentioned improper parking as a crucial reason for conflicts. This finding is in line with prior research and corresponding recommendations (Gössling, 2020; Gubman et al., 2019; Santacreu et al., 2020). In addition, the experts interviewed claimed that a high-quality bike infrastructure is extremely important when aiming to increase the safety of both cyclists and e-scooter users as vulnerable traffic participants. This finding is in line with earlier research (Arndt et al., 2020; Gössling, 2020; Gubman et al., 2019; Markvica et al., 2020; Santacreu et al., 2020).

It can be seen that all hazard hotspots are located in the inner city with many large intersections identified. At these locations, pedestrians, cyclists, public transport passengers, motorists, and e-scooter users caused many interactions. Crash accumulation lines are also of interest. This is plausible since the e-scooter as a vehicle with high acceleration but limited maximum speed may be responsible for additional passing maneuvers with bicycles. This finding is supported by the results of the online poll, the expert interviews and the qualitative workshop.

The present study identifies and characterizes e-scooter-specific hazard hotspots. It therefore adds to the status of research which has mainly specified risky types of locations to date (Cicchino et al., 2021; English et al., 2020).

Since the approach relies on official crash statistics that are available for most regions in Germany and the tracking data are available for a few other cities, the clustering approach can be transferred at least partially to other regions.

The limitations of the approach are discussed below. The online poll is based on a self-selective and not representative sample. Hence, there are substantial distortions compared to the sociodemographics of the whole population. Due to the recruitment method, the sample is also specific regarding preferences for social media and ICT. Given the large number of participants and the extra recruitment of disabled persons, we assume the sample represents e-scooter users and other traffic participants affected by e-scooter usage. Regarding the quantitative analyses, the data-driven approach uses mainly data referring to bicycles as a mode of transport. As seen in the expert interviews and the final workshop, this procedure is considered good as the modes are related. Both are single-track vehicles unprotected by any vehicle body and move with comparable speed. E-scooter users also have to use the bike infrastructure wherever available. The approach is also supported by further research (Gehrke et al., 2022; Leschik et al., 2022). On the other hand, there are structural differences between an e-scooter and a bicycle as vehicles. This is taken into account specifically by looking at hotspots not only at intersections but also along the road. Nevertheless, we do not know if the locations determined are the riskiest places for e-scooters. Given the lack of data on e-scooters specifically, the present approach appears to be the best approximation. Future research will need to prove the assumptions.

5. Conclusions

E-scooters are a relatively new phenomenon in urban mobility. The present contribution demonstrates an approach to identifying hazard hotspots where there is a high risk of conflicts and crashes occurring between e-scooters and active modes of transport. The key findings are as follows. First, a great many conflicts with pedestrians are caused by parked and unused e-scooters. Second, as scooter trips are concentrated in the inner city and along specific routes, hotspots along these routes can be identified using data gathered by cyclists. Third, these hotspots are mainly located at large intersections and to a lesser extent along roads between intersections. Results show that the approach is suitable for the task and delivers the basis for further research.

Based on the results, we offer recommendations for future research as well as practice and planning. First, future research should focus on the locations identified and investigate the movements of e-scooters as well as interactions with cyclists and pedestrians, e.g. using video analyses. This may add to the status of research which has focused to date on the analysis of reported crashes and injuries in order to evaluate the risk of this new type of vehicle. The authors are currently conducting this research. Second, there is a need for more data on e-scooters because the present approach uses mainly bicycle data, and it is only most recently that e-scooter data are becoming available. Third, municipalities and operators need to address the issue of e-scooter parking. A great many conflicts could be prevented by orderly parking.

Conflict of interest

The authors do not have any conflict of interest with other entities or researchers.

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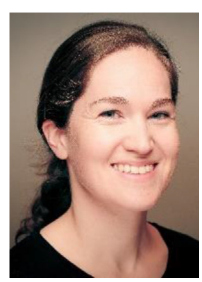

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