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An exploration of e-scooter injuries and severity: Impact of restriction policies in Helsinki, Finland

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ABSTRACT

Introduction: The emergence of shared electric scooter (e-scooter) services has introduced a new mobility option in numerous urban areas worldwide. Safety concerns surrounding e-scooter riding have prompted some cities to impose bans or restrictions on shared e-scooters. This study aims to assess the impact of e-scooter restriction policies, on the spatiotemporal distribution of e-scooter injuries and factors influencing injury severity in Helsinki, Finland, in 2021 and 2022. These restrictions include banning shared e-scooter use from midnight to 5 a.m. on weekends and reducing speeds during certain hours. *Method:* This study employed an ordered logit model, heatmap analysis of crash locations, and temporal analysis across different time frames to achieve these objectives. *Results:* The findings indicate a 64% reduction in the number of e-scooter injuries after the restrictions. However, the severity of injuries experienced only a slight decrease. Notably, the trend of injury severity appeared smoother in 2022 compared to 2021, with spikes occurring from Friday to Sunday. The spatial distribution of crashes revealed that, in 2021, most crashes were concentrated in the city center, while in 2022, the crash locations were more scattered, partly due to the increased area serviced by e-scooters. The results also underscored the substantial impact of alcohol intoxication, as it significantly increased the probability of more severe injuries. Furthermore, higher age groups and people using e-scooters from 4 p.m. to 9 p.m. are more likely to experience higher injury severity after the restrictions were implemented. These research outcomes offer valuable insights for other cities, providing lessons on how to tailor policies to effectively reduce the number of e-scooter-related injuries.

1. Introduction

In recent years, micro-mobility transport modes, particularly electric scooters (e-scooters), have experienced a remarkable surge worldwide (Hosseinzadeh et al., 2021; Dibaj et al., 2021). E-scooters have gained immense popularity due to their ease of use while providing an enjoyable electrically-assisted riding experience and fulfilling various mobility needs (Christoforou et al., 2021; Laa & Leth, 2020). E-scooters have swiftly become a global trend, with their extensive usage spanning over 200 cities and a market valued at billions of dollars (McKenzie, 2020; Yang et al., 2022). In the United States, e-scooter trips exceeded 38.5 million in 2018, surpassing other forms of micro-mobility (Younes et al., 2020). This trend of rapid e-scooter adoption has also been observed in numerous European cities (Li et al., 2022), highlighting the global significance of e-scooters as an emerging mode of transportation.

The rapid influx of e-scooters has presented significant challenges for planners and policymakers, requiring effective planning for the integration of e-scooters within the transport system (Kazemzadeh & Sprei, 2022). This lack of integration has resulted in compatibility issues with other modes of transport, leading to conflicts and collisions (Haworth et al., 2021). Consequently, several studies have highlighted a notable increase in emergency department (ED) admissions worldwide, reflecting a corresponding rise in crashes associated with the introduction of e-scooters (Vernon et al., 2020; Namiri et al., 2020). Several studies have focused on analyzing e-scooter crashes, leveraging upon the existing ED records, in the United States, New Zealand, Australia, Sweden, and

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Finland (Oksanen et al., 2020; Badeau et al., 2019; Cicchino et al., 2021; Stigson et al., 2021; Beck et al., 2020; Mitchell et al., 2019; Vasara et al., 2022).

In response to the growing number of crashes, there have been various policy interventions (Heydari et al., 2022). Some countries have implemented temporary bans, mandated helmet usage, and implemented regulations against riding under the influence of alcohol (Ma et al., 2021; Kazemzadeh et al., 2022). For example, after fatal e-scooter collisions in Atlanta, Georgia, USA, a temporary nighttime ban was implemented, restricting e-scooter use between 9 p.m. and 4 a.m. (Vernon et al., 2020). In Europe, the restrictions on e-scooter use vary between countries. Riding e-scooters on bike paths, for instance, is allowed in many European countries, however, there are restrictions against this behavior in Greece, the Netherlands, Norway, and the UK (Euronews, 2023). Recently, Paris has taken action by implementing a total ban on rental e-scooters[1].

The proliferation of injuries from e-scooter usage highlights that there is a need for regulations to ensure the safe behavior of e-scooter riders, in addition to complementing changes in infrastructure and the behavior of other users. In Finland, commercial e-scooter rideshare programs have an age restriction of 18 years, while there is no age requirement to operate a privately owned e-scooter (Murros et al., 2023). Due to the increasing number of e-scooter-related injuries and a significant debate in the media during the spring and summer of 2021, new rules for e-scooter usage were introduced in September 2021 in Helsinki. The City of Helsinki introduced new regulations, which included prohibiting the use of shared e-scooters between 12 midnight and 5 a.m. on weekends, imposing speed limits of 20 km/h during the day, and 15 km/h on weekdays between 12 midnight and 5 a.m.. In addition, the shared e-scooter companies introduced a "beginner mode" which restricts speed to a maximum of 15 km/h on the first ride (City of Helsinki Urban Environment Department, 2021).

Fig. 1 depicts the shared e-scooter restrictions in Helsinki. It is worth noting that during the study period, there was no ban on riding e-scooters while under the influence of alcohol.

Despite implementing policy interventions in response to the growing number of e-scooter-related crashes, there remains a scarcity of studies examining the impact of these policies on e-scooter crash characteristics, particularly in Finland. To bridge this knowledge gap, the present study aims to conduct a spatiotemporal comparison of e-scooter-related injuries as well as investigate the changes in the characteristics of individuals injured in e-scooter crashes in Helsinki, assessing the impact of the mentioned restrictions.

More specifically, this study contributes to three main areas. Firstly, it analyzes the temporal distribution of e-scooter-related injuries and their severity, focusing specifically on 2021 and 2022, before and after the implementation of the restrictions on different time scales. Secondly, the study investigates the spatial distribution of e-scooter crash locations in 2021 and 2022 based on the number and the severity of injuries to compare the spatial distribution of crashes before and after the restrictions. Finally, the study develops a model to assess the severity of e-scooter injuries, considering variables including demographic characteristics, and the presence of intoxication.

This paper is organized as follows: the *Literature Review* offers an overview of the contextual literature on e-scooter safety. Next the *Methodology* presents the data characteristics and the analysis adopted for this study. *Results and Discussion* presents the findings of the study and corresponding discussions. Finally, the *Conclusions*, summarises the study and the implications.

2. Literature review

This section provides an overview of the contextual literature on the following aspects of e-scooters: (i) characteristics of individuals involved in e-scooter crashes; (ii) spatial and temporal distribution of collisions; (iii) injury types and severity; and (iv) e-scooter usage in Finland. Finally, according to our literature review, we determine the knowledge gaps, research needs, and the contribution of the current study to the field.

2.1. Characteristics of individuals involved in e-scooter collisions

Analyzing the socio-demographic characteristics of e-scooter riders involved in collisions offers valuable insights for planners and the public health system. It helps identify high-risk groups and informs the development of relevant policies (Kazemzadeh et al., 2022). Several studies examining e-scooter literature find a higher frequency of crashes involving males (Sexton et al., 2023; Karpinski et al., 2022; Shah et al., 2021). Moreover, several epidemiological studies indicate that most injured riders are young individuals below the age of 40 (Stray et al., 2022; Kim & Campbell, 2021). Although shared e-scooter usage is typically restricted to individuals aged over 16 or 18 years, depending on the jurisdiction, some studies have documented collisions involving children and teenagers (Shah et al., 2021; Trivedi et al., 2019).

The issue of riding under the influence of drugs and alcohol poses a significant threat to all road users. An evaluation of e-scooter literature reveals a notable rate of users involved in crashes while under the influence, both when measured amongst injured users and when self-reported (Cicchino et al., 2021; Harbrecht et al., 2022; Bekhit et al., 2020). Furthermore, self-reported data has indicated instances of intoxication with substances such as marijuana in certain cases (Bloom et al., 2021). Additionally, a low percentage of riders involved in crashes were found to be wearing helmets, despite the fact that helmets are known to have a significant protective effect (Stray et al., 2022; Singh et al., 2022).

2.2. Spatial and temporal distribution of collisions

Understanding conflicts and collisions' spatial and temporal patterns is crucial for implementing effective planning and engineering solutions that enhance safety (Kazemzadeh et al., 2022). However, previous research in both the medical and transport sectors has often been overlooked, despite this information providing detailed data about collision locations for e-scooter crashes (Kazemzadeh et al., 2022). Nonetheless, studies indicate that e-scooter collisions tend to occur frequently in city centers (Shah et al., 2021; Pobudzei et al., 2023; Brauner et al., 2022), aligning with the prevalent riding patterns in these areas. Studies have also revealed that e-scooter crashes occur throughout the road reserve including on the street, in bike lanes, and on sidewalks, demonstrating the variation in riding locations for these vehicles (Cicchino et al., 2021; SFMTA, 2019).

In contrast, the time and date of collisions have been more commonly reported. E-scooter usage typically peaks during the spring, summer, and autumn seasons, which coincides with a higher number of reported injuries (Sexton et al., 2023; Shah et al., 2021). Furthermore, collisions are more likely to occur outside regular business hours, particularly on weekends and at nighttime (Kazemzadeh et al., 2022; Stray et al., 2022; Shichman et al., 2022; Thoenissen et al., 2021). Notably, several studies have highlighted that nighttime collisions account for a disproportionate number of e-scooter rider fatalities (Karpinski et al., 2022; Santacreu et al., 2020).

2.3. Injury types and severity

E-scooter collisions can generally be classified based on the agents involved, distinguishing between single and multiple-agent collisions. Single collisions refer to obstacles collisions or instances where a rider falls from an e-scooter. On the other hand, multiple-agent collisions involve more than one vehicle or road user, such as rear-end and head-

[1] https://www.bbc.com/news/world-europe-65154854

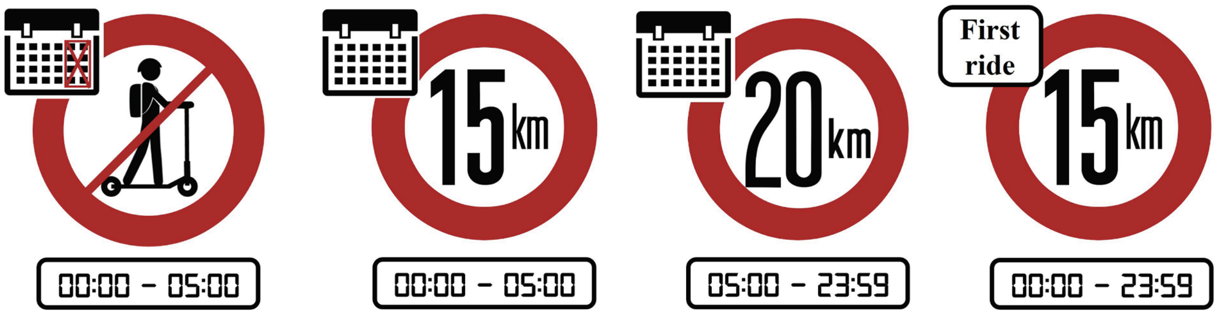

Fig. 1. Shared e-scooter restrictions in Helsinki introduced from September 2021.

on collisions (Kazemzadeh et al., 2022). Among e-scooter collisions, single collisions, particularly falling from e-scooters, have been found to be the most common type (Cicchino et al., 2021; Bloom et al., 2021; English et al., 2020). Additionally, colliding with other road users and vehicles is also a prevalent type of e-scooter collision (Hourston et al., 2021; Yang et al., 2020).

The severity of e-scooter crashes can range from minor to fatal injuries. The extent of injuries is often correlated with the typology of collisions and the types of vehicles and road users involved (Billah et al., 2021). For instance, factors, such as increasing age, female gender, frequent e-scooter ridership, and intoxication, are often associated with greater injury severity (Cicchino et al., 2021; Kowalczewska et al., 2023; Azimian & Jiao, 2022; Stray et al., 2022). Among these factors, higher injury severity for riders injured on the road may be linked to elevated travel speeds (Cicchino et al., 2021; Posirisuk et al., 2022; APH, 2019), emphasizing the necessity for further regulation of e-scooter practices. Head and face injuries have been consistently identified as the primary types of injuries associated with e-scooter collisions (Harbrecht et al., 2022; English et al., 2020; Dhillon et al., 2020; Mebert et al., 2018). These injuries are predominantly reported within the medical research domain, emphasizing their significance in understanding the impact and severity of e-scooter crashes (Kazemzadeh et al., 2022).

2.4. E-scooter Usage in Finland

E-scooters were introduced in Finland during the summer of 2019 (Simpanen, 2020), with five active operators initially serving the major Finnish cities of Helsinki, Espoo, Tampere, and Turku. By the end of 2019, operators grew interested in expanding their market presence to other Finnish cities (Simpanen, 2020). In Finland, e-scooter services have been recognized as a potential solution for addressing first and last-mile connectivity needs of public transport trips (Sundqvist-Andberg et al., 2021). However, the rapid expansion of e-scooters in Finnish cities has raised concerns about traffic safety for road users. Several studies have highlighted the high rate of crashes associated with e-scooter use in Finland (Oksanen et al., 2020; Murros et al., 2023). For instance, Reito et al. (2022) examined patients who visited the Tampere University Hospital emergency department for e-scooter-related injuries from April 23, 2019, to April 23, 2021. In total, 331 patients (335 visits) presented to the emergency department, which was estimated to represent 18 ED presentations per 100,000 rides (Reito et al., 2022). Further, analysis of e-scooter crash trends in Finland reveals a prevalence of incidents involving riders under the influence of alcohol and a lack of helmet usage (Oksanen et al., 2020; Murros et al., 2023; Vasara et al., 2022). Moreover, another study conducted in Helsinki investigated the number of e-scooter-related injuries in 2021 (Vasara et al., 2022). The results revealed that 59% of the injured individuals were male, with 58% minor injuries. Notably, there was a significant surge in crash rates during weekend nights, corresponding to an increase in patients affected by alcohol intoxication (Vasara et al., 2022).

2.5. Knowledge gaps and research needs

While the literature on e-scooter usage has witnessed rapid development in recent years (O'Hern & Estgfaeller, 2020), several significant knowledge gaps still exist in the field. Firstly, there is a lack of research examining the impact of regulations on e-scooter usage and the subsequent effects on the riders' safety (e.g., the new instructions introduced by the City of Helsinki). Secondly, there is a need for detailed analysis to understand the relationship between the severity of collisions and demographic characteristics. Lastly, there is a lack of research investigating spatiotemporal changes after the implementation of restrictions based on the number of collisions and injury severity. Therefore, this study aims to address the aforementioned knowledge gaps by conducting a retrospective analysis in Helsinki to identify changes in temporal and spatial distribution and injury severity of e-scooter-related emergency department presentation cases. The manuscript is guided by the following three research questions:

- RQ1: What is the temporal distribution of e-scooter-related injuries and the severity of injuries before and after restrictions in 2021 and 2022, respectively?
- RQ2: What is the spatial distribution of e-scooter-related injuries and the severity of injuries before and after restrictions in 2021 and 2022, respectively?
- RQ3: What are the key factors influencing the severity of e-scooter-related injuries in 2021 before the implementation of restrictions, compared to those in 2022 after the implementation of restrictions?

3. Methodology

3.1. Data

The e-scooter-related injuries for 2021 and 2022 were collected by Helsinki University Hospital (HUS) (Vasara et al., 2022). They were granted to us for further analysis. Four e-scooter-related keywords were used to extract the injuries[2]. Data were retrieved from a collective electronic patient information system encompassing three trauma hospitals, which collectively represent all public healthcare facilities catering to acute trauma patients in Helsinki. The injury data for 2022 is only available from January to August, Therefore, we utilized data from January 1st until August 31st in 2021 and 2022, which represent periods before and after the implementation of e-scooter restrictions by the City of Helsinki, respectively. After cleaning the data, there were 353 e-scooter-related injuries in 2021 and 125 e-scooter-related injuries in 2022 from January 1st until August 31st. It is worth mentioning that injured people who were brought from other cities to Helsinki were removed from our analysis as well as cases where no injury severity score was reported. The severity of the injury was graded based on the patient's most severe injury utilizing the Abbreviated Injury Scale (AIS)

[2] "Sähköpotkulau-", "Sähköskoot-", "Skoot-" and "Scoot-".

(Vasara et al., 2022). The scale comprises six scores ranging from 1 to 6, where 1 represents minor injuries and 6 illustrates an unsurvivable injury. In 2021, the severity of injuries was classified with the highest AIS ranging from 1 to 4, with a small number of cases classified as level 4, whereas in 2022, the severity of injuries ranged from 1 to 3. Other characteristics of injured people included: gender and age as categorical variables and breath alcohol test value as a continuous value; the nurse's evaluation of the patient being intoxicated besides the breath alcohol test values (a dummy variable); helmet usage; date and time of injury; the methods of arrival to the hospital (e.g., by themselves, ambulance, referral, etc.); crash type (e.g., single-person, e-scooter crashes, multiple e-scooter riders on the same e-scooter (multi-riding), etc.); hospital treatment requirement (e.g., ED presentation only, basic hospital ward, and ICU ward); and weather-related parameters such as cloud coverage, precipitation, temperature, horizontal visibility, wind direction, and wind speed. We also examined the optional description section for each injury, which was completed by the nurse, to gather additional information about the incident. As a result of inconsistent data collection in the emergency room, there is a significant amount of missing data for specific characteristics of injured individuals, such as helmet usage. Table 1 presents the number of injuries and characteristics of injured people in 2021 and 2022. The mean age of emergency department presentations was 27.9 and 31.8 and the median age was 25.3 and 28.0 in 2021 and 2022, respectively. A t-test was applied to the continuous parameters, while a chi-square test was used for the categorical parameters in order to identify statistically significance differences. Due to a high number of unknown helmet (un) usage cases, the reliability of this variable is compromised. Therefore, no statistical tests were performed. It is important to note that there could be some missing data for each parameter, potentially leading to inconsistencies in the number of observations mentioned in the preceding paragraph. We also obtained the temporal distribution and number of shared e-scooter trips from January to August 2021 and 2022 from the Vianova Cityscope[3] (Mladenović et al., 2022). Based on trip data in Table 1, the number of shared e-scooter trips in 2022 has increased by 20%.

Table 1
Injured people's characteristics in 2021 and 2022 - January to August.

Characteristics	2021		2022	
	Frequency	Percent	Frequency	Percent
Gender				
Female	150	42.6%	53	41.6%
Male	202	57.4%	76	58.4%
Age*				
Under 18	25	7.1%	6	4.8%
18–22	79	22.4%	24	19.0%
22–26	88	25.0%	19	15.1%
26–32	75	21.3%	19	15.1%
32–36	29	8.2%	6	4.8%
36–40	14	4.0%	9	7.1%
40–50	30	8.5%	13	10.3%
More than 50	12	3.4%	30	23.8%
Intoxication*				
Yes	164	46.5%	40	31.0%
No	189	53.5%	89	69.0%
Helmet usage				
Yes	6	1.7%	6	4.7%
No	93	26.3%	79	61.7%
Unknown	254	72.0%	43	33.6%
Collision type				
Single person	292	83.2%	104	82.5%
e-scooter crashed	36	10.3%	15	11.9%
Multi-riding e-scooter	10	2.8%	3	2.4%
Pedestrian or cyclist hit by or crashed with e-scooter	9	2.6%	3	2.4%
Being pushed off the e-scooter	4	1.1%	1	0.8%
Method of arrival to ED				
By themselves	193	54.7%	78	62.9%
Ambulance	137	38.8%	42	33.9%
Referral	21	5.9%	4	3.2%
Police	2	0.6%	0	0.0%
Hospital treatment requirement*				
ED presentation only	318	90.1%	115	91.3%
Basic hospital ward	32	9.1%	10	7.9%
ICU ward	3	0.8%	1	0.8%
Worst injury severity (AIS)				
1	209	59.2%	70	55.6%
2	122	34.6%	49	38.9%
3	20	5.7%	7	5.6%
4	2	0.6%	-	-
Number of shared e-scooter trips*	2,851,751	-	3,412,674	-
Weekdays	1.941.301	68.1%	2.432.970	71.3%
Weekends	910.450	31.9%	979.704	28.7%

Significance level, *: 90% (*p-value*≤ 0.1), ***: 99% (*p-value*≤ 0.01)

3.2. Temporal Analysis

In order to answer RQ1, we employ a temporal analysis of data. The temporal distribution of e-scooter injuries is defined as the changes in characteristics of injuries over time. The features of the temporal distribution of injuries were analyzed monthly, daily, and hourly. To standardize the number of injuries in 2021 and 2022, we employed the ratio of e-scooter injuries per 100,000 shared e-scooter rides as the number of trips for private e-scooters was not available. In order to compare different AIS levels in various periods, the following equation is used to determine the weighted abbreviated injury scale, *WAIS*, (Billah et al., 2021):

$$WAIS = \frac{\sum_{i=1}^{6} AIS_i \cdot X_i}{\sum_{i=1}^{6} X_i}, \quad (1)$$

where AIS_i is the AIS expanding from 1 to 6 and X_i is the number of injuries in the i^{th} AIS level.

3.3. Spatial Distribution

To address RQ2, we employ a Kernel Density Estimation (KDE) heatmap technique (Pobudzei et al., 2023) in QGIS software[4] to visualize the density of e-scooter-related crashes in Helsinki based on reported crash locations. Specifically, we generated a heatmap using injuries that had corresponding crash locations to depict the injury distribution in the study area. We developed the KDE heatmaps using two approaches: one considering the total number of injuries, and the other incorporating the number of injuries weighted by the AIS (1 to 4) (Billah et al., 2021; Truong & Somenahalli, 2011; Geurts et al., 2004).

3.4. Model Specification

Employing discrete choice models, in addition to the statistical analysis, can provide a better understanding of the factors affecting injury severity. In this study, as in many previous studies on modeling the crash injury severity (Yasmin et al., 2014; Abegaz et al., 2014; Chen et al., 2016; Rezapour et al., 2019; Mphekgwana, 2022), an ordered logit model (Greene & Hensher, 2010) was applied to the data to address RQ3. Ordered logit models are used to estimate the relationships between a dependent variable measured on an ordinal scale and a set of independent variables.

In the ordered logit models, the dependent variable is assumed to

[3] https://www.vianova.io/
[4] https://qgis.org/en/site/

have an underlying continuous latent variable. The latent and continuous measure of injury severity experienced by the e-scooter rider i,L_i, in a crash is computed as follows:

$$L_i = \beta\prime \cdot x_i + \epsilon_i, \tag{2}$$

where β is a coefficient vector to be estimated, x_i is vectors of explanatory variables describing rider i, and ϵ_i is the random error term following the Gumbel distribution.

Let us assume there are N ordered outcomes for the dependent variable (e.g., N can be 6 levels of AIS) and n is a possible outcome. The cut points, κ_k ($k = 0, 1, ..., N$), divide the latent variable into distinct intervals, each corresponding to a specific AIS score. In other words, the cut points translate the latent variable to AIS by determining the boundaries where the probability of observing a particular AIS injury changes. Thus, the coded discrete injury severity that rider i can face in the crash, $S - i$ is defined as follows:

$$S_i = \begin{cases} 1 & \kappa_0 \leqslant L_i < \kappa_1 \\ 2 & \kappa_1 \leqslant L_i < \kappa_2 \\ \dots & \\ N & \kappa_{N-1} \leqslant L_i < \kappa_N \end{cases}, \tag{3}$$

where κ_0 and κ_N are taken as -∞ and +∞, respectively. Note that $S - i$ is equivalent to the AIS scores in our study.

Therefore, in this model, the probability of observing outcome n is:

$$P_i(n) = Pr(S_i = n) = Pr(\kappa_{n-1} < L_i < \kappa_n). \tag{4}$$

The estimation of the cut points and coefficients can be handled automatically by statistical software (e.g., Stata) simultaneously to maximize the likelihood of the observed data (i.e., maximum likelihood approach).

We estimate an ordered logit model using all the data collected in 2021 and 2022, and including interactive variables with the year to represent factors affecting the severity of e-scooter crashes before and after the bans. In this study, the model is estimated in the Stata package (Acock, 2008), using *ologit* commands. It should be noted that the injury severity in our data has 4 levels of AIS, and due to the limited number of observations in level 4 (i.e., four injuries with AIS 4 in 2021), we aggregated the crashes with AIS 3 and AIS 4. Consequently, the injury severity model is developed considering three levels of injury (N=3 in our model).

4. Results and Discussion

4.1. Temporal Distribution of E-scooter-related Injuries in 2021 and 2022

Fig. 2 depicts the monthly and weekly distribution of injuries based on intoxication in 2021 and 2022 for April to August. Because of the snowy season in Helsinki from January to March, shared e-scooters are not in operation. Consequently, the first three months of the year have been omitted from this data due to the limited number of observations during that period. Two months of June and July account for 64% and 55% of the injuries between April to August of the year 2021 and 2022, respectively. Moreover, the average proportional injuries per 100,000 rides for 2021 is 21.6, while the same number in 2022 is 3.7. Therefore, there is a 70% reduction in proportional injuries in 2022 compared to 2021. This reduction in quantity and proportional injuries in 2022 highlights the effect of the nighttime ban and speed reduction (Cicchino et al., 2021; Posirisuk et al., 2022). However, there are other parameters involved such as improvement in e-scooter social learning in 2022 and the post-COVID-19 outbreak. Considering the intoxicated injuries in 2021 and 2022, the overall percentage of intoxicated injuries between April to August 2021 was 46.7%, while this number in 2022 is 31.7%, therefore, intoxication-related e-scooter injuries in 2022 has reduced by 32% compared to 2021. This is likely due to the weekend nighttime ban and can be seen in Fig. 4.

Fig. 3 depicts the monthly distribution of injuries based on the AIS scores in 2021 and 2022. In order to investigate the injury severity changes in 2021 and 2022, we calculated the WAIS in different time frames. For instance, the WAIS for June 2021 is calculated as the following:

$$WAIS_{June} = \frac{\sum_{i=1}^{4} AIS_i \cdot X_i}{\sum_{i=1}^{4} X_i} = \frac{1 \times 67 + 2 \times 27 + 3 \times 5 + 4 \times 1}{67 + 27 + 5 + 4} = 1.4 \tag{5}$$

According to Fig. 3, there is no observation with AIS 4 in 2022, and AIS 3 in 2022 has reduced by 17% compared to the same period in 2021. On the other hand, the proportion of AIS 1 showed no statistically significant changes in 2022 compared to 2021, while the proportion of AIS 2 in 2022 is different compared to 2021 especially in April, June, and August at a 95% confidence level. The average WAIS from April to August is 1.47 and 1.5 in 2021 and 2022, respectively. However, there is a 22% reduction in WAIS in April 2022.

Fig. 4 illustrates the daily distribution of injuries based on intoxication in 2021 and 2022 from January to August. This figure shows the trend of the proportional number of injuries per 100,000 rides has a much more steady trend over the weekdays in 2021, while there was a spike near the weekend (Uluk et al., 2022; Thoenissen et al., 2021). The reductions in proportional injuries on Friday, Saturday, and Sunday in 2022 compared to 2021 are 70%, 83%, and 79%, respectively. As there is a nighttime ban on Saturday and Sunday from midnight to 5 a.m., the intoxication-related injuries have reduced by 71% and 62%, respectively, while it has increased by 6% on Friday. Despite the temporal redistribution, these changes imply the effectiveness of the restrictions.

Fig. 5 shows the daily distribution of injuries based on the AIS and WAIS in 2021 and 2022. Based on this figure, the WAIS from Tuesday to Thursday in 2022 has reduced compared to 2021, while there is a slight increase in WAIS on the other days.

Fig. 6 demonstrates the hourly distribution of e-scooter-related injuries based on WAIS and the proportional number of injuries in 2021 and 2022. Based on Fig. 6-a, -a, the WAIS from 12 a.m. to 4:59 a.m. on weekdays in 2021 and 2022 is the same and equal to 1.5, while the proportional number of injuries per 100,000 rides from 12 a.m. to 5 a.m. on weekdays in 2021 and 2022 are 52.5 and 21.3, respectively with a 60% decrease in 2022. On the other hand, the WAIS from 5 a.m. to 11:59 p.m. on weekdays in 2021 and 2022 is 1.6 and 1.5, respectively, while the proportional injuries per 100,000 rides from 5 a.m. to 11:59p.m.on weekdays in 2021 and 2022 are 6.51 and 2.82, respectively with a 57% decrease in 2022. The data indicate that the speed restriction on weekdays primarily impacted reducing the number of injuries rather than the severity of injuries. It is likely that injuries on weekdays are more linked to practical purposes like commuting, which the restrictions did not specifically target. As a result, the number of trips and injury severity remained relatively similar. On the other hand, weekend trips, even during the day, may have a higher likelihood of involving intoxicated riders or being associated with social activities, potentially leading to more reckless behavior and a higher risk of injuries. Overall, in 2022, the number of injuries and the proportion of injuries per 100,000 rides have considerably decreased for various reasons. One key factor is social learning among all road users, leading to better coexistence with e-scooters in the shared public space.

Fig. 6-b shows the hourly distribution of e-scooter-related injuries based on WAIS and the proportional number of injuries in 2021 and 2022 on weekends. According to this figure, the WAIS from 12 a.m. to 5 a.m. on weekends in 2021 is 1.4 while this WAIS in 2022 is 0.3,

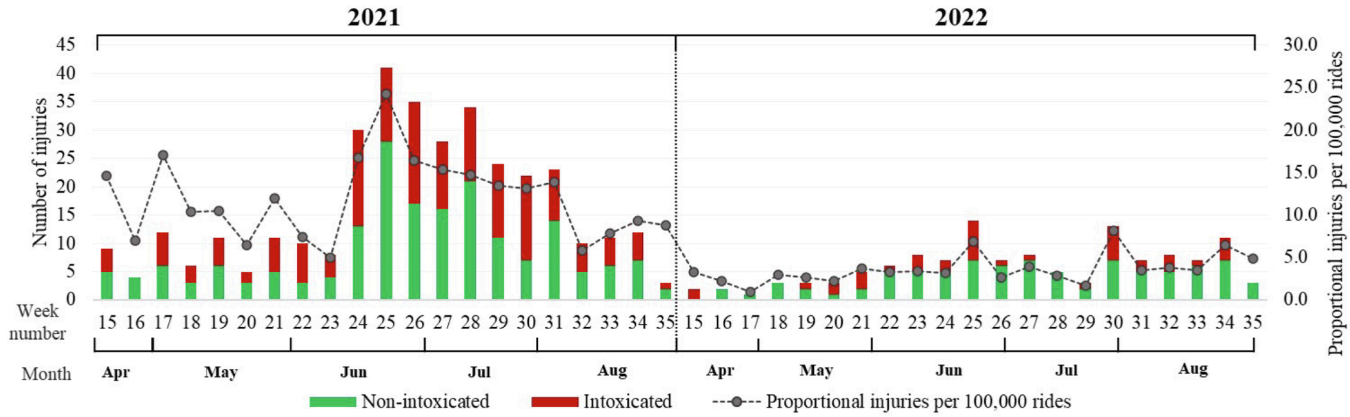

Fig. 2. Monthly and weekly distribution of injuries based on intoxication in 2021 and 2022.

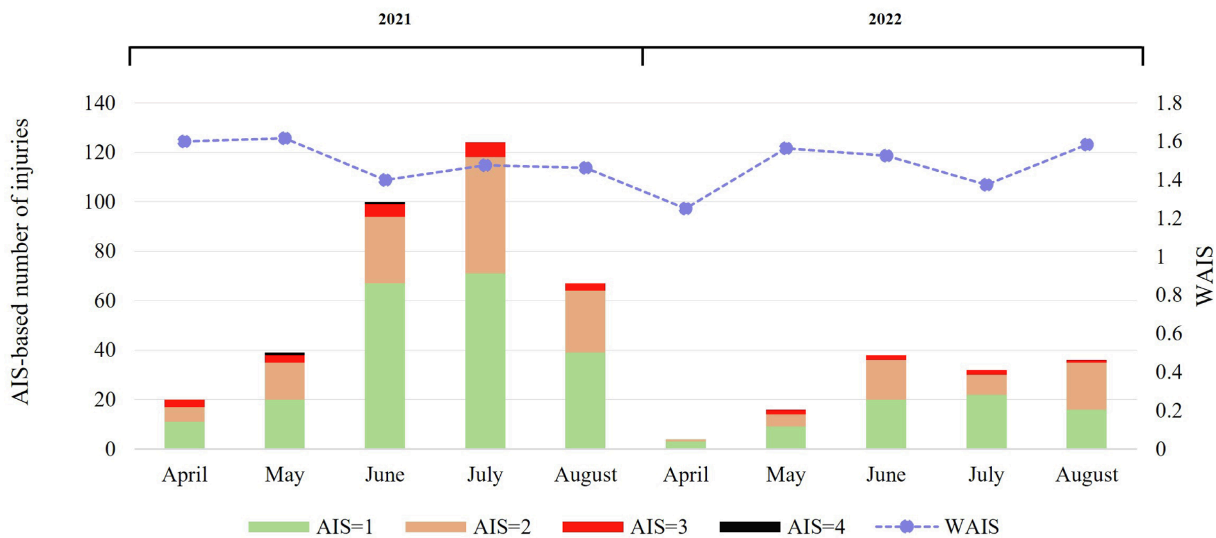

Fig. 3. Monthly distribution of injuries based on AIS score in 2021 and 2022.

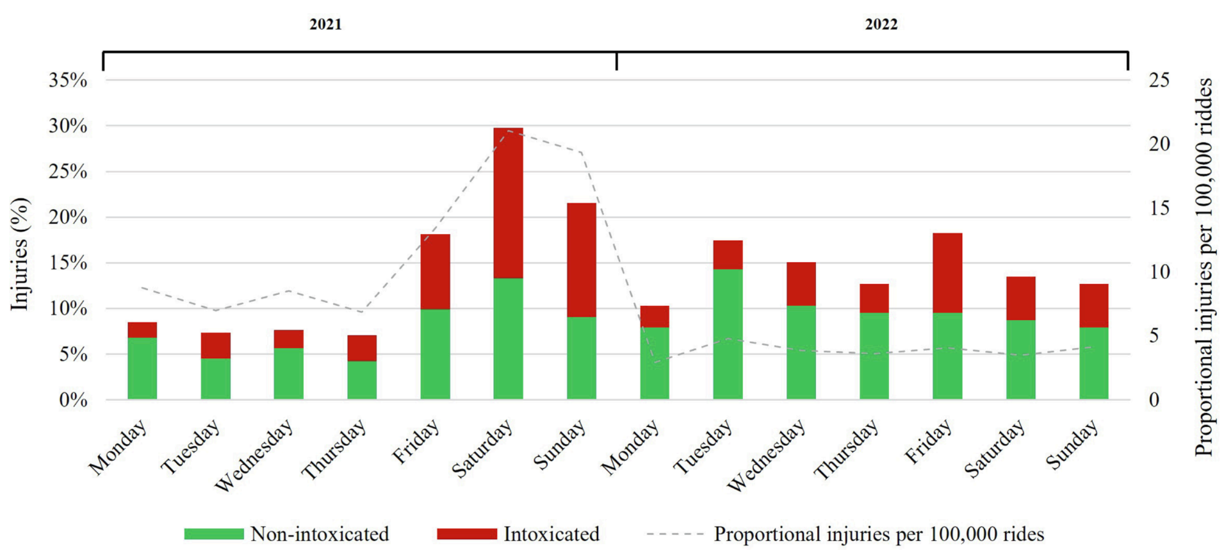

Fig. 4. Daily distribution of injuries based on intoxication in 2021 and 2022 - Jan-Aug.

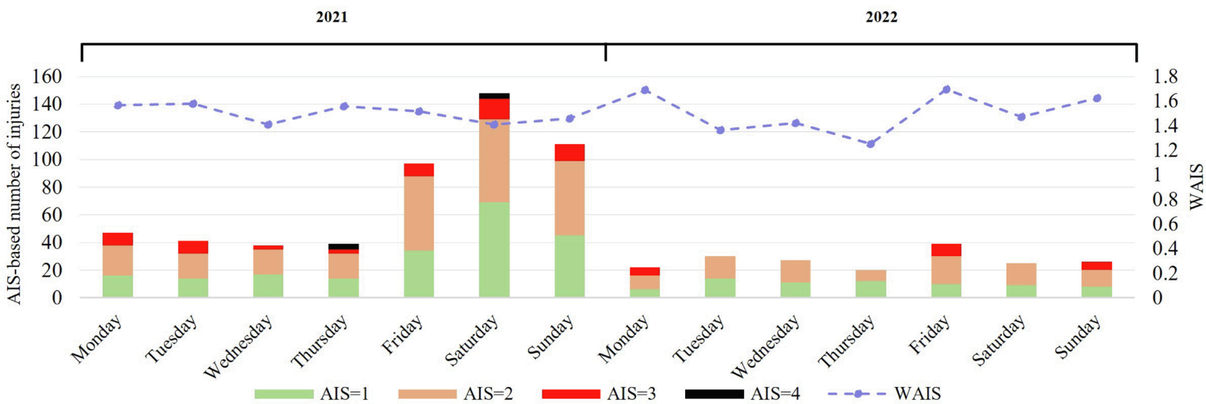

Fig. 5. Daily distribution of injuries based on AIS score in 2021 and 2022.

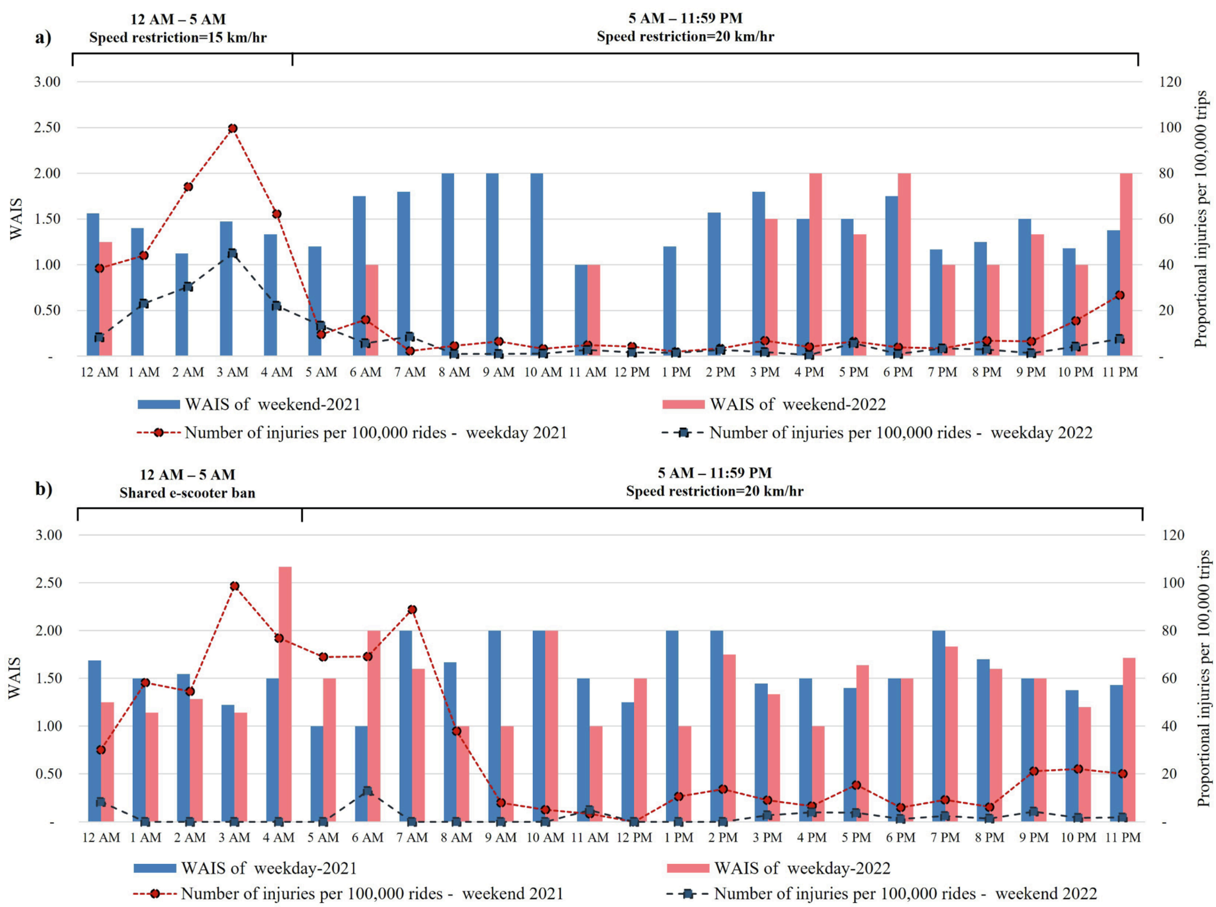

Fig. 6. Hourly distribution of e-scooter-related injuries based on WAIS and the proportional number of injuries in 2021 and 2022 - Jan-Aug a) on weekdays b) on weekends.

representing a 82% decrease in 2022. On the other hand, the proportional number of injuries per 100,000 rides from 12 a.m. to 5 a.m. on weekends in 2021 is 54, while this number for 2022 is not calculated due to the limited number of shared e-scooter trips around 12 a.m.[5]. Therefore, we are facing a 100% reduction in the proportional number of shared e-scooter injuries. On the other hand, the WAIS from 5 a.m. to 11:59 p.m. on weekends in 2021 and 2022 is 1.5 and 0.8, respectively, while the proportional injuries per 100,000 rides from 5 a.m. to 11:59 p.m. on weekends in 2021 and 2022 are 13 and 2, respectively with an 84% decrease in 2022. These numbers show that besides the total elimination of shared e-scooter-related injuries from midnight to 5 a.m. on weekends in 2022, the speed reduction during the day has effectively contributed to the injury severity reduction on weekends which is the direct impact of the restriction policies. These results are in line with the findings of Cicchino et al. (2021) where there is a speed cap of 10 mph (16 km/h) in Washington, D.C. which is associated with less severe injuries compared to other cities in the United States.

[5] Throughout the period from midnight to 5 AM, a group of the shared e-scooter trips were those that had commenced before midnight and continued past it. Additionally, there were some trips conducted by operators during this time, focusing on redistributing the shared e-scooters across the city.

4.2. Spatial Distribution of E-scooter-Related Injuries in 2021 and 2022

In our data, the injured people who had been transported by ambulance to the hospital have corresponding crash locations. Accordingly, the number of records used for developing the KDE heatmap representing the spatial distribution is 140 injuries (40% of the injuries) for 2021 and 40 injuries (32% of the injuries) for 2022. Fig. 7 illustrates the areas with relatively higher densities of crash occurrences by visualizing the total number of crashes according to their respective locations in 2021 and 2022, before and after the restrictions. According to this figure, the density of e-scooter-related injuries is higher in the city center area, particularly near the central railway station followed by Kamppi metro station and around Esplanadi park. The previous literature also supports the finding in Helsinki. In Nashville, Tennessee, USA, most of the e-scooter crashes were located in the downtown area (Shah et al., 2021). Moreover, in Munich, Germany, e-scooter crashes were more concentrated in the vicinity of public transport hubs, which are in close proximity to the main city attractions and nightlife areas (Pobudzei et al., 2023). The e-scooter crashes are mostly within the city center between 3 p.m. to 6 p.m. (Pobudzei et al., 2023). The injury locations in 2022 (i.e., the green spots in Fig. 7) are more sparse in the whole city compared to 2021, while there are almost no injuries near the central railway station in 2022. Additionally, Fig. 7 and Fig. 8 illustrate the presence of tram lines. The proximity of the crashes to these tram lines suggests that it could be due to a combination of factors: the distribution of shared e-scooters by operators along these routes, as well as the uneven surface caused by the presence of tram lines. This uneven surface might contribute to difficulties in controlling e-scooters while riding, potentially leading to loss of control incidents (Gildea et al., 2021; Utriainen et al., 2023).

Fig. 8 demonstrates the areas with relatively higher densities of crash occurrences by visualizing the weighted number of crashes by AIS score according to their respective locations in 2021 and 2022, before and after the restrictions. According to this figure, while the injury severity as well as the density of injuries, is high in the city center, the injury severity in the southern part of Helsinki is also high in 2021. Whereas, this area has seen a considerable decrease in injury severity in 2022.

A possible reason for the increased spatial distribution of injuries in 2022 compared to 2021 is the spread of shared e-scooter services into outer parts of Helsinki (Pobudzei et al., 2023). We can conclude that the active transportation infrastructure in the outer city areas offers more space, less congestion, and less challenging conditions for riding e-scooters. As a result, there are fewer crashes with less severity in these areas. Moreover, public social learning regarding e-scooters has increased, leading to greater awareness of how to interact with e-scooter riders. It should be noted that the analysis of crash locations has only been conducted for 30% of the entire dataset on e-scooter-related injuries, as only cases that arrived at the hospital via ambulance were included. Hence, it is inaccurate and biased to generalize the findings to the entire database and conclude the impacts of implemented bans on the spatial distribution of the injuries.

4.3. Model Outputs

Table 2 presents the results of the model[6]. While it is generally recommended to exclude the variables with *p-values* above the predetermined threshold (e.g., a *p-value* of 0.10), we decide to include the same variables for both years, particularly the time-of-day-related variables. This allows us to assess the impacts of the implemented bans on e-scooter injury severity, comprehensively. The reference in this model is an e-scooter crash that caused an injury that needed an ED presentation only, and happened between 5 a.m. to 4 p.m. while the rider was not intoxicated. It is also worth noting that following the bans in 2022, there is no crash observation during the weekend between 12 a.m. to 5 a.m., and that is why *Weekend 12–5 AM* is excluded from the model in 2022 and no coefficient is estimated for it.

Based on the model outputs presented in Table 2, it appears that being intoxicated increases the probability of more severe injuries, significantly (Stray et al., 2022; Alwani et al., 2020; Trivedi et al., 2019). However, a noteworthy observation emerged in 2022 following the implementation of bans on scooter speed during weekdays, particularly after midnight, and prohibiting scooter usage during weekend nights, the previously significant relationship between the intoxicated variable and injury severity is no longer evident in 2022. This change may be attributed to the bans' effectiveness in reducing the overall number of intoxicated riders, thereby potentially mitigating the impact of alcohol-related incidents on injury severity.

Regarding the time-of-day-related variables, there is limited statistical evidence to support the impact of *Weekday 12–5 AM* on e-scooter injury severity, in 2021, implying that implementing the proposed ban may not significantly change injury severity during these hours when crashes do occur. Similarly, as it is clear from the table, in 2022, no significant evidence is found to indicate that the e-scooter crashes during *Weekday 12–5 AM* are more severe compared to other hours. Yet, in 2022, the number of crashes during the mentioned time is small (e.g., 18 observations), thus, the lack of significance could potentially be attributed to insufficient statistical power rather than a true absence of relationship.

Furthermore, the injury severity levels observed during *Weekend 12–5 AM* appear to be significantly lower compared to other time intervals on weekends. This might be due to reduced traffic volume on the roads during late-night hours, leading to fewer opportunities for collisions with other vehicles (Portland Bureau of Transportation, 2019; Sexton et al., 2023). It should be noted that the proposed bans were designed to target reducing the number of e-scooter crashes and they appear to have been successful, as shown in Table 1. Besides, when the overall crashes are significantly reduced, there is a significant reduction in trauma. It is also important to consider the broader goal of improving overall safety and reducing the severity of injuries in scooter crashes. If the policy fails to address or reduce the injury severity despite reducing the number of crashes, it suggests that additional measures may be necessary to address the underlying factors contributing to the severity of injuries.

Interestingly, following the implementation of speed reduction on the e-scooters during weekday nights and the prohibition of shared e-scooter usage on weekend nights, the hours between 4 p.m. and 9 p.m. show a positive significant coefficient in the injury severity model, as shown in Table 2. This indicates that the bans may result in a temporal redistribution of e-scooter injury severity, resulting in a significantly higher share of WAIS during this time period in 2022. Also, due to coinciding with the evening rush hour with more vehicles on the streets, the risk of crashes involving e-scooters may escalate, leading to a higher likelihood of more severe injuries during this time period (Stray et al., 2022; Ahluwalia et al., 2022). To address this emerging trend, further investigation is required to assess the effectiveness of the implemented bans during peak evening hours.

Another significant variable in the model is *Age*, and its positive coefficient is aligned with findings from previous studies in the field (Stray et al., 2022; Kim & Campbell, 2021). The higher injury severity observed in older individuals could potentially be explained by their limited familiarity with and experience in controlling the e-scooters.

Two other significant factors associated with e-scooter injury severity have been identified: the requirement of Intensive Care Unit (ICU) admission and basic hospital ward treatment. As expected, both factors exhibit positive correlations with e-scooter injury severity, compared to the cases where only treatment in the emergency department was needed, indicating that more severe injuries are associated with a higher likelihood of requiring ICU admission or basic hospital ward treatment. Notably, the impact of ICU admission on e-scooter

[6] Pseudo R-squared of this model is computed as 0.125.

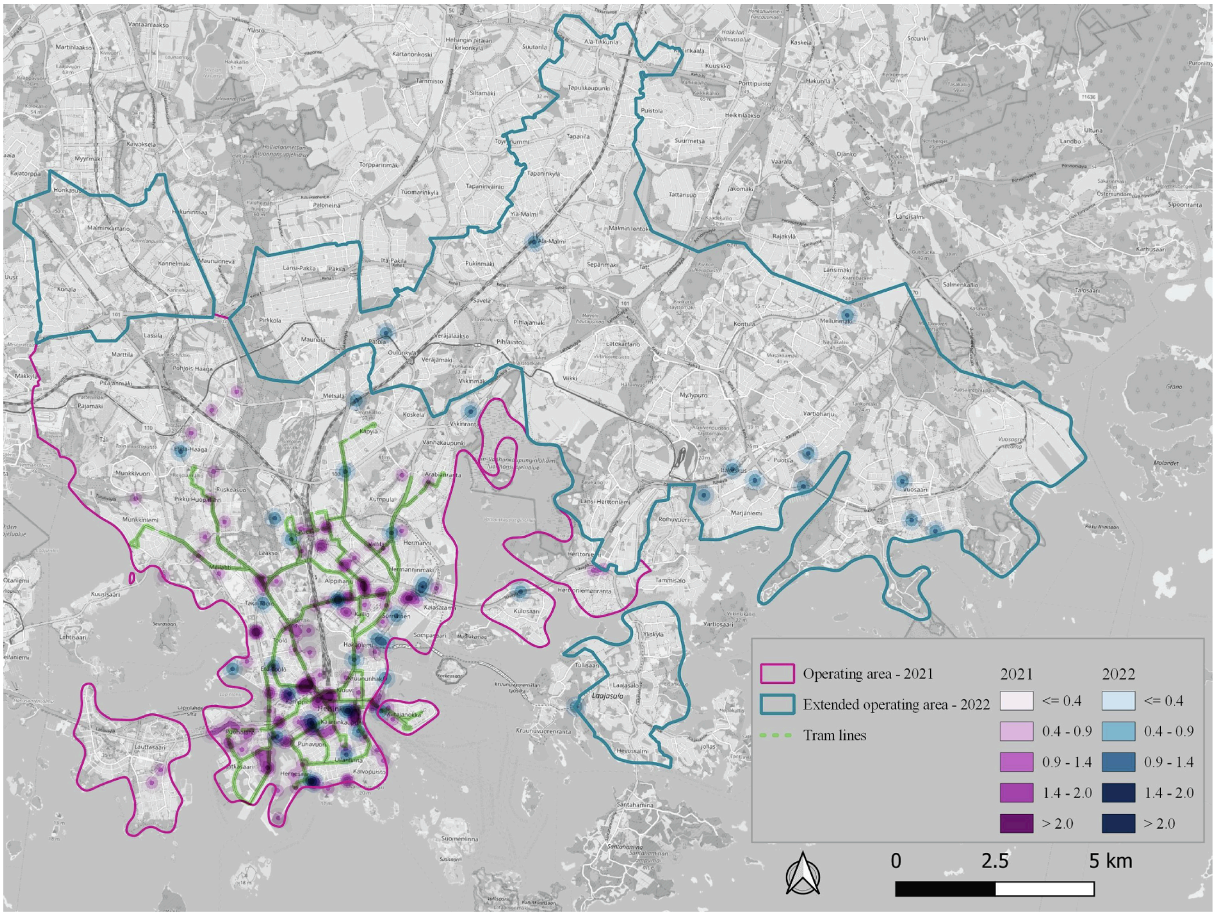

Fig. 7. Spatial distribution of injuries in 2021 and 2022 from January to August - non-weighted.

injury severity appears to be approximately 1.5 times as pronounced as that of basic hospital ward treatment.

These findings may lead to new potential bans, as listed below, with the goal of reducing injury severity.

- Drunk riding: Implementing a ban on riding e-scooters under the influence of alcohol or any intoxicating substances would emphasize the importance of responsible and safe behavior[7].
- Low experience mode: The beginner mode is typically designed to assist novice users in getting familiar with e-scooter operation, potentially reducing the risk of crashes during the first ride. By extending this mode beyond the first ride (e.g., first five rides), older users, as well as users of all ages, would have additional opportunities to gain experience and improve their e-scooter riding skills, enhance safety awareness, and potentially reduce the severity of injuries.

We, interestingly, did not find any significant relationships between injury severity level and factors such as gender, meteorological information (including wind speed, temperature, cloud amount, etc.), and type of crash. This does not imply that these factors have no effect. Rather, it may suggest that the influence of these factors could be context-specific or weaker in comparison to the impact of several other factors in the given cultural or spatial setting. Further research is needed to explore the nuanced relationships between these factors and injury severity.

5. Conclusions

This study aimed to identify changes in injury severity of e-scooter-related emergency cases in Helsinki while investigating the effect of the nighttime ban and speed reduction policies in 2022. To this end, an ordered logit model was developed to assess e-scooter injury severity based on individuals' demographics, date, time, and weather-related parameters. Furthermore, the temporal and spatial analysis of e-scooter-related injuries were conducted to investigate the potential impacts of implemented bans on the distribution of injuries.

The temporal analysis demonstrated that the number of injuries over the first eight months of 2022 has reduced by 64% compared to 2021. However, the AIS of crashes has only reduced slightly in 2022 compared to 2021. This may be due to the fact that the bans implemented during this period were primarily focused on reducing the number of e-scooter crashes rather than specifically targeting injury severity, or due to other safety-related reasons. The findings of the model also support this observation, as the coefficients of the corresponding variable indicated that there is no statistical evidence to support the impacts of bans on e-scooter injury severity. Furthermore, the proportional e-scooter-related injuries in 2022 on Saturday and Sunday have reduced by 83% and 79% compared to 2021 which is strongly associated with the implemented e-scooter nighttime ban on weekends as well as the speed reduction policy. Furthermore, the WAIS in 2022 has a smoother trend over the months, weeks, and days of the week compared to 2021 where there was a significant spike on Friday and the weekend. The hourly distribution of

[7] This ban is already implemented in Finland, started from March 2, 2023. Further information about the drunk riding ban can be found in https://www.lausuntopalvelu.fi/FI/Proposal/Participation?proposalId=026ac049-269e-439f-95e2-d43d613373fc&proposalLanguage=da4408c3-39e4-4f5a-84db-84481bafc744

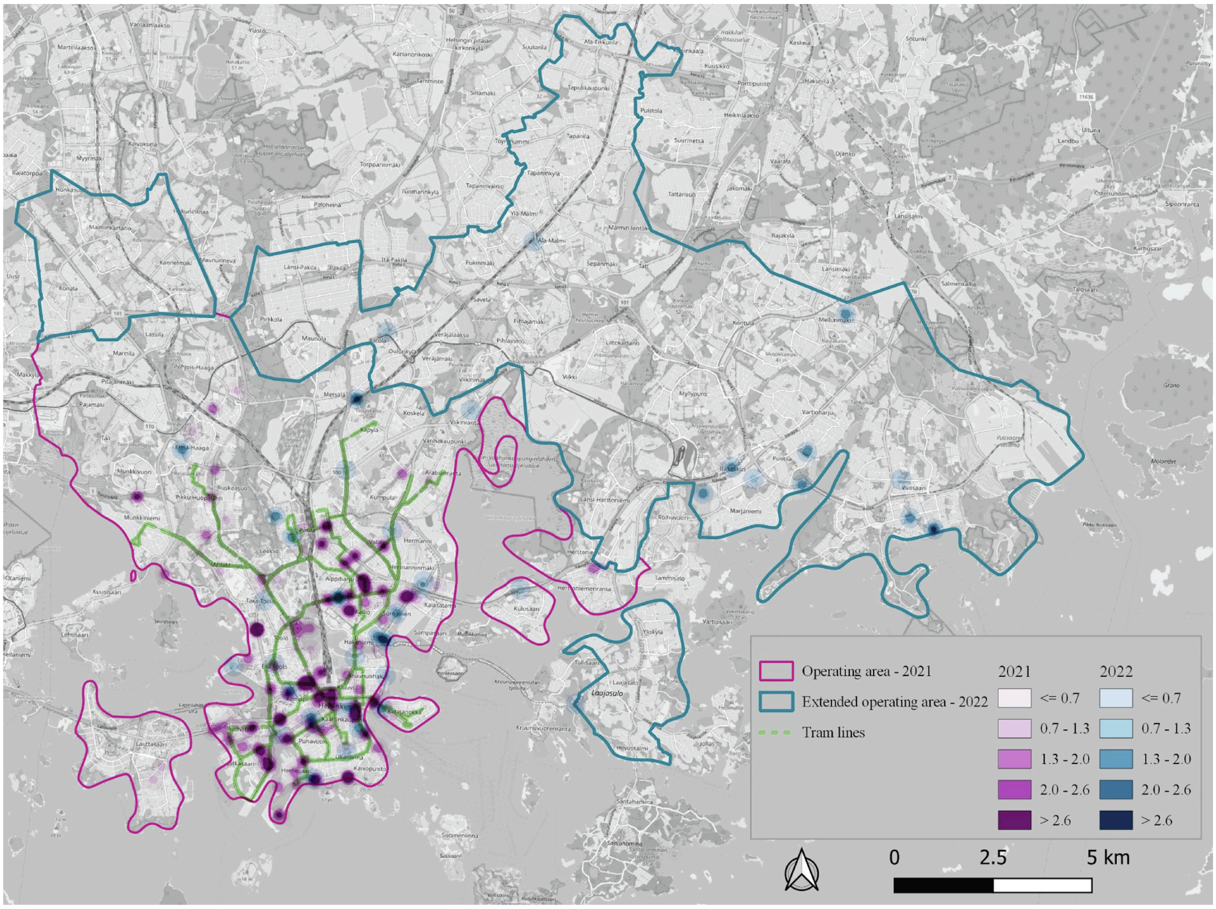

Fig. 8. Spatial distribution of injuries in 2021 and 2022 from January to August - weighted by AIS scores.

injuries also revealed that injuries were reduced in quantity by 55% from midnight to 5 a.m. while the proportional number of injuries per 100,000 rides has reduced by 76%. The spatial distribution of injuries also revealed that the concentration of injuries in 2021 was mostly in the city center and near main metro stations, while in 2022, the crash locations are more spread. The findings of the ordered logit model reveal that alcohol intoxication significantly increases the probability of more severe injuries among e-scooter users. Additionally, after the restrictions were implemented, during the evening peak hours (4 p.m. to 9 p.m.) when the number of vehicles on the streets is at its maximum, e-scooter users are more likely to experience more severe injuries. Higher age was also found to significantly increase the probability of more severe injuries.

Overall, this study contributes to tailoring policies that promote the safe integration of e-scooters into transport systems, providing valuable insights for planners and policymakers regarding the impact of restrictions on the safety and usage of e-scooters in Helsinki. However, further investigation is required to fully understand the implications of these findings and determine the most effective measures to reduce e-scooter injury severity. Recommendation for policy design is to carefully evaluate packaging of different actions, such as drunk riding restrictions, the low-speed mode for first rides, lowering motor vehicle speed limits, or infrastructural changes. Besides improving safety as an important goal, pragmatic policy-making will have to take into account other goals, such as reducing greenhouse gas emissions, and the necessary trade-offs between those goals (Mladenović et al., 2022).

This study represents one of the initial investigations into the influence of shared e-scooter restriction policies on the quantity and severity of e-scooter-related injuries. However, several limitations should be considered. Firstly, the data collection process was not executed systematically, and there was no specific code for e-scooter-related injuries within the comprehensive patient database. Consequently, extracting the entire dataset required extensive and laborious manual work. The crash location was only available for the injured people who had been transported by an ambulance to the hospital, which was about 30% of the whole database. Furthermore, the dataset had many incomplete variables such as helmet usage, relative speed, accurate time of crash other than the time of visiting the ED, and whether the crash happened with a private or shared e-scooter. The effect size of each variable can also be computed in future studies to further enhance our understanding of their impact on injury severity. Additionally, while there has been a noticeable decrease in the proportional number of injuries and the severity trend, it would be inaccurate to attribute this solely to the nighttime ban and speed reduction policies implemented in Helsinki. Various other factors, such as social learning surrounding e-scooters and the ongoing adaptation of citizens to coexist with these devices in society, likely contribute to the observed outcomes. Moreover, the relaxation of COVID-19 quarantine restrictions in 2021, compared to 2020, could have also played a role in the significant spikes observed in the temporal distributions in 2021. Furthermore, it is important to note that the City of Helsinki has implemented other policies, such as fleet reduction in specific inner city areas, which were not investigated in this particular research. In addition, there were not enough crash location data to perform a thorough spatial analysis of injury distribution. As a future study, it would be valuable to explore shared e-scooter users' perspectives on these restriction policies and their impact on users' usage patterns and everyday mobility. Furthermore, investigating the effect of differences in the built environment with the expansion of e-scooter services to the outer parts of the city could bring valuable insights into the spatial distribution and built

Table 2
Ordered logit model estimation for e-scooter users' injury severity level (No. of obs. = 478).

Variable	Coeff.	Std. Err.	z	P>|z|	[95% Conf.	Int.]
Age	0.01	0.01	1.64	0.10	0.00	0.03
Basic hospital treatment[1]	2.92	0.39	7.55	0.00	2.16	3.68
ICU hospital treatment	4.63	1.21	3.84	0.00	2.26	6.99
Intoxicated - in 2021[2]	0.44	0.25	1.76	0.08	−0.05	0.93
Weekend: 12–5 AM - in 2021	−0.58	0.33	−1.75	0.08	−1.24	0.07
Weekday: 12–5 AM - in 2021	−0.55	0.37	−1.48	0.14	−1.27	0.18
Any day: 4–9 PM - in 2021	−0.17	0.32	−0.53	0.60	−0.79	0.46
Any day: 9–11:59 PM - in 2021	−0.50	0.32	−1.58	0.11	−1.12	0.12
Intoxicated - in 2022	−0.30	0.40	−0.74	0.46	−1.09	0.49
Weekend: 12–5 AM - in 2022	-[3]	-	-	-	-	-
Weekday: 12–5 AM - in 2022	−0.71	0.75	−0.95	0.34	−2.18	0.76
Any day: 4–9 PM - in 2022	0.57	0.34	1.67	0.09	−0.12	1.26
Any day: 9–11:59 PM - in 2022	−0.22	0.55	−0.40	0.69	−1.30	0.86
Cut point[4] κ_1	0.87	0.33			0.22	1.51
Cut point κ_2	3.97	0.42			3.14	4.79

[1] In this model, the reference is an e-scooter crash that resulted in an injury requiring an ED presentation, occurring between 5 AM to 4 PM while the rider was not intoxicated.
[2] To investigate the impact of various variables, specifically intoxication and time of day, before and after the implementation of restrictions, we utilized interaction terms.
[3] Following the implementation of bans in 2022, no rides or crashes have been observed during weekends between 12 AM and 5 AM.
[4] Cut points are used to divide the continuous latent variable into distinct intervals corresponding to AIS scores.

environment factors associated with e-scooter-related injuries.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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