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Micro-mobility and road safety: why do e-scooter riders use the sidewalk? Evidence from a German field study

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Abstract

Objectives Since their introduction in 2019, the use of e-scooters has become widespread in Germany. Concerns about road safety, especially pedestrian safety, have arisen as the popularity of micro-mobility has grown. In light of this context, the present study investigates which types of road infrastructure e-scooter riders use, with a focus on riding on the sidewalk, which is not permitted in Germany. We considered the following infrastructures: (1) off-road bike lane (+ sidewalk and road), (2) on-road bike lane (+ sidewalk and road), and (3) road (+ sidewalk).

Methods Observations at six sites (recording 738 e-scooter riders) and on-site surveys (involving responses from 129 e-scooter riders) were conducted in two German cities in August 2020 and September 2020.

Results Self-reported sidewalk riding was not found to be linked directly to a lack of rule knowledge, a preference for this type of infrastructure, or perceived safety. Observations indicated that using the sidewalk might be related to situational components, such as comfort or convenience, comprising up to 40% of instances of sidewalk riding.

Conclusion Considering the comfort and convenience factor of sites when building or improving cycling infrastructure can help keep e-scooter riders from riding on the sidewalk.

Keywords e-scooter rider, Micro-mobility, Sidewalk riding, Pedestrian safety, Observational study, Infrastructure use

1 Introduction

E-scooters, a term that describes electrically powered two-wheeled scooters with a handlebar that allows them to be ridden while standing on a board between the two wheels, have appeared relatively suddenly and on a large scale on roads around the globe. In fall 2017, e-scooter sharing services emerged in the United States, eventually becoming widespread in major US cities [19]. In Europe, launch dates varied across countries, beginning in summer 2018 in Paris, France [11]. By 2019, shared e-scooters were present in all major European cities except London [7]. Since a national regulation on light electric vehicles came into force in June 2019, Germany has experienced an increasing number of e-scooter riders, culminating in the establishment of e-scooter sharing services in approximately 50 German cities (status: 01/2021) [13].

1.1 E-scooter riding in Germany

At the time of data collection in the study cities, two scooter-sharing services were active in Dresden, while Berlin featured six active scooter-sharing companies. To date, no modal split data on e-scooter use in Germany is available. According to German regulations and similar to bicycles, [1] e-scooters (limited to 20 km/h) must be

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[1] Sidewalk riding is also prohibited for cyclists unless explicitly permitted by an additional traffic sign ("Radfahrer frei").

used on cycling infrastructure or, if such is unavailable, they must share the road with other motorized means of transportation [49]. In addition, e-scooter riders must be at least 14 years old, and the e-scooter needs to have an insurance license plate. Wearing a helmet is not mandatory for e-scooter riders.

1.2 E-scooter crash data

The growing popularity of e-scooter usage has led to questions about the safety of these vehicles [28]. Hospital and police reports provide a first impression of the current situation. In the United States, 2 to 2.5 e-scooter-related injuries per 10,000 trips were reported [2, 34]. Official figures for Germany show that, in the first nine months of 2020, 1,096 e-scooter riders were lightly and 269 severely injured in police-reported crashes. Seven e-scooter riders died following their crashes in the first nine months of 2020 [43]. Hospital reports show that single-vehicle crashes represented a major portion of injury crashes, including about 75% of e-scooter crashes in Berlin in the month of July 2019 [47] and more than 90% in Frankfurt between July 2019 and March 2020 [45].

One aspect that stands out from the current crash data is that a considerable number of incidents is accompanied (or even caused) by the rider's incorrect use of the road infrastructure. Nevertheless, according to the Berlin Police [3], of the 284 crashes[2] recorded between June 2019 and December 2019, around 24% occurred on sidewalks. Moreover, between June 2019 and March 2020, approximately 1000 traffic violations were filed in Berlin for e-scooters ridden on sidewalks [4]. A recent US review study states the rate of e-scooter incidents on the sidewalk is between 10 and 58% [39]. Another review study of international hospital reports, including over 5.000 injured in an e-scooter crash, showed that 26.2% of patients were hurt on the sidewalk [41].

1.3 Perception of e-scooter riders by other vulnerable road users

This type of behavior is specifically concerning to other vulnerable road users who may be negatively impacted by the presence of e-scooters using pedestrian infrastructure. Even before e-scooters were legal in Germany, pedestrian/cyclist interest groups raised concerns about potential negative consequences, which the media then echoed [37, 51]. Pedestrian organizations especially note risks for children, impaired individuals, and older people in potential conflicts with e-scooter riders [10]. According to a survey conducted in Rosslyn, VA, when asked about their perception of safety while walking around e-scooter riders, 56% of respondents felt "unsafe" or "very unsafe" [17]. Similarly, Mayer et al. [24] found in an Austrian survey study that 77% of non-riders and 71% of e-scooter riders thought that an e-scooter could be "somewhat dangerous" or "very dangerous" for pedestrians. In addition, more than three-quarters (77%) stated that they had experienced a near crash with an e-scooter rider in the past. Meanwhile, one report from the United States indicated that in approximately 8% of all e-scooter crashes that resulted in injury, the injured party was a pedestrian [46]. Mayer et al. [24] demonstrated that 7.4% of e-scooter crashes involved pedestrians and that one-quarter of e-scooter crashes occurred on pedestrian infrastructure. A study by Useche et al. [48] utilizing external raters (non-e-scooter riders and non-cyclists) showed that e-scooter riders are expected to show more risky riding behavior than cyclists.

1.4 E-scooter riders' infrastructure preferences

At the same time, it must be noted that e-scooter riders do not necessarily prefer to ride on the sidewalk. Initial studies have shown that the majority of e-scooter riders actually reported a preference for cycling infrastructure (62% to 82%) [1, 24]. That said, research findings have indicated that sidewalk riding occurs despite the riders' stated preference for other types of infrastructure, dependent on what infrastructure is available as well as the presence of motorized traffic [24, 34]. Accordingly, observational studies found variable use of dedicated infrastructure ranging from 21 to 73% [24, 34]. Specifically, as proximity to motorized traffic and roadway speeds increased, e-scooter riders more often chose to ride on the sidewalk [24, 29, 34]. This observation is in line with findings from cycling research showing that volume, speed, and distance of motorized traffic are crucial factors when determining perceived safety [42]. A pilot evaluation by Currans et al. [9] showed that the experience of a collision and the presence of bike lanes correlate with sidewalk use. In line with this, Pazzini et al. [29] showed that e-scooter riders preferred the bike lane over the road for sites with good separation between both. Where there was a bike lane at road level, e-scooter riders were more likely to ride on the sidewalk than use the on-road bike lane [29]. The observation study findings by Huemer et al. [16] imply that riders might use the sidewalk to compensate for secondary task engagement. The results showed a higher likelihood of sidewalk riding when users were operating a phone, eating, drinking, or smoking while riding. Also noteworthy is that different types of infrastructure are accompanied by different e-scooter riding speeds, with the lowest average speed typically observed for the illegal use of the sidewalk [24].

[2] A crash is recorded when reported to the police, including single-vehicle incidents and collisions with any type of road user.

1.5 E-scooter riders' rule knowledge

E-scooter riders' potential lack of rule knowledge, including understanding which infrastructure they may legally use, is worth considering in this context. In the absence of standardized training, whether the riders know the rules becomes the riders' responsibility (and, to some degree, that of the providers of shared e-scooters), which is likely to result in considerable variations in the level of knowledge. This variability is also reflected in findings from some surveys; for example, while Petzoldt et al. [30] reported a rate of up to 92% correct responses when determining whether to use sidewalks or pedestrian areas, Mayer et al. [24] found that as many as one-fifth of riders believed they were allowed to use the sidewalk. A follow-up evaluation in Portland showed that riders' rule knowledge improved within one year, from 77% of respondents rating that e-scooters are not allowed on the sidewalk in 2018 to only 5% wrongly assuming that sidewalk riding is legal one year later [33, 35]. The high share of rule knowledge, a possible improvement over time, and differences in the relative frequencies suggest also considering rule knowledge in the present study.

Overall, available figures and studies show that e-scooters, as a new means of transportation, pose a certain road safety risk to riders and other road users alike (especially those who are vulnerable). Even though the improper use of road infrastructure, particularly driving on sidewalks, seems to offer a partial explanation, a deeper understanding of the circumstances of this behavior and of riders' general infrastructure preferences is lacking.

1.6 Aim and research design

Therefore, this study aimed to describe how the available road infrastructure might be linked to where e-scooter users ride, how those riders' decisions might contribute to safety–critical events, and what implications can be derived for interventions to improve road safety.

The second aim was to understand whether riding on the sidewalk (as well as riders' use of infrastructure in general) reflects e-scooter riders' actual preferences and whether knowledge of the rules is related to the suspected improper behavior. We hypothesized that knowledge of the rules is a necessary (but insufficient) condition and that perceived safety is a key factor for infrastructure choice. In addition, we hypothesized that situational components, such as comfort or convenience, may outweigh the former two components.

To address these research questions, we combined on-site observation with on-site survey data in an explorative manner. Observation data were needed to explore e-scooter riders' revealed preferences for various road infrastructures and incidents involving other road users. The survey data completed this picture by providing both stated preferences and information about e-scooter riders' rule knowledge.

In the next sections, the observation methods and results are described first, followed by the survey methods and results, and finally brought together in the discussion.

2 Observation

2.1 Observation methods

The data were collected from on-site observations in the German cities of Dresden and Berlin in August 2020 and September 2020. The data used in this study are part of a larger dataset collected in a German research project that examined various aspects of e-scooter riders' road safety [36].

2.1.1 Observation sites and tool

In the selection of our observation sites, we took care to include only streets and locations that e-scooter riders frequently used. For this purpose, personal observations were made, and traffic volume maps were consulted (for Berlin based on the findings of civity [7], and for Dresden based on information provided by the city administration). Also, we chose sites with varying infrastructure facilities that were also potentially prominent nightlife activity locations. This selection resulted in a broad spectrum of behavioral options (regarding infrastructure use, speed, etc.) for the observed riders. In terms of the type of infrastructure, e.g., cycling infrastructure, the sites are a good representation of common urban settings in German cities.

Table 1 provides an overview of the six observation sites' characteristics. Figures 1 and 2 show the observation sites on a map detail per city. A more detailed description of each site, especially in terms of infrastructure characteristics, is provided in the results section.

The observation sites were located mid-block rather than at intersections to limit the level of complexity for the observers and to exclude other traffic issues related to intersections. The length of the observation areas varied between 70 and 80 m. Two hypothetical lines defined by landmarks (such as lamp posts) marked the beginning and end of the observation areas. Observation started as soon as an e-scooter rider entered the area indicated by the landmarks and ended when the rider left that area.

To record e-scooter riders' characteristics and behavior, we developed an observation protocol based on the open source tool Observation 3.0 [50]. The digital protocol allowed for a free definition of observation categories and implementation on mobile devices (e.g., tablets). During its development, the observation protocol was tested and adjusted several times. The four observers were trained

Table 1 Characteristics of observation sites. Infrastructure dedicated to e-scooter riders is underlined

Type of infrastructure	Sites	Speed limit (road)	Characteristics
<u>Off-road bike lane</u>[a] (+ sidewalk and road)	B1	50 km/h	Nightlife hotspot; physical barrier to sidewalk
	B2	30 km/h	Bus station next to bike lane; high pedestrian density
<u>On-road bike lane</u>[b] (+ sidewalk and road)	D1	20 km/h	Tourism hotspot; large square with high amenity value
	B3	50 km/h	Nightlife hotspot
Road (+ sidewalk)	B4	50 km/h	Tourism hotspot
	D2	7 km/h	Tourism hotspot; high pedestrian density; cobbled road

D Dresden, *B* Berlin

[a] Off-road bike lane = bike lane above road level next to, but segregated from the sidewalk by a physical barrier, solid marking line, and different paving and color

[b] On-road bike lane = bike lane at road level, segregated from motorized traffic by a solid marking line; motorized traffic is not allowed to drive over the marking for overtaking

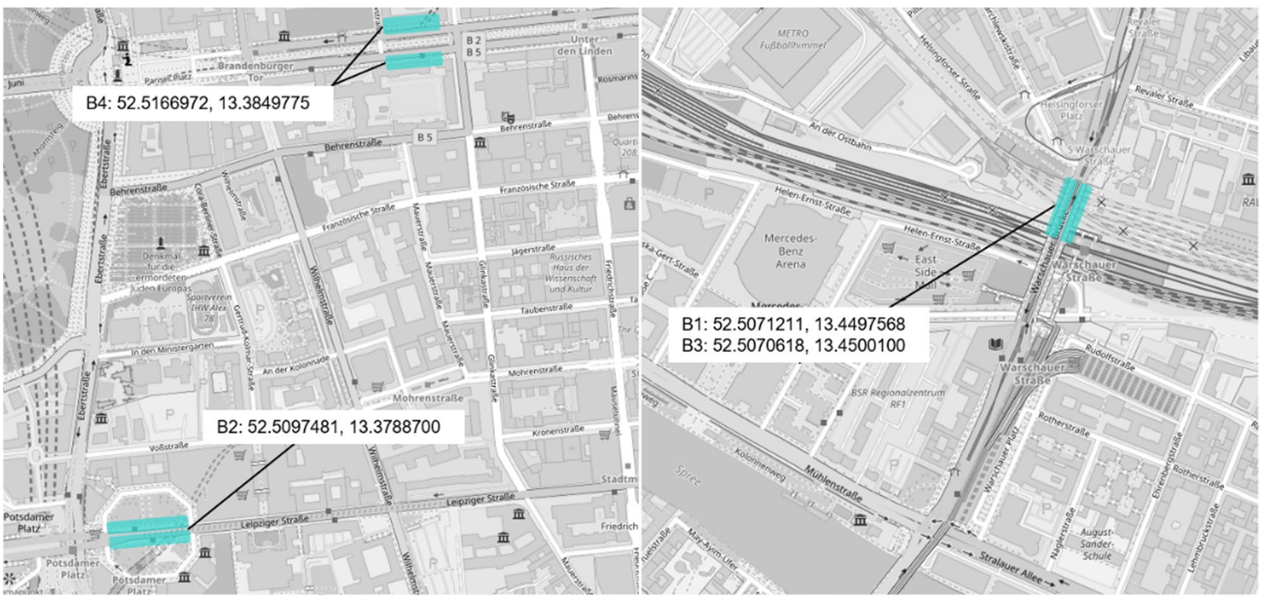

Fig. 1 Observation sites in Berlin. Map: © openstreetmap.de, 2022

Fig. 2 Observation sites in Map: © openstreetmap.de, 2022

together to maximize inter-rater reliability. Results are reported at the beginning of Sect. 2.2.

2.1.2 Observation measures

On-site observations were used to describe the observed e-scooter riders, investigating the infrastructure they used, along with any critical events. The measures were defined as follows:

- *Apparent sex* Coded as female, male, and not answerable (when unidentifiable).
- *Apparent age* Coded by trained observers as child (< 14 years), adolescent (15–20 years), young

adult (21–40 years), adult (41–65 years), senior (>65 years), or N/A (when unidentifiable).

- *Mode* Type of vehicle used by the observed e-scooter rider; coded as shared e-scooter, private e-scooter, or N/A (when unidentifiable).
- *Type of infrastructure* Infrastructure the e-scooter rider was using when they entered the observation area. Available infrastructure depended on the site (see Table 1 for details).
- *Incidents* Based on definitions within the German Traffic Conflict Technique Manual [12], interactions and conflicts were differentiated by the appearance of evasive actions. In addition, near single-vehicle crashes were coded. In recording potentially problematic events, we differentiated between interactions, conflicts, crashes, near single-vehicle crashes, and none.
    - *Interaction* A situation that would have led to a collision between the observed e-scooter rider and another road user if no one had braked or changed direction. The situation was easily resolved and controlled by the road users involved.
    - *Conflict* A situation that would have led to a collision between the observed e-scooter rider and another road user if no one had braked or changed direction. However, different from an *Interaction*, the observed e-scooter rider or the other involved road user had to brake or change direction of travel abruptly to prevent a collision (i.e., the level of urgency for action was heightened considerably).
    - *Near single-vehicle crash* E-scooter rider almost falls.
    - *Crash* Collision of an observed e-scooter rider with another road user.
    - *None.*
- *Other road user(s) involved in incidents*. The types of road user(s) involved in an interaction, conflict, or crash were coded as follows:
    - *Motorized transport*
    - *Cyclist*
    - *E-scooter*
    - *Pedestrian*

2.1.3 Observation procedure

Four trained observers conducted the observations in Dresden (August 18–22) and Berlin (September 1–5). We developed our observation schedule based on the findings of civity [7], which revealed that e-scooters are predominantly used between 2:00 p.m. and 8:00 p.m. on workdays. On Friday and Saturday, however, usage continues into the late evening hours. Accordingly, to capture potential e-scooter use in the dark, we extended the observation times for the two tourism hotspot observation sites and two nightlife hotspot observation sites into the late evening/night. Street lighting at the selected sites allowed all measures to be observed even under nighttime conditions. For each city, observations took place Tuesday–Thursday, 2:00 p.m.–8:00 p.m., Friday, 2:00 p.m.– 12:30 a.m., and Saturday, 2:00 p.m.–11:00 p.m. In total, we collected 67 h of data in Dresden and 56 h of data in Berlin.

Table 2 Sociodemographic characteristics of observed e-scooter riders (n = 738) in percentages

Sociodemographic characteristic	Definition	%
(Apparent) sex		
	Female	24.7
	Male	75.3
(Apparent) age		
	< 14	1.0
	14–20	16.5
	21–40	67.6
	41–65	14.6
	65 +	0.1
Mode		
	Shared e-scooter	94.4
	Private e-scooter	5.6

2.2 Observation results

2.2.1 Observation sample

We observed 923 e-scooter riders in total. Only observations of e-scooter riders traveling in the direction of other motor vehicles were analyzed (90% of cases), as the focus of the current paper does not include e-scooter riders who choose to travel against traffic ("wrong-way" riders) [3]. In addition, observed e-scooter riders at one site where only a pedestrian area was available were excluded because the focus of the current study is on infrastructure choice, which required at least two different infrastructures to be available per site. Thus, the analyzed observation sample comprised 738 e-scooter riders. The sample was dominated by e-scooter riders using sharing services and male riders (see Table 2 for sample details).

[3] The group of wrong-way riders comprised 10% of the sample and was not evenly distributed between the observation sites and therefore omitted.

Fig. 3 Site B1 – Berlin, Warschauer Brücke west; length of observation area: 80 m; off-road bike lane width: 1.7 m; sidewalk width: 3.6 m; pedestrians per 5 min: 50; cyclists per 5 min: 41

2.2.2 Inter-rater reliability

Inter-rater reliability was determined by asking teams of two observers to record data on the same site for the same one-hour sessions. Unweighted Cohen's Kappa [8] was used to calculate observer agreement. Inter-rater reliability was excellent for observations on the infrastructure used (κ = 0.94), incidents (κ = 0.94), and involved road users in incidents (κ = 0.98) [20].

2.2.3 Infrastructure use

2.2.3.1 Off-road bike lane (+ sidewalk and road) At site B1, featuring an off-road bike lane, almost none of the observed e-scooter riders used the sidewalk or the road. Instead, most of the e-scooter riders (> 90%) used the off-road bike lane in accordance with regulations. This observation is unsurprising, as there was a physical barrier between the sidewalk and the off-road bike lane (see Fig. 3), and the height difference between the bike lane and the road was a considerable 16 cm.

In contrast to site B1, there was no physical barrier between the off-road bike lane and the road at site B2 (Fig. 4). However, the observation results were very similar, with no differences in the use of infrastructure compared to sites B1 and B2 (Fig. 9) ($\chi^2 = 0.05$, df = 2, $p = 0.975$). E-scooter riders rarely used the sidewalk or the road (around 3% of observed riders each). The results indicated that a physical barrier might not even be necessary to encourage e-scooter riders to use the dedicated infrastructure.

2.2.3.2 On-road bike lane (+ sidewalk and road) Nearly one-third of e-scooter riders observed at site D1, where an on-road bike lane was available, rode on the sidewalk. Site D1 (in Dresden) featured two large squares with fountains and adjacent seating directly in front of the Kulturpalast, a tourist attraction (Fig. 5). According to the survey results, the e-scooter riders were primarily not locals (see Sect. 3.2). Combined with the high amenity value of the site, it is plausible that their visitor status might lead many e-scooter riders to use the sidewalk to look around the square, take a break, or take photos. In addition, the height difference between the on-road bike lane and the sidewalk is quite small at 3.5 cm.

Fig. 4 Site B2 – Berlin, Leipziger Platz; length of observation area: 80 m; off-road bike lane width: 1.5 m (1.9 m at bus stop area); sidewalk width: 3 m; pedestrians per 5 min: 71; cyclists per 5 min: 25

Fig. 5 Site D1 – Dresden, Kulturpalast south and north; length of observation area: 70 m each; on-road bike lane width: 1.6 m; sidewalk width: 6.3 m (north), 3.7-m opening into a 4.1-m pedestrian area (south); pedestrians per 5 min: 35; cyclists per 5 min: 9

Fig. 6 Site B3 – Berlin, Warschauer Brücke east; length of observation area: 80 m; on-road bike lane width: 1.2 m transitioning to 2 m; sidewalk width: 3.6 m; pedestrians per 5 min: 101; cyclists per 5 min: 52

Fig. 7 Site D2 – Dresden, Schloßstraße; length of observation area: 70 m; road width: 8 m; sidewalk width: 9.3 m (west), 13.1 m (east); pedestrians per 5 min: 123; cyclists per 5 min: 21

Different observations regarding infrastructure use were made at site B3, which also features an on-road bike lane. The chi-square test also confirmed different use of the same available infrastructure at B3 and D1, $\chi^2=26.17$, df $=2$, $p<0.001$. E-scooter riders at site B3 (Fig. 6) primarily used the on-road bike lane (over 90% of observed riders) and drove less frequently on the sidewalk than at site D1. Site B3 differs from site D1 via the inclusion of a physical barrier that extends over one-third of the observation area, along with a significant 16-cm height difference between the on-road bike lane and the sidewalk. These features make it difficult to switch freely between the on-road bike lane and the sidewalk. Apart from these differences, the commonality for both sites was that none of the observed e-scooter riders used the road.

2.2.3.3 No bike infrastructure (+ sidewalk and road) Differences in infrastructure use were also observed for sites D2 and B4, where only sidewalk and road were available. A considerable proportion of observed e-scooter riders—over 30%—drove on the sidewalk at site D2 (Fig. 7), whereas almost no sidewalk riding (only 4%) was observed at site B4 (Fig. 8). The most notable difference between both sites is the paving. While D2 features historic cobblestones on the road and a much smoother sidewalk, the road at B4 is made of smooth asphalt and has an extra bus lane and parking lane (B4 north), all readily used by e-scooter riders.

Figure 9 displays an overview of all observation sites in terms of which infrastructure the observed e-scooter riders used. Although a sidewalk was available at all sites, the percentage of observed sidewalk riding varied widely across the examined infrastructure combinations (2–38%). Regardless of whether cycling infrastructure or only the road was available, up to 90% or more of compliant use was observed at four sites (B1, B2, B3, B4). However, at sites where other features, such as paving or amenity value, have more impact (such as sites D1 and D2), up to 38% of sidewalk riding was observed.

2.2.4 Incidents involving other road users and type of infrastructure

In total, 36 incidents were observed, representing 5% of all observed e-scooter riders. We observed no actual crashes. Most cases we observed ($n=33$) were labeled as interactions (collisions avoided by braking or changing direction; easily resolved and controlled by the road users involved). The remaining cases featured e-scooter riders almost falling ($n=2$) and one case where an e-scooter rider and a following cyclist had to brake abruptly to prevent a collision with a cyclist who suddenly stopped directly in front of them.

Figure 10 shows the incidents dependent on the infrastructure used by the e-scooter rider. According to

Fig. 8 Site B4 – Berlin, Unter den Linden (south and north); length of observation area: 80 m each; road width: 6.6-m bus lane (south), 3.9-m bus lane (north) and 2.8-m parking lane (north); sidewalk width: 4.2 m (south); 3.4 m (north); pedestrians per 5 min: 41; cyclists per 5 min: 17

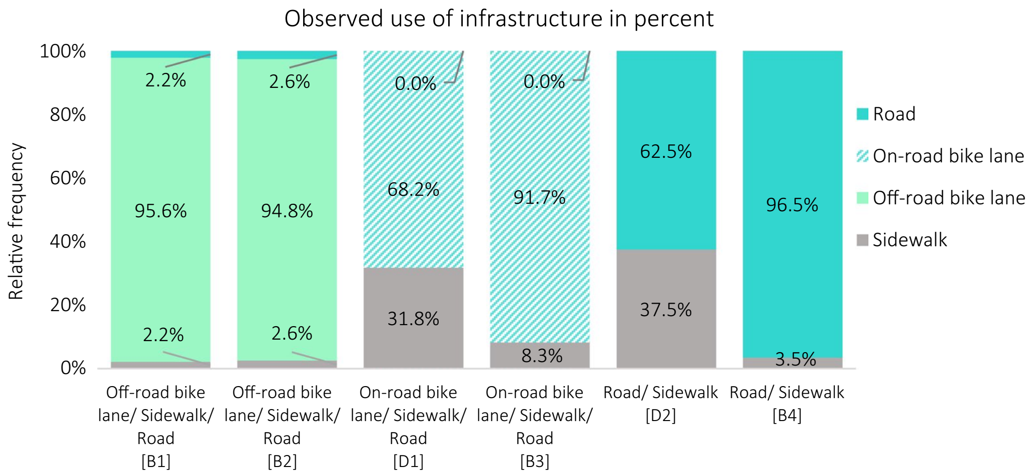

Fig. 9 Observed e-scooter riders' use of different available types of infrastructure (in percentage; *n* = 733; B1, *n* = 90; B2, *n* = 77; D1, *n* = 44; B3, *n* = 120; D2, *n* = 32; B4, *n* = 370)

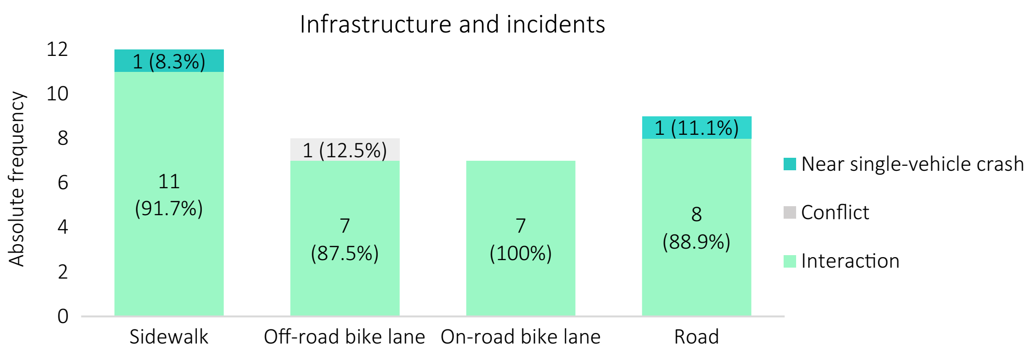

Fig. 10 Observed incidents per infrastructure used, *n* = 36. Sidewalk, *n* = 12; off-road bike lane, *n* = 8, on-road bike lane, *n* = 7; road, *n* = 9. Total observations, *n* = 702; sidewalk, *n* = 58; off-road bike lane, *n* = 159; on-road bike lane, *n* = 148; road, *n* = 373

the observers' reports, one-third of all incidents were observed on pedestrian infrastructure. In addition, the incident rate was also highest for pedestrian infrastructure based on total e-scooter riders observed per type of infrastructure, as follows: sidewalk: 20.7%, off-road bike lane: 5.0%, on-road bike lane: 4.7%, road: 2.4%.

Nearly all observed incidents involved another road user, most commonly pedestrians, followed by cyclists and motorists (Table 3). Incidents involving other e-scooter riders were rare. It should be noted, however, that the involvement of motorists may have been underestimated because the observation sites were located between intersections and did not include any driveways or exits.

Table 3 Frequencies of road user type in observed incidents (*n* = 36)

Incident	**Involved road user(s)**	***n***	**%**
Interaction	N/A	3	8.3
	Pedestrian	16	44.4
	Cyclist	7	19.4
	E-scooter rider	1	2.8
	Motorist	6	16.7
Conflict	Pedestrian and cyclist	1	2.8
Near single-vehicle crash	–	2	5.6

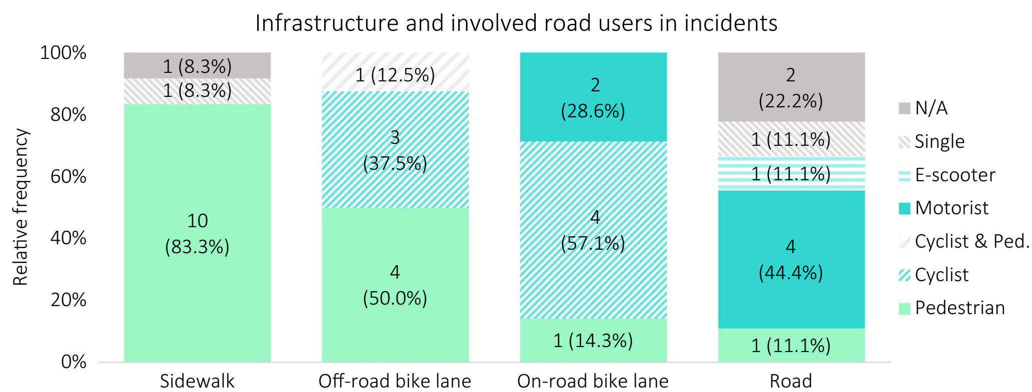

Fig. 11 Involved road users in incidents per type of infrastructure in absolute numbers, *n* = 36. Sidewalk, *n* = 12; off-road bike lane, *n* = 8; on-road bike lane, *n* = 7; road, *n* = 9. Three cases where the involved road user was not coded are not shown

Figure 11 shows the distribution of road users who were involved in incidents as well as the respective infrastructure that the e-scooter rider was using. Most e-scooter–pedestrian interactions occurred on sidewalks. In addition, one of the two observed near single-vehicle crashes was a situation that involved riding on the sidewalk. Pedestrian involvement in interactions with e-scooter riders was also observed for off-road bike lanes, which could indicate pedestrians stepping into the bike lane without looking. It is also worth noting that two unanticipated e-scooter–pedestrian interactions were observed on the road. No incidents were observed between e-scooter riders and cyclists on sidewalks or the road. Instead, cyclists were most likely to be involved in interactions with e-scooter riders while riding in on-road bike lanes. They also had the second-largest share of interactions with e-scooter riders in off-road bike lanes. Four of the six interactions with motorists were observed on the road (44% of observed incidents for road infrastructure). However, two of these motorist–e-scooter interactions occurred in the on-road bike lane, which motorists are not allowed to drive on (57% of observed incidents for on-road bike lanes).

3 Survey

3.1 Survey methods

3.1.1 Survey sites and tool

In parallel to the observations, on-site surveys were conducted with e-scooter riders at one location in Berlin (Brandenburger Tor) and another in Dresden (Kulturpalast). These sites represent tourism hotspots associated with a significant number of e-scooter rentals and drop-offs, which allowed us to approach a large number of potential participants.

The survey was created and pre-tested with LimeSurvey 2.72.3 [22]. The final version was run on tablets using the Offline Surveys app 1.57 [25]. The overall survey comprised 40 total items with dynamic filters, resulting in a maximum of 30 questions per participant. As mentioned in the section on observation methods (see 2.1), the data used in the present paper are part of a more extensive data set collected as part of a larger research project [36].

3.1.2 Survey items

For the purpose of the present study, survey items were developed to determine the sociodemographic characteristics of e-scooter riders and to learn about correlations between infrastructure use and rule knowledge on dedicated infrastructure, infrastructure preferences, and perceived safety of different facilities (Table 1, see 3.2 for sociodemographic items). All items were self-developed, tested, and revised before actual data were collected. Ringhand et al. [36] include a complete list of the survey items in German. The authors can also provide this list in English upon request.

3.1.3 Survey procedure

Two trained interviewers conducted the surveys for 26 total hours in Dresden and 24 total hours in Berlin on the same days that the observations took place. In order to avoid potential behavioral adaptations as a result of the survey, the observed e-scooter riders were never riders who had just completed the survey. Survey participants were recruited on-site when renting

Table 4 Survey items and response categories

Items and response categories
Which infrastructure did you primarily use during your last trip? (a pictorial representation of the response categories was shown, see appendix)
Off-road bike lane
On-road bike lane
Advisory bike lane[a]
Road
Sidewalk
Pedestrian area[b]
First time borrowing (never ridden before)
Other: [free entry]
Where do you feel safest when riding the e-scooter? (a pictorial representation of the response categories was shown, see appendix)
Off-road bike lane
On-road bike lane
Advisory bike lane[a]
Road
Sidewalk
Pedestrian area[b]
Other: [free entry]
Are you allowed to ride an e-scooter on the bike lane/bike path? (No response options were presented. The answers were coded by the interviewers.)
Yes (correct)
No (incorrect)
Don't know
Are you allowed to ride an e-scooter on the sidewalk? (No response options were presented. The answers were coded by the interviewers.)
Yes (incorrect)
No (correct)
Don't know

[a] Advisory bike lane = Bike lane at road level, segregated from motorized traffic by a dashed marking line; may be used by motorized traffic for overtaking

[b] Pedestrian area = Pedestrians always have priority; motorized vehicles (including e-scooters) are generally not allowed

or dropping off an e-scooter. The interviewers read out the questions (Table 4) to the participants and entered the responses on a tablet. For non-German-speaking riders, there was the option to survey in English. The survey took approximately five minutes per participant.

3.2 Survey results

3.2.1 Survey sample

A total of 129 e-scooter riders took part in the on-site surveys ($M = 29.8$ years of age, $SD = 11.5$). The survey sample (see Table 5) was very similar to the observed sample in terms of the age characteristics and proportion of shared and private e-scooters. However, the survey sample contained a slightly higher portion of women compared with the number of women in the observation sample.

3.2.2 Preferred infrastructure

Figure 12 shows the relative frequencies of the survey participants' preferred infrastructures in terms of perceived safety. Most respondents chose some form of cycling infrastructure, though they preferred by a considerable measure off-road bike lanes over all other choices, with on-road bike lanes a distant second. A remarkable 13% indicated a preference for pedestrian infrastructures (sidewalks or pedestrian areas) when riding an e-scooter. No one chose riding on the road as their preference. A detailed description of type of infrastructure is provided in Sects. 2.1, 2.1.1, and 3.1.2.

Table 5 Sociodemographic characteristics of interviewed e-scooter riders ($n = 129$) in percentages

Sociodemographic characteristic	Definition	Survey ($n = 129$)
(Apparent) sex	Female	31.8
	Male	66.7
	N/A	1.5
(Apparent) age	< 14	0.8
	14–20	18.6
	21–40	63.6
	41–65	14.7
	65 +	0.8
	N/A	1.6
Mode	Shared e-scooter	92.2
	Private e-scooter	7.8
	N/A	0
Locals	Yes	14.0
	No	83.7
	N/A	2.3
Reason for stay, if not from the city	Tourist/visit/recreation	73.6
	Business trip	7.0
	Commuter	0
	N/A	19.4

3.2.3 *Infrastructure used during last trip*

Figure 13 shows what infrastructure the survey participants used primarily during their last trip. More than three-quarters (78%) of riders reported primarily using some form of cycling infrastructure, whether on-road or off-road bike lanes or, to a lesser degree, advisory bike lanes. In contrast, nearly one-fifth of those surveyed reported having primarily used pedestrian infrastructure (sidewalk or pedestrian area) during their last trip. Fisher's exact test was used to identify any significant association between used and preferred infrastructure; however, no statistically significant association between the two variables was found (two-tailed $p = 0.088$).

3.2.4 *Rule knowledge related to infrastructure use*

The survey results showed that the majority (93%) of e-scooter riders knew they were allowed to use bike lanes. Nevertheless, one-quarter (25%) of the riders erroneously believed using the sidewalk was legal. No significant association was found for rule knowledge and use of pedestrian infrastructure during the last trip, $\chi^2 = 1.31$, $df = 2$, $p = 0.441$.

4 Discussion

This study sought a better understanding of e-scooter riders' sidewalk riding and general infrastructure use and the resulting implications for road safety. The study examined whether a lack of knowledge about the rules, a rider's perceived safety, or situational factors might be key variables and how the use of the infrastructure might be linked to the facilities available. Contrary to our expectations, neither the preference for one type of infrastructure in terms of safety (within a set of all available infrastructures) nor insufficient rule knowledge seem to be linked directly to self-reported sidewalk riding.

4.1 Relation of rule knowledge and sidewalk riding

Rule knowledge was strong among the respondents; moreover, as Petzoldt et al. [30] reported, most users also accepted the regulations concerning dedicated infrastructure. Presumably, e-scooter riders who use the sidewalk are most likely aware of the rule violation, suggesting that sidewalk riding must have other influencing factors besides a lack of rule knowledge. This conclusion is supported by findings of other researchers showing a high share of rule knowledge in terms of sidewalk use

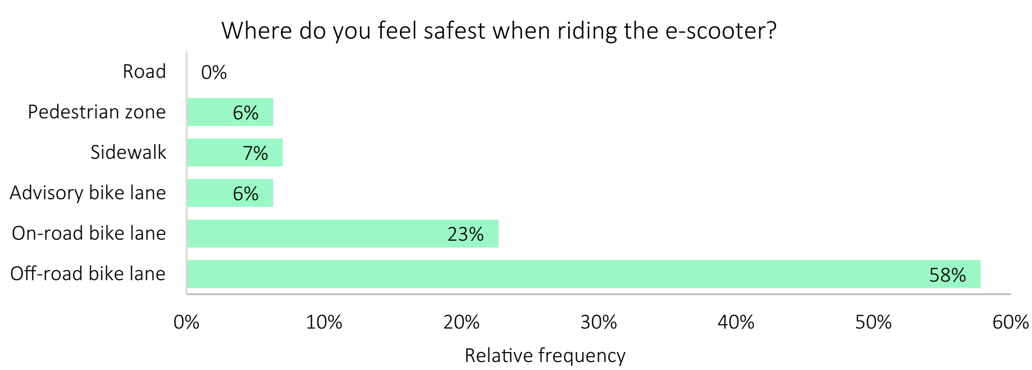

Fig. 12 Distribution of responses (in percentage; $n = 128$) for the question, "Where do you feel safest when riding the e-scooter?" (A pictorial representation was shown; see appendix.)

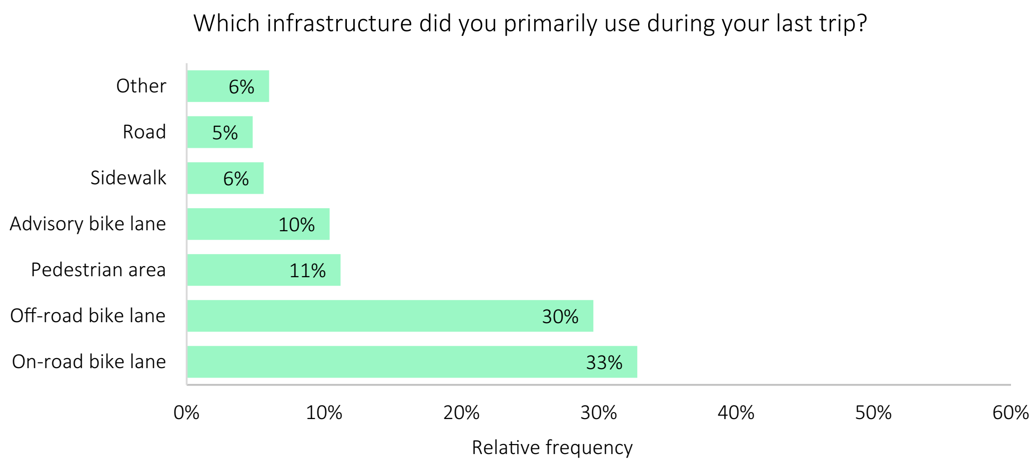

Fig. 13 Distribution of responses (in percentage; $n = 125$) for the question, "Which infrastructure did you primarily use during your last trip?" (A pictorial representation was shown; see appendix.)

for e-scooter riders, e.g., [40] and findings from cycling research exploring the background and rationale of cyclists' rule violations, e.g., [6].

4.2 Preferred infrastructure

In addition, the study sought to identify whether a relationship could be found between e-scooter riders who indicated that they primarily used the sidewalk on their last trip and perceived safety, but no correlation was observed. The data revealed a clear preference for cycling infrastructures, which is in line with previous studies [1, 24, 29]. Also, consistent with other e-scooter and cycling research [24, 34, 42], none of the e-scooter riders reported feeling safest in motorized traffic, and the road (mixed traffic) represented the lowest percentage of infrastructure primarily used on the last trip. Thus, perceived safety may be linked to some extent to infrastructure use, but it does not account for all sidewalk riding scenarios, where other factors must be more influential.

4.3 Observed infrastructure choice

The field observations showed a large variance for sidewalk riding across the examined infrastructure combinations. This outcome is in line with previous findings of variances regarding the use of dedicated infrastructure [24, 29, 32] and is supported by the high inter-rater reliability (see 2.2). The highest compliance was seen for the *sidewalk–road* combination at one site in Berlin (B4), although none of the e-scooter riders chose the road as their preferred infrastructure. This report may also seem counterintuitive to recent findings noting that sidewalk riding increases with proximity to motorized traffic and higher speeds of motorized traffic [24, 29, 34]. In the present study, however, traffic volume was low (subjective assessment) at this site, while the areas were very wide (6.6-m bus lane or 3.9-m bus lane in addition to a 2.8-m parking lane), and the pavement surface was very smooth. E-scooter riders preferred to use the bus lane, which was also used by cyclists and seemed to represent an oversized on-road bike lane in the eyes of the users. It is likely that the road (bus lane) at this site was readily used by e-scooter riders for those reasons. The second-highest rate of compliant use was observed for the *off-road bike lane (+sidewalk and road)*, followed by the *on-road bike lane (+sidewalk and road)*, which overall emphasizes the preference of e-scooter riders for cycling infrastructure (also expressed in the survey).

4.4 Relevance of situational factors

Differences in the use of dedicated infrastructure between sites where that same infrastructure is available indicate that situational factors, such as amenity value or purpose of the trip, may cause e-scooter users to ride on the sidewalk. Additionally, the quality of pavement surfaces can result in sidewalk riding. As shown by Platt and Rybarczyk [31], e-scooter riders especially prefer smooth surfaces because of the small wheel size of their vehicles. Sidewalks are therefore typically used for comfort, as in the case of site D2 (where the dedicated infrastructure is made of cobblestones), alternatively, convenience (high amenity value and/or tourism background) makes sidewalk use more attractive than remaining within the dedicated infrastructure, as was observed for site D1 with the *on-road bike lane (+sidewalk and road).*

4.5 Practical implications

To derive recommendations concerning the promotion of infrastructure settings, especially cycling infrastructure, a look at similarities and differences between e-scooter riders and cyclists is needed. Lanza et al. [21] have shown that e-scooter riders will be less likely to use the designated infrastructure compared to cyclists. Nevertheless, cyclists on the sidewalk can also pose a problem to pedestrian safety. Cycling research has revealed that poor surfaces and convenience factors, e.g., taking shortcuts, can result in greater use of off-road facilities, including sidewalks [18, 44]. In addition, studies on cyclists' route choice describe infrastructure (surface) quality and directness, among other factors, as important determinants of route choice [5, 38]. Thus, improving the comfort factor, which, based on our findings, is formed by "pavement surface quality" and "directness", and considering the location-specific convenience factor, formed by "amenity and/or tourism value" and "ease of infrastructure switch", could encourage both e-scooter riders and cyclists to use the dedicated infrastructure. Thus, a high surface quality, a well-connected cycle route network, and barriers (e.g., height differences, built or planted elements) that prevent an easy switch between types of infrastructure might prevent sidewalk riding.

Those situational factors are part of the invitational quality of the infrastructure. This means that road users not only perceive the infrastructure design as intended by planners but also interpret the design according to how they can use it and where they can and cannot ride [14, 26]. Thus, the design limits or expands the road users' scope of action (e.g., through curbs or surface conditions). This understanding seems to be a key factor not only but also for e-scooter riders' use of the infrastructure. Thus, we recommend that road infrastructure be improved to invite e-scooter riders to use the dedicated infrastructure. In light of e-scooter riders' stated preference for cycling infrastructure and no desire to ride on the road in mixed traffic, planners and policies should focus on improving cycling infrastructure. In the case of ambiguous infrastructure design (e.g., coloring or boundary of bike lane not well visible), additional measures, such as on-site information (e.g., additional signage) or enforcement, must be implemented to ensure dedicated use of the infrastructure.

Although a better understanding of traffic regulations would certainly not be detrimental to road safety, improving e-scooter riders' rule knowledge does not need to become the primary focus of interventions or preventive measures against sidewalk riding. Other practical measures, such as limiting the option in the providers' app to start and end e-scooter rides near tourist attractions, as well as other technical solutions, such as geofencing or feedback-enabled e-scooters [23], may be more effective in preventing riding on the sidewalk.

4.6 Interactions with other vulnerable road users

Despite the small sample of incidents, it might appear that e-scooter riders on the sidewalk are especially at risk of being involved in incidents with pedestrians. In most cases, these events are interactions, meaning the situation is easily resolved and controlled by those involved. Nevertheless, such encounters can be stressful or unpleasant, especially for pedestrians, and they can even result in crashes. The results might lead to the conclusion that the concerns expressed regarding risks for pedestrians upon interactions on the sidewalk are justified [37, 51]. However, the question of responsibility for this rule-violating behavior is not easy to answer. On the one hand, interactions with pedestrians were also observed in the case of non-pedestrian infrastructure, such as off-road and on-road bike lanes or the road. On the other hand, the distribution of e-scooter riders using the sidewalk was high only when there was no bike infrastructure available or when a tourist attraction was close by. Additionally, one of the two cases of near single-vehicle crashes occurred on the sidewalk.

Observations showed that cyclists were the second most frequent interaction partners after pedestrians, indicating a potential for conflict between these groups, especially on cycling infrastructure. Although the locations were not suitable for assessing interactions between e-scooters and motorists, two cases were observed in on-road bike lanes, indicating a potential for conflict between these two types of road users, even when traveling in the same direction and in the case where bike infrastructure is available.

5 Limitations

Data collection was limited to six selected sites in two German cities and the course of one week per city. Accordingly, the present study's confounders might be the presence or absence of other road users, the average and maximum speeds of motorists which have impacted the decision of where to ride, but also the probability of observing interactions between e-scooter riders and other road users. Here, future data will show whether, for example, more pedestrians are a deterrent and whether more motorized traffic influences the infrastructure use of e-scooter riders, as previous research has suggested [24, 34]. Other possible confounders might be the time of day, and the surroundings, e.g., shops, bars, bus/ tram stops, that might have an influence on user characteristics, trip purpose, or risky riding behavior. We addressed these confounders first by observing on the same weekdays and times of day at all observation sites, which civity [7] identified as the times of highest e-scooter use. And second, by including sites with varying contexts, such as bus stops and proximity to nightlife locations such as clubs and bars. It should be noted that there might be influences, e.g., road safety culture or infrastructure characteristics, that are unique to Germany and that might limit the generalizability to other countries or traffic contexts.

Crashes are rare events; despite the high number of observations and observation hours, the number of observed incidents was quite low; hence, sub-analyses of these incidents could not be performed. In light of the descriptive results indicating a certain risk for pedestrians, future crash data and analysis will provide valuable information on the numbers, involved road users, and crash scenarios for e-scooter riders.

Future studies will examine the effects that growing expertise and decreasing numbers of first-time riders have on the safety of micro-mobility. The presented results of the current paper mainly account for users of shared e-scooters with primarily recreational trip purposes. In this context, it will also be interesting to see if the use of private e-scooters and commuting by e-scooter will increase and whether that phenomenon will be accompanied by greater rule obedience, as observed and discussed by Haworth et al. [15]. The present study did not research psychological and social factors such as age, trip purpose, riding with peers, or risk awareness, which might also influence rule violations such as sidewalk riding and e-scooter riding in general. Future studies could gain more insight into these person-related variables and their contribution to e-scooter riding behavior.

6 Conclusions

E-scooter sidewalk riding is of specific concern to pedestrians who are apprehensive about safety problems on sidewalks. In general, it was observed that e-scooter riders comply with the rules in the majority of cases, regardless of the available infrastructure. However, there are also situations where increased sidewalk riding can be observed.

The data suggest that compliance seems more dependent on the quality and state of the available infrastructure than the type of infrastructure. When certain comfort and/or convenience factors, e.g., the possibility to switch easily between the facilities or poor surface quality, occur at a site in combination, a greater incidence of sidewalk riding can be expected.

At the same time, the survey data do not indicate that sidewalk riding does reflect e-scooter riders' actual preferences, a lack of rule knowledge on their part, or their perceived safety. Instead, situational characteristics are central to the decision to (not) ride on the sidewalk.

For policies and planning practice and in light of a rising number of increasingly diverse users (i.e., cargo bikes, e-bikes, micro-mobility users) of cycling infrastructure, the results of the present study support the request to invest in cycling infrastructure and a coherent network of facilities. Until then, limiting the options for e-scooter riders to switch freely between types of infrastructure wherever the design is ambiguous and restricting e-scooter rides at certain sites, i.e., not allowing for rentals or drop-offs at tourist hotspots, might be feasible measures.

Appendix

See Fig. 14.

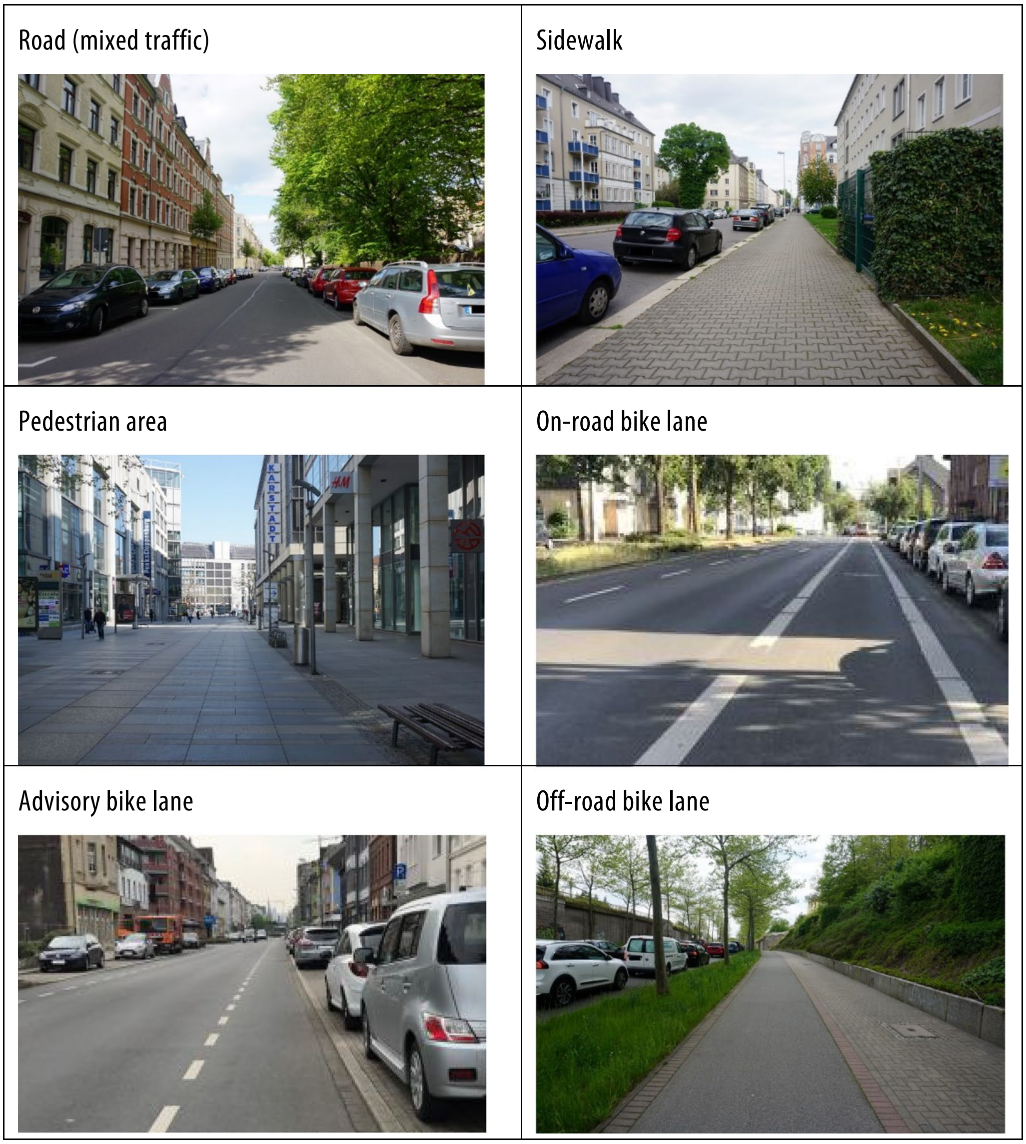

Fig. 14 Pictorial representation of types of infrastructure presented to survey participants with the items "Where do you feel safest when riding the e-scooter?" and "Which infrastructure did you primarily use during your last trip?"

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Author contributions
JA: Conceptualization, Methodology, Investigation, Formal analysis, Writing—Original draft preparation, Writing—reviewing and editing. MR: Conceptualization, Data curation, Methodology, Investigation, Writing—reviewing, and editing. TP: Supervision, Writing—Original draft preparation, Writing—reviewing and editing. TG: Conceptualization, Supervision, Writing—reviewing and editing.

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Availability of data and materials
The datasets used and analyzed during the current study are available from the authors upon reasonable request.

Declarations

Competing interests
The authors declare that they have no competing interests.

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