E-Scooter and Bicycle Accidents: Spatial, Temporal, and Demographic Characteristics in Munich, Germany

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ABSTRACT

Since June 2019, e-scooters have been allowed on German public roads and enhanced the micromobility landscape in urban areas. E-scooter riders are subject to the same rules as bicyclists. Comparing the casualties of both modes over an extended time frame gives an insight into the evolution of micromobility crashes in the city. This study i) analyzes comprehensive data on e-scooter and bicycle collisions during 31 months in Munich, Germany; and b) uncovers the spatial, temporal, and demographic characteristics of both e-scooter and bicycle accidents. In Munich, micromobility incidents concentrate on primary roads with many adjacent intersections and mixed land use. E-scooter crashes occur predominantly in the city center, whereas bicycle collisions are distributed more across the city. The incident rates increase when the weather is mild. E-scooter casualties are more common on Fridays and Saturdays, in the evening and night, whereas bike crashes prevail on weekdays in the morning and afternoon. The bicyclists are, on average, older than e-scooter drivers and their age distribution is more expansive. The percentage of intoxicated casualties and hit-and-run cases is relatively higher among e-scooter users than among cyclists. The accident data showed an increased probability of involved drunk men at night. Severe injuries and single-person accidents, presumably due to lost control, are more common when driving intoxicated. Understanding the dynamics of e-scooter and bicycle accidents provides value to policymakers managing these modes' usage and safety measures and micromobility planners making operational and safety strategies decisions.

Keywords: e-scooter, bicycle, micromobility, Munich, Germany, accident, collision, casualty, crash, traffic safety

INTRODUCTION

Electric scooters (e-scooters) have been allowed on public roads in Germany since 15th June 2019 (1). These novel transport modes were immediately popular with riders in urban areas, presumably due to their ease of use, convenience, and relatively low cost (2, 3). Their speed is limited to 20 km/h, carriage of passengers is not allowed, and the maximum weight of the vehicle without the rider is 55 kg. Each e-scooter must have vehicle liability insurance: about 180,000 e-scooters are insured in Germany (4). These electric vehicles must have front and rear lights, two separately functioning brakes, a narrow platform, and a waist-high rod with handlebars for steering. After kicking off with one foot, riders accelerate and brake the scooter using triggers activated with their thumbs (5). Wearing a helmet while riding an e-scooter is not compulsory.

E-scooter riders do not require a driving license but must be older than 14. They must share the infrastructure with bicyclists. If there is no bike path, they can drive on roads with cars. Riding on sidewalks is taboo (1). An alcohol limit of 0.5 per mille applies. Individuals under 21 years old and drivers holding a driving license for fewer than two years are not allowed to consume alcohol before riding an e-scooter. Although local governments and e-scooter service providers strive for regulations for safe riding, the public discussion focuses on the increasing involvement of e-scooters in traffic accidents. On the one hand, some riders might not have enough experience handling e-scooters due to the novelty of the vehicle concept. On the other hand, offenses such as e-scooters riding on sidewalks or while intoxicated have occurred regularly in the press (6–10).

Several studies explored the characteristics of e-scooter crashes (5, 7, 11–24). However, few studies approached the spatial, temporal, and demographic characteristics of accidents involving bicyclists and e-scooter riders to create a comparable database on the dangers of these micromobility modes. Furthermore, there is still a lack of public awareness of the proper use of e-scooters and the consequences of the incidents. Our study makes several novel contributions to the existing literature by analyzing comprehensive data on e-scooter and bicycle accidents during 31 months in Munich, Germany, and uncovering and comparing the spatial, temporal, and demographic characteristics of both e-scooter and bicycle collisions. Understanding the dynamics of e-scooter and bicycle accidents provides value to policymakers managing these modes' usage and safety measures and micromobility planners making operational and safety strategies decisions.

RELEVANT LITERATURE

Bicycles and electric scooters are popular micromobility modes, but they carry different patterns of injury risks (**Table 1)**. 5.3 reported injuries to e-scooter riders and 385.4 pedal bicycle injuries per 10,000 emergency department injuries were in the United States (25). Injuries on rented e-scooters account for 2.2 emergency department visits per 10,000 miles traveled (26) - much higher than the national average for motorbikes (0.05 per 10,000 miles) and cars (0.1 per 10,000) (27). In Germany, e-scooter crashes in 2021 increased due to more people using these transport modes (28, 29). Many accidents and near-accidents might not be reported to the police (16, 24, 29, 30). In 2020, the insurers in Germany paid an average of €3,850 for each e-scooter incident (4). The figure was only €700 lower than the average sum paid to those injured in car accidents throughout Germany (4).

Around the world, patients presenting to the emergency departments after e-scooter-related accidents are around 30 years and the majority are male (5, 7, 8, 11, 16, 31–33). A significant subset of injuries occurs in patients younger than 25 (5, 32, 34). The most significant number of people involved in bicycle collisions is between 33 and 49 (25). People between 10 and 24 account for nearly one-third of all injuries due to bicycle incidents (35). Males make up most cyclist casualties (25, 35, 36). Peaks of e-scooter-related emergency department visits are during summer, on weekends, and during the late evening and night hours (7, 11, 15, 17, 18, 24). Most bicycle accidents occur when traffic is saturated during the week and on weekends when light conditions are low (24, 37). Due to the relatively high speed and the low fall height with a short reaction time, the extremities, especially the upper and lower limbs, head, and neck, are the most commonly affected body areas for both e-scooter riders and cyclists (5, 7, 8, 11, 16, 17, 20, 31, 33, 38). Many researchers insist on mandatory helmet usage that would reduce the rate of concussions and severe traumatic brain injuries (5, 7, 16, 17, 20, 38). The use of e-scooters without a helmet is in almost all

TABLE 1 Bicycle and E-scooter Accident Characteristics in Literature

Accident Characteristic	Bicycle	E-scooter
Sex	> 50 % male (25, 35, 36)	> 50 % male (5, 7, 8, 11, 16, 31–33)
Age	33 – 49 years (25, 35)	~ 30 years (5, 7, 8, 11, 16, 31–33)
Time	Daytime on workdays; late evening and night on weekends (24, 37)	Summer, weekends, late evening, and night (7, 11, 15, 17, 18, 24)
Affected body areas	Extremities (5, 7, 8, 11, 16, 17, 20, 31, 33, 38)	
Spatial distribution	City centers, major employment centers, universities, and commercial strips (18, 24, 25, 37, 39, 40)	

accident cases (5, 7, 8, 17, 20, 31, 38), but most cyclists wear headgear (16). Even in countries where helmets are mandatory, e-scooter riders rarely wear them (23). E-scooter riders with crashes without wearing a helmet have significantly more extended hospital stays than cyclists using protective gear (16). To determine how much emphasis is on safety in the marketing of e-scooters, researchers in the U.S. examined the official Instagram account of a leading shared e-scooter provider (41). The company's official posting lacked protective gear in pictures and comments, which might impact its customers as it normalized risky behavior.

Regarding spatial distribution, the e-scooter and bicycle crashes are near the major employment centers, universities, and commercial strips in urban regions (18, 24, 25, 37, 39, 40). Compared to traffic incidents, e-scooter incidents tend to occur adjacent to traffic signals and on central primary roads (40). In Milan, the density of e-scooter accidents is associated with the concentration of sidewalk surfaces, road intersections, and neighborhood shops (18). Weaker positive correlations were between e-scooter casualties and population density, pedestrian areas, public transport stops, bike paths, urban fabric, commercial activities, and local streets (18). Similar results were in Texas: residential land use, street length and type, number of street nodes, and traffic signals were statistically significant determinants of e-scooter accidents (40). One of the causes of collisions involving e-scooters was intoxication (6, 8–11, 19, 31, 34) and incorrectly using cycle lanes or riding on the sidewalks (4, 13, 32, 42). Driving on pathways creates tensions with pedestrian categories, such as children, seniors, and people with disabilities (23). One of the reasons why e-scooters go on footpaths is a lack of dedicated infrastructure that could guarantee road safety (18). Most e-scooter accidents resulting in personal injury involve only the e-scooter rider (17, 19, 32) when they lose their balance and fall (8, 23). Furthermore, collision with a curb is among the common causes of e-scooter crashes (17), while for cyclists, it is slipping away on tram rails (16). Both e-scooter riders and cyclists crash into cars (32) coming from the car's right, where car drivers are not expecting the vehicles to enter traffic (43).

E-scooter fatalities are rare (43): a trip by standing e-scooter in a dense urban area is less likely to result in a traffic fatality than a car, bicycle, or motorcycle trip (44). The data suggests that severe injuries are similar to those caused by bikes. However, the representation of e-scooters in the mainstream media is generally very damaging, particularly regarding safety issues (45). In 80% of the recorded fatalities, the accidents involved a car resulting from unsafe infrastructure for nonmotorized vehicles (13, 43). About 80% of e-scooter crashes happened at intersections (13). In many cities, bicycle lanes end suddenly, leaving riders in a flow of moving vehicles (13, 43). Enhancing the infrastructure by connecting bike lanes, limiting right-turn-on-red, and providing intuitive ways to cross and turn at intersections would improve the safety of micromobility modes (13, 43). In Germany, e-scooter riders are subject to the same rules as cyclists, including mandatory helmet usage for children below 15. This study examines the micromobility crashes reported to the police in Munich, Germany, since June 2019 for 31 months. The development of the spatial and temporal distribution of micromobility accidents is examined in the context of the general trend of e-scooter and bicycle usage in Munich. In addition, we explore the characteristics of micromobility casualties and demographic attributes in the city.

METHODS

Data

For the study commissioned by the City of Munich, e-scooter and bicycle accidents reported to the police department in Munich from June 2019 to December 2021 were analyzed. The accident datasets would offer the type, GPS location, time of the accident, the number of involved persons, their level of injury (dead, seriously, light), monetary damage, age, sex, intoxication, and a statement if they committed a hit-and-run act. No data on if the collisions involved a private or shared vehicle, usage of protective gear, or an injury overview was available. Hourly aggregated weather data such as air temperature, wind speed, precipitation, air humidity, and visibility were acquired from the German Weather Service (46) to analyze the meteorological effects of e-scooter and bicycle accidents. The data were merged with the accident datasets based on the respective hour. The summary statistics on characteristics of e-scooter and bicycle accidents are in **Table 2**.

TABLE 2 Summary Statistics on E-Scooter and Bicycle Accidents, June 2019 – December 2021

Variable	Vehicle	Mean	Std	Min	Q1	Q2	Q3	Max
Number of people involved in the accident	Bicycle	1.9	0.5	1	2	2	2	8
	E-scooter	1.7	0.6	1	1	2	2	4
Number of dead persons in the accident	Bicycle	0.0	0.0	0	0	0	0	1
	E-scooter	0.0	0.0	0	0	0	0	0
Number of serious-injured persons in the accident	Bicycle	0.1	0.3	0	0	0	0	2
	E-scooter	0.1	0.3	0	0	0	0	2
Number of light-injured persons in the accident	Bicycle	0.9	0.5	0	1	1	1	4
	E-scooter	0.8	0.5	0	0	1	1	2
Age, years	Bicycle	41.2	18.4	3	27	39	54	96
	E-scooter	30.4	13.7	8	21	27	37	94
Sex (2: female)	Bicycle	1.4	0.5	1	1	1	2	2
	E-scooter	1.3	0.5	1	1	1	2	2
Damage, euro	Bicycle	784.6	2,849.5	0	0	150	800	150,300
	E-scooter	798.1	2,571.8	0	0	50	900	51,000
Alcohol consumed (1: yes)	Bicycle	0.0	0.2	0	0	0	0	1
	E-scooter	0.2	0.4	0	0	0	0	1
Drugs consumed (1: yes)	Bicycle	0.0	0.0	0	0	0	0	1
	E-scooter	0.0	0.1	0	0	0	0	1
Hit-and-run accident (1: at least one party runs away)	Bicycle	0.2	0.4	0	0	0	0	1
	E-scooter	0.3	0.5	0	0	0	1	1
Air humidity, %	Bicycle	61.6	19.4	16	46	61	78	99
	E-scooter	68.5	18.8	16	53	72	85	97
Air temperature, °C	Bicycle	16.0	7.9	-6	11	17	22	35
	E-scooter	14.9	7.4	-3	10	15	20	34
Precipitation, mm	Bicycle	0.1	0.8	0	0	0	0	28
	E-scooter	0.1	0.6	0	0	0	0	10
Visibility, m	Bicycle	47,342.5	17,968.9	120	36,608	49,950	60,320	75,000
	E-scooter	46,650.9	18,986.1	140	35,480	48,670	61,010	75,000
Wind speed, m/s	Bicycle	2.7	1.4	0	2	3	3	14
	E-scooter	2.5	1.3	0	2	2	3	9

Since June 2019, during 31 months, there have been 565 collisions involving e-scooter drivers and 7,284 accidents involving bicyclists, which translates into 38 e-scooter and 486 bicycle accidents per 100,000 population in Munich. 36% of e-scooter crashes were single-person accidents, and 59% involved two parties. The preponderance of police-reported bicycle incidents (76%) involved two parties; single-person accidents accounted for 19%. 11 bicyclists died in Munich between June 2019 and December 2021. No e-scooter riders were deadly injured. In 10% of crashes, e-scooter riders and bicyclists were seriously, and 90% were lightly injured. The mean age of bicyclists in traffic accidents (41.2 years) is a decade higher than that of e-scooter riders (30.4 years). 90% of e-scooter riders and 62% of bicyclists involved in crashes are younger than 50 years. 33% of accidental e-scooter drivers and 41% of accidental bicyclists were female.

Among those in e-scooter collisions involving two or more parties, 51% were other scooters, 31% were cars, 9% were bicyclists, 7% were pedestrians, and 1% were other vehicles. In bicycle crashes, other parties were 56% other bicycles, 34% cars, 5% pedestrians, 2% trucks, 1% scooters, and 2% other vehicles. The mean monetary damage in the case of both micromobility modes was under 800 euros. 20% of e-scooter drivers and 4% of bicyclists were alcohol intoxicated during the accidents. People consumed other drugs in 2% of e-scooter and 0.2% of bicycle incidents. E-scooter riders more often committed hit-and-run acts than bicyclists. Most bicycle and e-scooter crashes happen when mild weather with moderate air temperatures and humidity, no rain, light wind, and good visibility prevails.

Approach

This study analyses spatial, temporal, and demographical characteristics of e-scooter and bicycle crashes in Munich, Germany. Heatmaps, where the GPS markers close to each other are grouped, depict the spatial allocation of police-reported incidents. Histograms and kernel density estimates (KDE) represent continuous probability density curves. Relative to a histogram, KDE does not produce discrete bins but smoothes the observation with a Gaussian kernel. This creates an interpretable plot but has the potential to introduce distortions if the underlying distribution is not smooth. An over-smoothed estimate might erase meaningful features, but an under-smoothed estimate can obscure the actual shape within random noise (47). This was addressed by choosing the proper smoothing bandwidth. To explore the relationships between the determinants of e-scooter and bicycle accidents, the strength and direction of the association were computed using Spearman's rank-order correlation (r_s) (48). This correlation is not very sensitive to outliers and can be used for non-normally distributed ordinal or continuous data. A significance level (p) less or equal to 5% is chosen for data exploration.

RESULTS AND DISCUSSION

There is a high degree of crash clustering in Munich areas with commercial stripes, recreation activities, parks, major employment centers, and university campuses (**Figure 1**). This corresponds to the previous findings that the e-scooter and bicycle accidents concentrate in downtown areas with mixed land use and multimodal traffic (18, 25, 37, 39, 40). Many micromobility accidents are proximate to major public transport hubs such as Hauptbahnhof (central station), Laim, Pasing, and Ostbahnhof. The highest incident rates in Munich are on the streets of Leopoldstrasse, Landsberger Strasse, Dachauer Strasse, Arnulfstrasse, Lindwurmstrasse, and Ludwigstrasse. These are long central arteries featuring shops, cinemas, hotels, open-air cafés, and restaurants. There is a lot of multimodal traffic and intersections. Separate bicycle lanes are available on these streets, but they often operate at high capacities.

In 2019, e-scooter accidents concentrated primarily in the city center but gradually grew in number and sprawled to other city parts in 2020 and 2021. Even though we do not have data on accidents with shared or private vehicles, the sprawl of e-scooter locations corresponds to the extension of e-scooter sharing service areas in Munich. Over the analyzed period, bicycle accidents were across all Munich regions, focusing mainly on central locations. The daytime parameter (**Figure 1**) depicts that at night (11 PM – 5 AM), the e-scooter accidents are concentrated near public transport hubs such as Hauptbahnhof (central station), Karlsplatz (Stachus), Münchner Freiheit, and the city's grandest boulevards such as Ludwigstrasse and Leopoldstrasse. These areas concentrate on the main city sights and nightlife venues. In

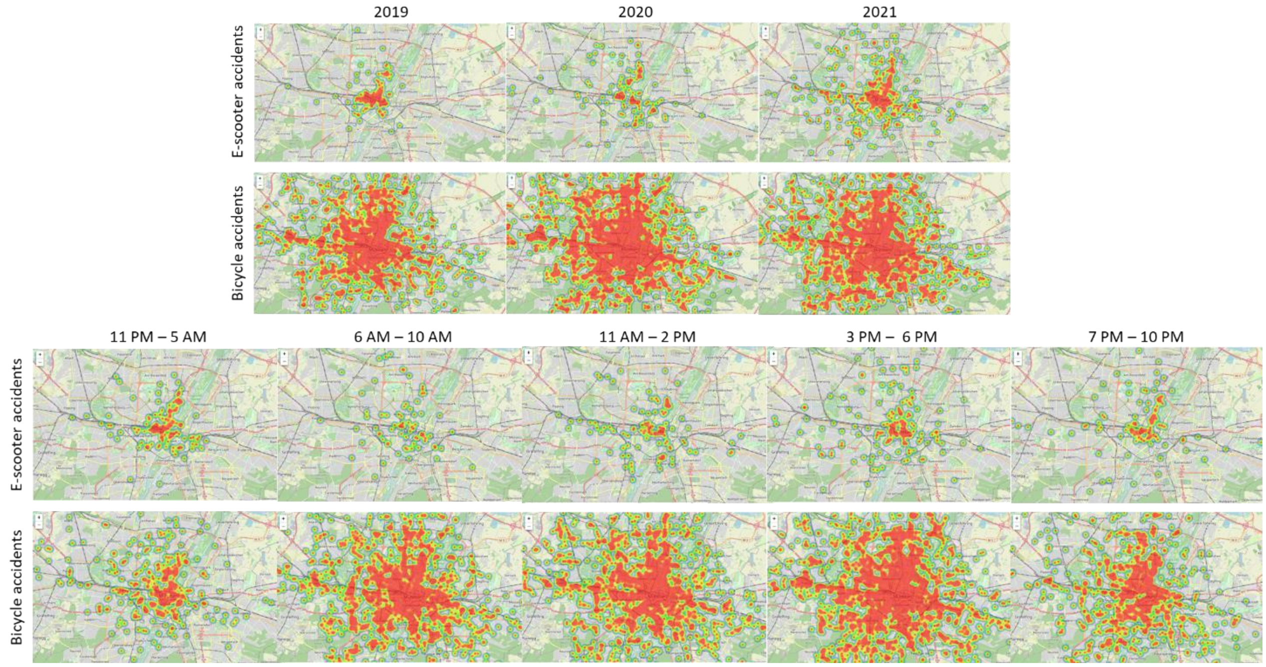

Figure 1 Spatio-Temporal Distribution of E-scooter and Bicycle Accidents in Munich (6.19 – 12.21)

the morning, separate accidents were across the city and clustered in the city center at midday and afternoon. Ludwigsstraße was again among the significant incident hot spots in the evening. Bicycle collisions at night and evening were primarily in the city's core. During the day, bicycle accidents increased along the main speed railway line (Stammstrecke) and in eastern and western city parts.

The kernel density estimates of hourly and monthly police-reported e-scooter and bicycle accidents in Munich accumulated for the study period are in **Figure 2**. The number of e-scooter crashes in 2021 in Munich has tripled since June 2019, while the bicycle accident rate stayed constant. Due to the COVID-19 pandemic, German states imposed a strict lockdown in March 2020. Schools, kindergartens, and borders with neighboring countries were closed, and physical contact with more than one person from outside one's household was prohibited. As a result, there was a decrease in traffic and outdoor recreation activities, which might cause a reduction in police-reported e-scooter accidents during this period. In early May 2020, the lockdown eased, and e-scooter collisions grew. There was a slightly increasing trend in bicycle accidents in March – April 2020 compared to 2021. This might be due to the "bike boom" when bike ridership increased due to the heightened anxiety over public transportation and a surge in exercise (49). Both e-scooter and bicycle accidents peaked from May to October, corresponding to the increased use of micromobility modes in warmer months (50).

Most e-scooter crashes were in the afternoon (3 PM – 7 PM) and at night (8 PM – 3 AM), while bicycle accidents peaked in the morning (7 AM – 9 AM) and afternoon (3 PM – 7 PM). June and July 2021 distinguished the highest e-scooter accident rates in the afternoon, whereas, in August, there was a distinct e-scooter accident peak between night and early morning (3 AM – 6 AM). There were significantly more bicycle collisions in July 2019 and 2020 than in other months, but in 2021 the number decreased to the level of other months with higher air temperatures. More night-time bicycle accidents happen in summer. 38% of all e-scooter collisions occurred on Fridays and Saturdays. On Fridays, e-scooter accidents peak between 4 PM and 8 PM. Nights between Fridays and Saturdays show the highest rate of night-time e-scooter crashes. Bicycle accidents in Munich were evenly distributed during the working days decreasing on the weekends and holidays. On working days, bicycle accidents top in the morning and afternoon, which overlaps with commuting times in Germany (50). No morning peaks are observed on weekends, but more bicycle accidents are during midday and evening hours. Spatial (**Figure 1**) and temporal (**Figure 2**) characteristics of e-scooter crashes depict that the incidents might have happened during trips for recreation,

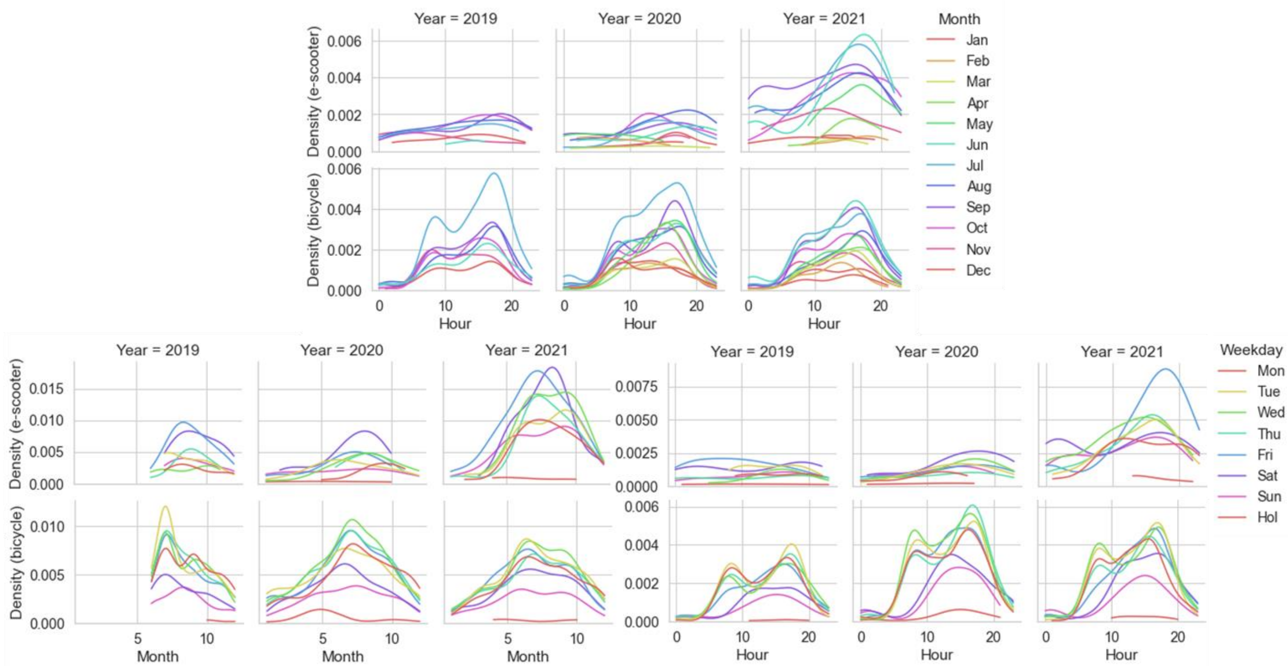

Figure 2 Temporal Distribution of E-Scooter and Bicycle Accidents, June 2019 – December 2021

dining, and going out. Compared to bicycle incidents, there are fewer weekday morning e-scooter crashes associated with commuting times. Most bicycle accidents happen during weekday commuting peaks which could be connected to bike usage.

The correlation between the variables of e-scooter and bicycle crashes gives us insights into micromobility accident patterns (**Figure 3**). Blue cells represent negative correlations: relationships between two variables such that as the value of one variable increases, the other decreases. Red cells are positive correlations that move in the same direction. The intensity of the color represents the intensity of the relationship. The statistical significance can be derived from the matrix with black and beige cells, where beige depicts a significance level (p) less or equal to 5%. Single-person e-scooter and bicycle accidents happen at night (1 PM – 4 PM), on weekends, and on holidays. This might be due to a decrease in traffic flow during this period and an increased probability of lost coordination due to lower visibility or intoxication. On the other hand, more traffic participants are involved in incidents during the midday and afternoon or on weekdays. Furthermore, a slight significant positive correlation is between the number of severely and light injured persons involved in collisions and higher air temperatures. This could be explained by the fact that more participants are involved in the casualties during daylight when the air temperatures tend to be higher.

A significant portion of accidents involving one person is under alcohol. There would be a higher probability of severe injuries if the micromobility driver consumed alcohol or drugs. These statistics confirm that alcohol and drugs affect the ability to concentrate, make sound judgments, and quickly react to situations required for safe driving. The most significant number of intoxicated accidents by e-scooter and bicycle are at night (9 PM – 4 AM). This supports that night is the time with the highest percentage of alcohol-impaired drivers (51). There are relatively more alcoholized accidents involving e-scooters when the air temperature is lower. This might be due to lower temperatures in the evening and night when most alcoholized accidents occur. Collisions are strongly positively correlated with alcohol consumption when other drugs are consumed.

The characteristics of e-scooter drivers and bicyclists were further analyzed (**Figure 3**). Women involved in an accident while riding a bicycle are older than men, which is statistically significant. Female e-scooter riders were slightly younger than male riders, but no statistical significance was identified. Youthful individuals and males commit hit-and-run incidents more often than older people and females.

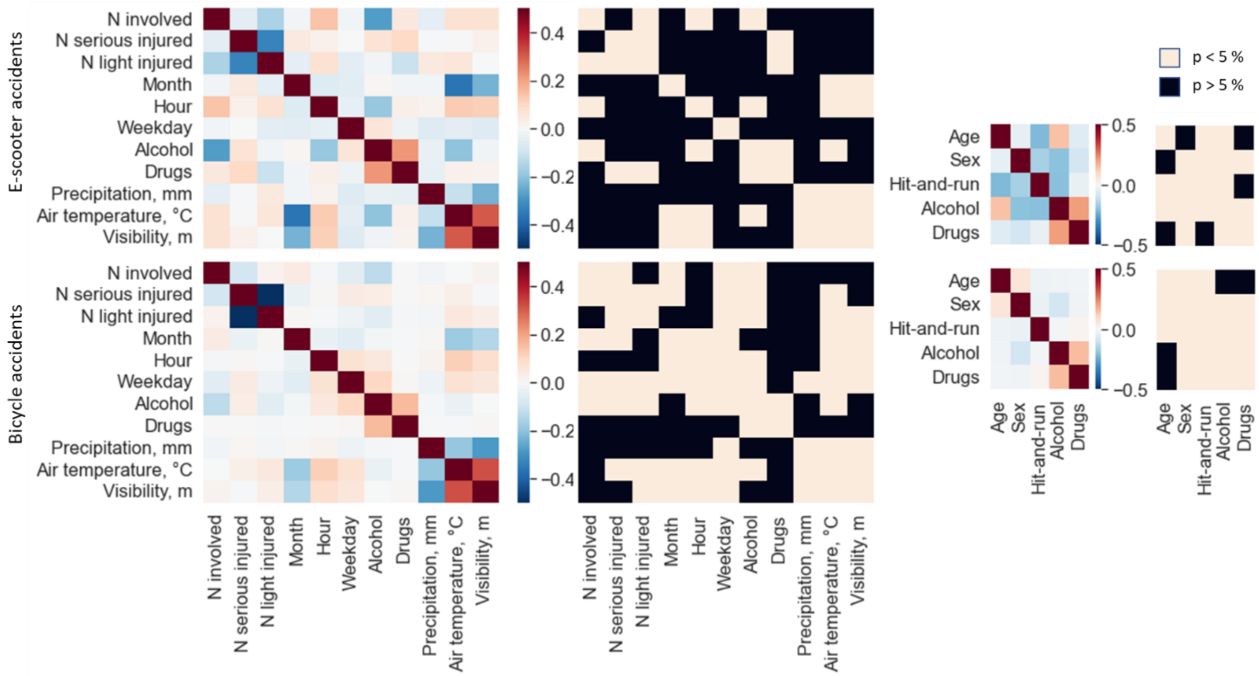

Figure 3 Spearman's Rank-Order Correlation of Accident Characteristics in Munich (6.19 – 12.21)

Other studies confirm that drivers in hit-and-run accidents are likelier than young males (52). The age of e-scooter drivers in alcoholized accidents is higher than in crashes without alcohol consumption. No statistically significant connections between the age of micromobility drivers and drug consumption could be observed. Male e-scooter drivers and bicycles are more often in alcohol and drug consumption accidents than females. The U.S. Department of Health confirms that men are likelier to have been intoxicated in traffic incidents than women (53).

CONCLUSIONS

This study of spatial, temporal, and demographic characteristics of micromobility collisions in Munich over 31 months detected differences and similarities between e-scooter and bicycle crashes. In Munich, the spatial attributes of casualties resemble the literature trend: micromobility incidents tend to occur in downtown areas and central primary roads with many adjacent intersections and mixed land use. When e-scooters emerged on Munich roads in 2019, the accidents were primarily concentrated in the city center. But when the vehicles became more common over time, they sprawled to other regions. Future research could examine incidents on a micro-scale by studying individual hot spots and possible infrastructure inconsistencies. As in other countries in Western Europe, the micromobility incident rates are higher in warmer months when the weather is mild. E-scooter accidents are more common on Fridays and Saturdays, in the evening and night, whereas bike crashes prevail on weekdays in the morning and afternoon. Spatial and temporal distributions of e-scooter crashes depict that the incidents in Munich might have happened during trips for recreation, whereas most bicycle collisions occur during commuting.

Most accident participants are young males. However, on average, bicyclists are older than e-scooter drivers, and the age distribution is more expansive. One-person crashes were more common among e-scooter users than bicyclists. The distribution of serious and light injuries was similar in bicycle and e-scooter incidents. In incidents involving several participants, collisions with vehicles of the same type and cars were the most frequent for both micromobility modes. The percentage of intoxicated casualties and hit-and-run cases was relatively higher among e-scooter users than among cyclists. Analysis of the incidents with drunk micromobility drivers depicted that drunken driving is dangerous: severe injuries and single-person accidents presumably due to lost control are more common when driving intoxicated. The data showed an increased probability of drunk men forcing at night.

Policymakers, service operators, and transportation practitioners could benefit from investigating settings, causes, and effects of traffic incidents to be aware of local features and make informed safety regulation decisions. Cities must balance the critical safety aspects: of vehicles, users, and infrastructure. The micromobility vehicles must have the necessary safety and visibility equipment and be regularly inspected. Training might help inexperienced riders learn how to drive micromobility modes in a less threatening environment and under less pressure. Safety awareness campaigns might be essential for introducing mandatory helmet-wearing and resigning from intoxicated driving. Creating a secure micromobility network requires investment and spatial distribution, but it might positively impact the safety of all road users, including pedestrians.

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AUTHOR CONTRIBUTIONS

The authors confirm their contribution to the paper as follows: study conception and design: M. Pobudzei; data collection: M. Pobudzei, M. Tiessler, S. Hoffmann; analysis and interpretation of results: M. Pobudzei, M. Tiessler, S. Hoffmann; draft manuscript preparation: M. Pobudzei, M. Tiessler, A. Sellaouti, S. Hoffmann. All authors reviewed the results and approved the final version of the manuscript.

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