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Revealing Spatial Patterns of Dockless Shared Micromobility: A Case Study of Košice, Slovakia

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Abstract: Air pollution, largely driven by car traffic, poses significant challenges in many cities, including Košice, Slovakia. As the city explores micromobility as a part of its smart city initiatives and sustainable alternative to individual car use, understanding its spatial dynamics becomes essential. Despite the growing adoption of shared micromobility systems, research on their spatial patterns in Central Europe is still limited. This study analyzes over 900,000 trips made between 2019 and 2022 using bicycles, e-bikes, e-scooters, and e-mopeds in Košice's dockless system. Using spatial analysis, we identified key hubs near public transport stops, pedestrian zones, and universities, highlighting how micromobility addresses the first/last mile transport challenge. A notable shift from bicycles to e-scooters was observed, enabling wider adoption in areas with fragmented terrain and neighborhoods farther from the city center. Our findings show a significant demand for shared micromobility, indicating its potential to reduce urban car dependency and support smart and sustainable urban transport. However, winter months remain a challenge, with high smog levels but near-zero demand for shared micromobility.

Keywords: micromobility; origin-destination data; modes of transport; spatial analysis; Slovakia

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1. Introduction

Micromobility is a dynamically evolving spatial phenomenon that, particularly in urban environments, contributes to changes in the nature of people's spatial mobility [1], promoting its sustainability [2]. It generally refers to transportation using lightweight individually used vehicles [3–5], such as bicycles, e-bikes, scooters, e-scooters, and e-mopeds, typically operating under a speed limit suited to urban conditions. These vehicles typically do not require a driver's license [1].

Micromobility is also defined by the maximum distances it can cover. While some studies consider daily travel limits [6], most focus on single-trip distances, which typically range between 5 and 15 km [7,8]. This range naturally reflects typical urban distances, where key points of interest (POI), such as residences, workplaces, shops, and schools, are relatively close to one another.

The ecological benefits of micromobility are often emphasized, as it relies on zero-emission or low-emission vehicles [6,9]. These vehicles can either be privately owned or accessed through shared micromobility systems. Shared systems operate as either docked systems, which use a network of stations for vehicle pick-up and return, or dockless systems, which allow flexible drop-off and pick-up within the designated areas [10,11].

Given the environmental benefits and development of shared systems, micromobility has risen in popularity. At the end of the 20th century, only 10 cities operated bike-sharing

systems, but by 2019, this number surged to over 2900 [12]. Similarly, shared e-scooter systems, introduced in 2017 in the US and 2018 in Europe, grew rapidly and became a transformative element in urban mobility [13,14].

As cities face growing sustainability challenges, new alternative transport modes, such as micromobility, are playing an increasingly important role in addressing these issues. McQueen et al. [2] identify three key ways in which micromobility supports sustainability: reducing car dependency to lessen environmental burdens, promoting social and economic equality through affordable and reliable transportation, and encouraging shifts towards non-automobile travel driven by environmental awareness. Transitioning to such alternative transport modes is widely recognized as an effective strategy for mitigating climate change and reducing reliance on fossil fuels. In addition to its environmental benefits, micromobility also contributes to improving urban quality of life, easing traffic congestion, lowering emissions, and fostering more livable public spaces [15].

However, research on shared micromobility systems in medium-sized cities remains underrepresented [16], particularly in Central and Eastern Europe, where air quality remains a significant concern [17]. Although Slovak urban areas generally maintain good air quality, Košice faces specific challenges due to the presence of heavy industry and dense urban traffic, particularly in the city center [18]. These factors contribute to elevated pollution levels, especially during the winter months, when poor dispersion conditions intensify smog formation. As a result, the city has higher rates of premature deaths linked to air pollution compared to the capital, Bratislava [19]. Recognizing these challenges, Košice aims to shape urban mobility in a sustainable, smart, and socially and environmentally just manner [20]. Reducing car dependency and improving air quality are central to this vision, with shared micromobility emerging as a key component of the city's strategy. In collaboration with a local provider of smart mobility solutions, Košice is integrating shared micromobility with public transport and envisions adapting transport infrastructure to support its development efectively [21].

Shared micromobility has recently become an essential component of innovative solutions in smart cities [22]. Several external factors suggest that Košice might lag behind in this domain. Firstly, cities in transitional economies of the former Eastern Bloc lag behind their Western counterparts in implementing smart solutions [23]. Secondly, within Slovakia, Košice is a second-tier city located in one of the country's economically weaker regions [24,25]. Such cities typically lag in the diffusion of innovations and smart solutions [26,27]. Moreover, despite numerous projects aimed at developing cycling infrastructure in recent years, Košice still faces a significant investment backlog in building bike lanes and cycling paths. While new bike lanes and paths are being added, they still do not form a continuous network. As a result, micromobility often takes place on pedestrian sidewalks or roads designated for motor vehicles, leading to hazardous conflict situations [28,29].

However, several recent studies [27,30] and rankings [31] indicate that even these cities can successfully transform into smart cities, primarily due to the presence of local universities and entrepreneurial ecosystems. This presents an opportunity for Košice, home to multiple universities fostering technological advancements and innovation, with its industrial economic base successfully transitioning into an IT- and service-oriented economy. Additionally, one of Slovakia's most prominent innovative companies, Antik Telekom, operates in Košice. The company has established itself in the smart solutions market for individuals, households, cities, and public administration. Košice is the first city where Antik deploys and operates its innovations before expanding them elsewhere. This is evident in several smart solutions developed in cooperation with local and regional governments [32]. One of the key areas of focus is the modern dockless shared micromobility system.

Understanding the spatial dynamics of shared micromobility systems is crucial for addressing these environmental, social, and infrastructural challenges in a smart way. Many studies focus on the spatial distribution of points of interest (POI), or the locations where users pick up or drop off transportation devices, which can vary depending on the specific transport modes used. For instance, research by Zhu et al. [33] in Singapore found that shared scooters exhibit a more spatially compact and quantitatively denser distribution than shared bicycles, with demand concentrated around tourist attractions, metro stations, and dormitories. Similar studies identify POI in high-traffic areas such as city centers, university campuses, and workplaces [16,34,35]. Public transportation hubs, including train stations and metro stops, also represent key POI for shared micromobility, highlighting their role in solving the first/last mile transportation problem [36].

This growing body of research underscores the importance of analyzing POI clustering in cities, which may reveal critical urban transport hubs. While previous studies have examined shared micromobility mainly in Western European cities, there is limited research on medium-sized cities in Central Europe. By the case of Košice, this research enriches the literature by providing insights into how micromobility systems function in a specific urban and economic context. It highlights how infrastructure, policy, and user behavior shape micromobility patterns and influence the spatial clustering of POI. Specifically, the study will explore the city's regularities and patterns of micromobility pick-up and drop-off points to identify areas where a shared system contributes to enhancing the urban transport network. By focusing on the origins and destinations of trips, rather than the entire routes, we can gain a clearer understanding of how shared micromobility POI are related to a city's geographic structure.

Between 2019 and 2022, Košice implemented a dockless shared micromobility system, allowing unrestricted drop-off and pick-up of vehicles, which facilitates the identification of natural patterns without regulatory interference. From 2022 onward, zoning regulations were introduced to designate specific drop-off areas, aligning the system more with a docked model. This research focuses on the pre-zoning period 2019–2022. This period also allows for the examination of shifts in user behavior, particularly during the COVID-19 pandemic, and the evolution of spatial patterns in response to changes in the structure of transport modes (bikes, e-bikes, e-mopeds, e-scooters) in the citywide shared micromobility system.

Research on transport modes within micromobility is extensive, with a focus on specific vehicles like bicycles and e-bikes [37,38], scooters and e-scooters [39–42], and mopeds [43,44]. More frequently, studies compare and analyze multiple modes simultaneously [45–47]. The differences between these modes are particularly evident in travel distances, with e-scooters typically covering shorter distances of up to two kilometers, while bicycles and e-bikes are used for longer distances, usually ranging from two to four kilometers [48–51]. However, the onset of the COVID-19 pandemic disrupted established travel patterns, leading to significant shifts in spatiotemporal mobility behavior [52], which still require further investigation.

A commonly discussed topic in the literature is the role of micromobility in addressing the first/last mile transportation problem (FLMTP) and supporting public transport systems [36,53,54]. Sustainable transport modes, such as e-scooters and bicycles, help bridge the FLMTP, improve accessibility, and reduce reliance on public transport [55,56]. Studies show that bicycles typically connect with public transport within distances of 1 to 4 km [57,58], while the introduction of e-mobility has extended these ranges, overcoming natural barriers like topography [14].

While micromobility research is underrepresented in Central Europe, growing attention is being given to this subject, as seen in studies from Hungary [1,59–62], Czechia [63,64],

Poland [65–69], and Slovakia [70–73]. These studies cover topics such as modal choice, factors influencing users, parking locations, and transport availability. However, research focusing on the spatial patterns of micromobility is still insufficient, especially in the context of post-socialist Central and Eastern Europe (CEE). This study aims to fill this gap by analyzing spatial patterns and their role in urban mobility in Košice, offering insights that can be applied to other cities in the region.

2. Materials and Methods

In the article, we use data from ANTIK Telecom (hereinafter referred to as Antik), a shared public transport provider in Košice. Data of a similar nature were used in recent studies by Chicco and Diana [51], who employed them for the study of spatiotemporal patterns of micromobility usage in the city of Turin (Italy), Reck et al. [34] who described usage and mode choice at a high spatiotemporal resolution in Zurich (Switzerland), Schwinger et al. [74] who researched micromobility trips by distance, locations and spatiotemporal trends in Aachen (Germany), and Zhao et al. [75], who used them to study the impact of data processing on deriving micromobility patterns in Zurich (Switzerland). This allows for a general comparability with our results.

The provided database contains over 900,000 records of trips made from the launch of Antik's service in May 2019 to the end of September 2022. During the period, transportation was affected by restrictions related to the COVID-19 pandemic. On the one hand, this temporarily reduced the demand for shared micromobility and transport in general; on the other hand, it allows us to at least to suggest whether these measures led to changes in the spatial patterns of micromobility in Košice.

While other shared micromobility providers, such as Bolt and Tier, operate in Košice [76,77], Antik remains the leading operator in terms of fleet size, diversity of transport modes, and total trip volume. Although shared micromobility accounted for only 2.2% of total micromobility in 2021 [78], the extensive dataset it generates provides valuable insights into broader micromobility trends. Moreover, the significant overall volume of micromobility use in the city highlights its relevance for urban transport policy and planning.

The advantage of this data lies in its simple structure, which enables the identification of spatial mobility patterns of various modes of shared micromobility transport, as well as the selection of time intervals. Each trip in the dataset contains records of the date, mode and route expressed by coordinates recorded during the trip. The number of GPS records in each row is extensive, as shown in the data sample (Table 1).

Table 1. Structure of original dataset as provided by Antik [79].

Date	Transport Mode	GPS Records
3 May 2019	Bicycle	21.251537 48.719108, 21.250547 48.7189, 21.25006 48.719694, 21.249392 48.72116, 21.249337 48.72141
3 May 2019	Bicycle	21.241571 48.727142, 21.242183 48.726613, 21.241844 48.727106, 21.242736 48.727348, 21.244212 48.72702
3 May 2019	Bicycle	21.258726 48.719172, 21.258884 48.719218, 21.258671 48.71994, 21.257914 48.720682, 21.257659 48.721402
...	...	...
30 September 2022	E-scooter	21.308286 48.674263, 21.308191 48.674278, 21.307979 48.674549, 21.307664 48.674884, 21.307399 48.675182

During the summer months, the dataset consistently recorded 1000–2100 daily rides on average (except 2020), demonstrating its strength in capturing peak micromobility usage. In

contrast, studies of comparable mid-sized cities, such as Milton Keynes, UK [16], reported significantly lower daily averages during peak months (around 110 rides). This disparity highlights the robustness of the dataset and its potential to reveal spatial distributions of key POI and patterns of high demand, while also indicating a significant integration of shared micromobility into the urban transport system.

Our research focuses on the origin and destination points, i.e., the locations where transport vehicles are picked up and dropped off. To achieve this, we extracted the first and last coordinates from the GPS records using a script developed in RStudio (Version 2024.04.1 Build 748). This process resulted in an origin-destination matrix where each record is assigned a unique identifier, allowing us to track and identify each record across different years (Table 2).

Table 2. The final structure of dataset.

Date	Transport Mode	ID	Start Longitude	Start Latitude	Finish Longitude	Finish Latitude
3 May 2019	Bicycle	1	21.251537	48.719108	21.252477	48.719935
3 May 2019	Bicycle	2	21.241571	48.727142	21.249833	48.729143
3 May 2019	Bicycle	3	21.258726	48.719172	21.253242	48.737618
3 May 2019	Bicycle	4	21.252447	48.723915	21.241585	48.727295
...	...	...	...	...	...	...
30 September 2022	E-scooter	900174	21.308286	48.674263	21.287839	48.688003

The processed dataset also enables a clear graphical visualization of the trends in the number and structure of trips made by various transport modes over selected time intervals (e.g., months and years). We address these trends further in the interpretation of the results.

Košice, with a population of 230,000 in 2021, serves as Slovakia's secondary metropolis, complementing the capital city of Bratislava [80]. The corresponding inter-municipal and intra-city commuting [81] creates considerable potential for the development of micromobility.

In this paper, we consider the entire territory of Košice within its administrative borders, which is covered by the Antik shared micromobility system. The topography allows for estimating whether and to what extent the slope of the area affects the spatial patterns of shared micromobility. The central and southern parts of the city boast a flat landscape, which may be advantageous for micromobility. In contrast, the western, northern, and eastern outskirts are at higher elevations and feature more rugged terrain (Figure 1), which could pose challenges for the adoption of shared mobility solutions.

During the observation period, Antik operated a dockless transportation system, where the destination of one trip becomes the origin of the next, except for vehicles withdrawn for maintenance and later returned to service. This suggests that the differences between the spatial distributions of origins and destinations should be insignificant, which was also confirmed through the visual representation of their clusters. This assumption was also statistically tested using the Near tool in ArcGIS Pro. This tool calculates the distance between input features and the closest feature in another layer [82]. In our case, it evaluates the set of all destination points and the set of all origin points, identifying the distances between the closest pairs. Low resulting values indicate minimal differences in the spatial distribution of origin and destination points, whereas high values suggest significant discrepancies. Given the similarity between the visual and statistical outputs, we will use only the destination locations to identify spatial clusters and POI distribution. We chose the destination because, while the location of the transport vehicle determines the origin of a trip, the destination in a dockless system is driven by user preference.

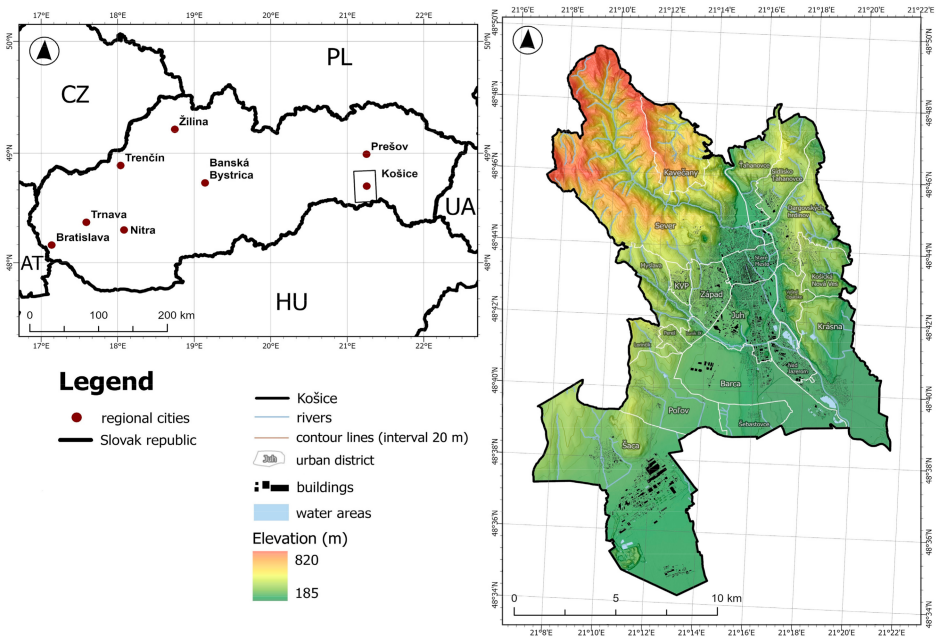


Figure 1. Study Area—Košice City.

To assess the spatial patterns of destinations and their tendency to cluster, we used the Average Nearest Neighbor (ANN) tool. The tool was applied in ArcGIS Pro—Spatial Statistics Tool. This function calculates the distance between each point and its nearest neighbor. The ANN ratio is computed as the ratio of the observed mean distance to the expected mean distance. The expected mean distance is based on the assumption of a hypothetical random distribution of the same number of points covering the same total area. If the ANN result is less than 1, or closer but not equal to zero, it suggests stronger clustering of points, meaning that the points are closer together in space. If the value is greater than 1, the trend in the spatial distribution of points suggests dispersion [83]. The ANN is calculated as:

$$\text{ANN} = \frac{\underline{D}_0}{\underline{D}_E} \tag{1}$$

where $\underline{D}_0$ is the observed mean distance between each feature and its nearest neighbor:

$$\underline{D}_0 = \frac{\sum_{i=1}^{n} di}{n} \tag{2}$$

$\underline{D}_E$ is the expected mean distance for the features given in a random pattern:

$$\underline{D}_E = \frac{0.5}{\sqrt{n/A}} \tag{3}$$

In these equations, di represents the distance between feature i and its nearest neighboring feature, n corresponds to the total number of features and A denotes the area of the minimum enclosing rectangle around all features, or it is a user-specified area value. Since our focus was on the observed mean distance, which is independent of the minimum bounding rectangle area, we used the value computed automatically by ArcGIS Pro and did not specify it separately in ANN.

Z-score for the statistic is calculated as:

$$z = \frac{\underline{D}_0 - \underline{D}_E}{SE} \tag{4}$$

$$SE = \frac{0.26136}{\sqrt{n^2/A}} \tag{5}$$

To determine statistical significance, the z-score and *p*-value are used. The z-score indicates the spatial distribution of points. It measures how many standard deviations the observed mean distance deviates from the expected mean distance. A negative value signals the clustering of points, indicating spatial concentration, while a positive value suggests a greater spatial distance between points, indicating dispersion. A value close to zero suggests a random distribution of points in space. The *p*-value determines the statistical significance of the result, indicating whether the observed distribution of points in space is random or not. The processing and visualization of big data pose several challenges. When displaying a large number of points, final maps often become cluttered, reducing the effectiveness of the visualization. Overlapping elements make it challenging to extract meaningful spatial patterns. However, this issue can be addressed using various visualization methods.

To enable reliable comparisons across different time periods, we created heatmaps using Kernel Density Estimation (KDE) method. This approach calculates the density of features around each point—in this case, spatial points. The final density is computed using the following formula [84]:

$$\text{Density} = \frac{1}{(\text{radius})^2} \sum_{i=1}^{n} [\frac{3}{\pi} \cdot pop_i \, (1 - (\frac{dist_i}{\text{radius}})^2)^2] \quad \text{For } dist_i < \text{radius} \tag{6}$$

where:

- $i = 1,\ldots,n$ are input points—only included to the sum if located within the radius distance of the (x,y) location,
- pop_i is the population field value of point i (optional parameter),
- $dist_i$ is the distance between point i and the (x,y) location.

We executed this visualization in ArcGIS Pro. While the default parameter values provided by ArcGIS Pro can be used, the platform also allows for direct adjustment of various parameters to fine-tune the calculations.

An important parameter for calculation and visualization is the search radius. It defines the distance within which points contribute to the density calculation. We set this parameter to 100 m for a city-wide level and 2.64 m for high-resolution localized visualization, which corresponds to the observed mean distance calculated from the ANN analysis for the entire destination points dataset (see Results). The choice of a 100-m search radius was inspired by Zhao et al. [75], who applied this value when analyzing spatial patterns of micromobility in Zurich. This radius effectively captures spatial patterns within an urban environment and allows comparing results across different cities. Additionally, this choice was validated using Global Moran's I, which confirmed that this value consistently exhibited strong clustering scores, reinforcing its suitability for identifying spatial patterns in the study area.

After computing the density, we applied the selected symbology and chose cubic resampling, which interpolates values from the nearest 16 points to generate the final raster. These settings were applied consistently across all map outputs to ensure uniformity and enable accurate comparisons between the resulting maps.

3. Results

The results of the Near analysis confirm that the most frequent distance between the origin and destination points is 0 m. Overall, 76% of the points are located within a two-meter distance, and 90% within four meters (Figure 2). This demonstrates that the differences between the spatial distributions of origin and destination locations are insignificant. Therefore, the POI identified in the subsequent sections of the study, based

on the distribution of destination locations, can also be considered representative of origin locations.

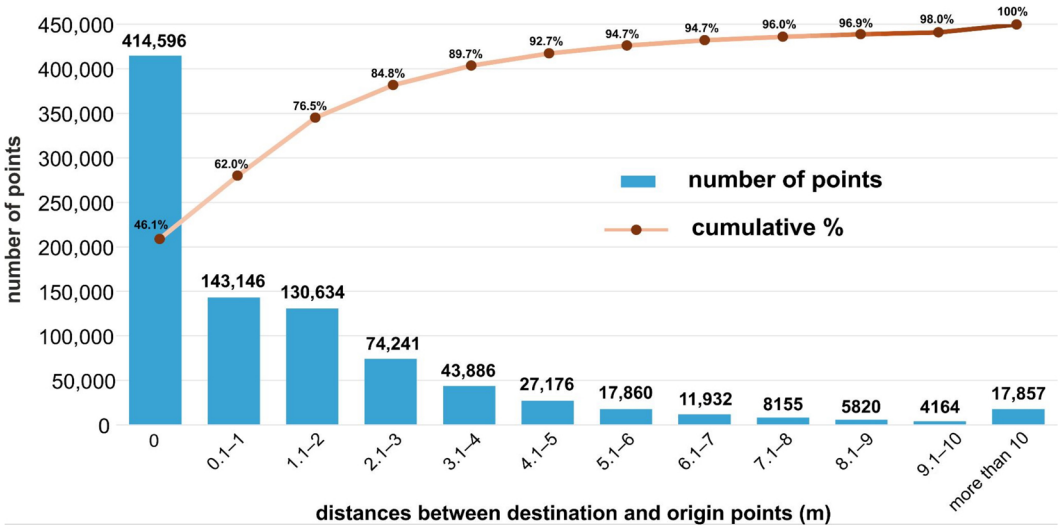


Figure 2. Distribution and cumulative frequency of distances between destination and origin points.

The analysis performed using the ANN tool yielded a Nearest Neighbor Ratio (NNR) significantly less than 1, indicating notable clustering of destination locations. The z-score value (−1460.6) is much lower than the critical value (−2.58), clearly suggesting a non-random spatial distribution of points. This finding is further corroborated by the *p*-value of 0, which confirms that the randomness of the distribution of destination locations is virtually nonexistent.

Additionally, the distances between individual points are of interest. The destination points dataset for all years combined shows an observed mean distance of 2.64 m and an expected mean distance of 13.54 m, further supporting the presence of significant spatial clustering. The datasets for individual years also exhibit statistically significant clustering of destination points, as evidenced by low observed mean distances compared to expected mean distances and low z-score values ranging from −561.5 to −804.7. The specific values for the annual datasets are presented in Table 3.

Table 3. ANN analysis results for each dataset.

Dataset	NNR	Expected Mean Distance	Observed Mean Distance	z-Score	*p*-Value
destination_all	0.194954	13.5356	2.6388	−1460.643198	0.000000
destination_19	0.236469	19.3758	4.5818	−698.380318	0.000000
destination_20	0.200861	32.6281	6.5537	−561.520258	0.000000
destination_21	0.211589	20.6598	4.3714	−804.746423	0.000000
destination_22	0.199942	24.3125	4.8611	−767.257334	0.000000

Figure 3 represents the annual number of recorded rides by transportation mode. Although the shared transportation service was launched only in May 2019 with a fleet of bicycles and e-mopeds, nearly 230,000 rides were recorded in that year. In 2020, the number of rides declined, probably mainly due to the COVID-19 pandemic, which brought concerns about virus transmission and mobility restrictions. Despite several restrictions still being in place in 2021, the total number of rides experienced a sharp increase. The data for 2022 cover only the period up to September, so it is expected that the total number of rides for this year would approximate that of 2021.

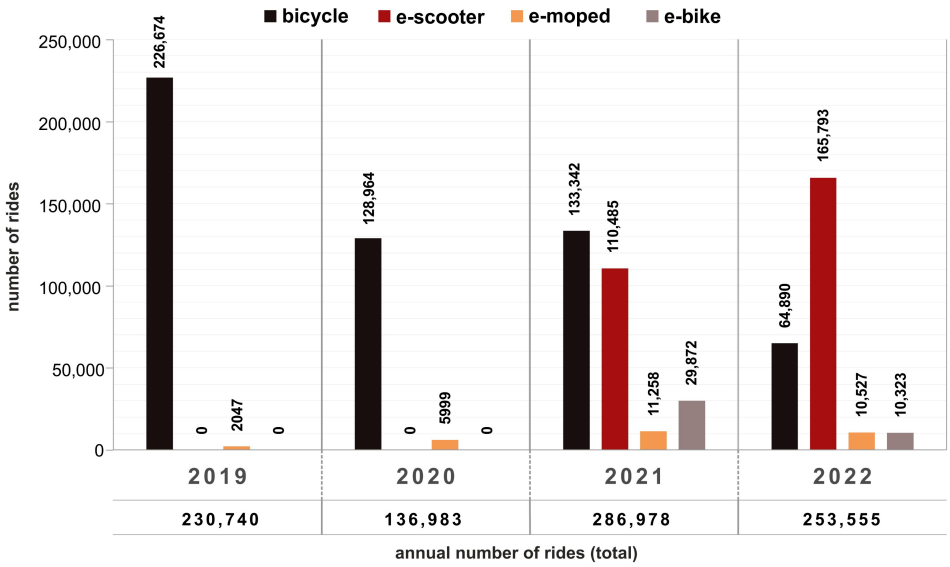


Figure 3. Annual number of rides by mode of transport based on Antik dataset [79].

The use of shared bicycles has shown a declining trend since the beginning of the observed period, mainly due to the rise of electric scooters, which became the most used mode of shared transportation in Košice in 2022. E-mopeds also increased, but their share of the total number of rides remains marginal. Similarly, the use of e-bikes has been limited and shows a slight declining trend.

Statistical heatmap (Figure 4) shows the number of rides by various transport modes during selected months since the launch of the service in 2019 to September 2022. Colorless areas indicate periods when a mode was not in use, providing insight into both seasonal trends and the introduction of new modes into shared micromobility system. Bicycles have been in continuous use (with winter breaks) since the launch of the system. The second mode introduced was e-mopeds, added in September 2019. The fleet further expanded in 2021 with the addition of e-scooters in April and e-bikes in May (Figure 5).

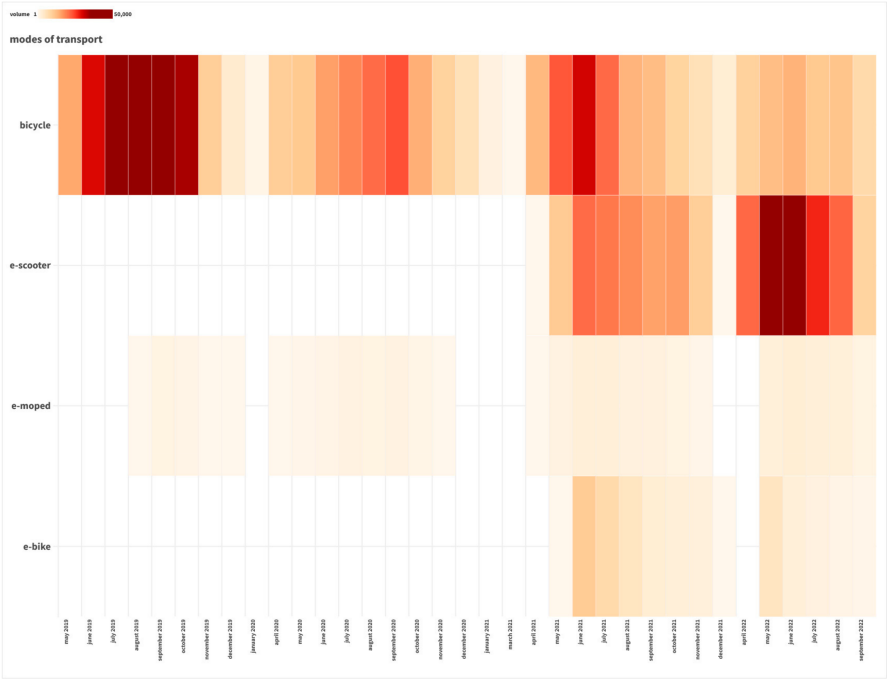


Figure 4. Statistical heatmap representing monthly ride counts based on Antik dataset [79].

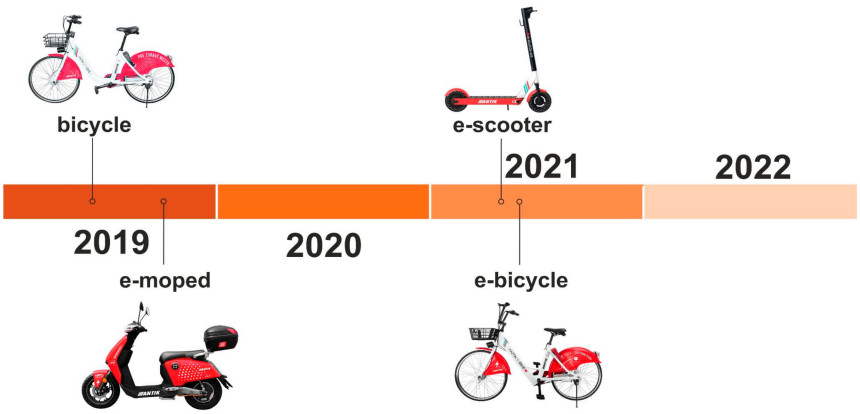


Figure 5. Introduction timeline of shared micromobility modes in Košice.

The highest numbers of bicycle rides were recorded shortly after the service launch, when bicycles were the only available mode of shared micromobility in the city. They were also intensively used during the summer months of 2020 and 2021. Although e-mopeds were also introduced in 2019, their share of rides remained minimal, with no significant fluctuations throughout the observed period. In contrast, the shared e-scooters by Antik showed consistently high demand, even with competition from Bolt (operating in the city from 2019 to 2021) and later Tier. The distribution of e-scooter rides indicates a more balanced demand throughout the year compared to bicycles, with strong representation even in the autumn months. Antik's e-bikes also saw limited usage, peaking in late spring and early summer.

A detailed examination of shared micromobility ride numbers reveals several notable features: Clear seasonal patterns are evident. Bicycle usage peaks in warmer months, particularly in late spring and summer. E-scooters follow a similar seasonal pattern but exhibit more consistent usage in other months. For e-bikes and e-mopeds, the overall ride numbers are too small to identify distinct seasonal trends.

The data also highlight a gradual shift in user preferences from bicycles to e-scooters, suggesting that new transportation modes are influencing the overall character of micromobility. Another key factor is the influence of the provider. Antik's introduction of new modes has significantly shaped usage patterns, underscoring the importance of strategies and the availability of new transportation options in influencing user behavior. Additionally, user behavior reflects varied adoption rates of new modes, with ride volumes showing progressive acceptance over time.

The analysis of ride distribution by mode and period reveals four key features in the evolution of the shared micromobility system: shifting user preferences, seasonal trends, provider influence, and varying degrees of user adoption.

After defining the input parameters, we conducted calculations for all years combined, focusing on destination locations. The city-wide level analysis highlights a strong concentration of POI around Hlavná ulica (Figure 6-1), the city's 1.2-km main pedestrian zone. Additionally, two prominent clusters emerge at Námestie osloboditeľov (Figure 6-2) and Staničné námestie (Figure 6-3), adjacent to the main train and bus stations. Other significant clusters include the Cassovar Business Center area (Figure 6-4) and the vicinity of Antik's headquarters (Figure 6-5). Peripheral areas of the city show minimal representation, with notable clusters only in the neighborhoods of Nad jazerom and Západ, in the southeastern and western parts of the city.

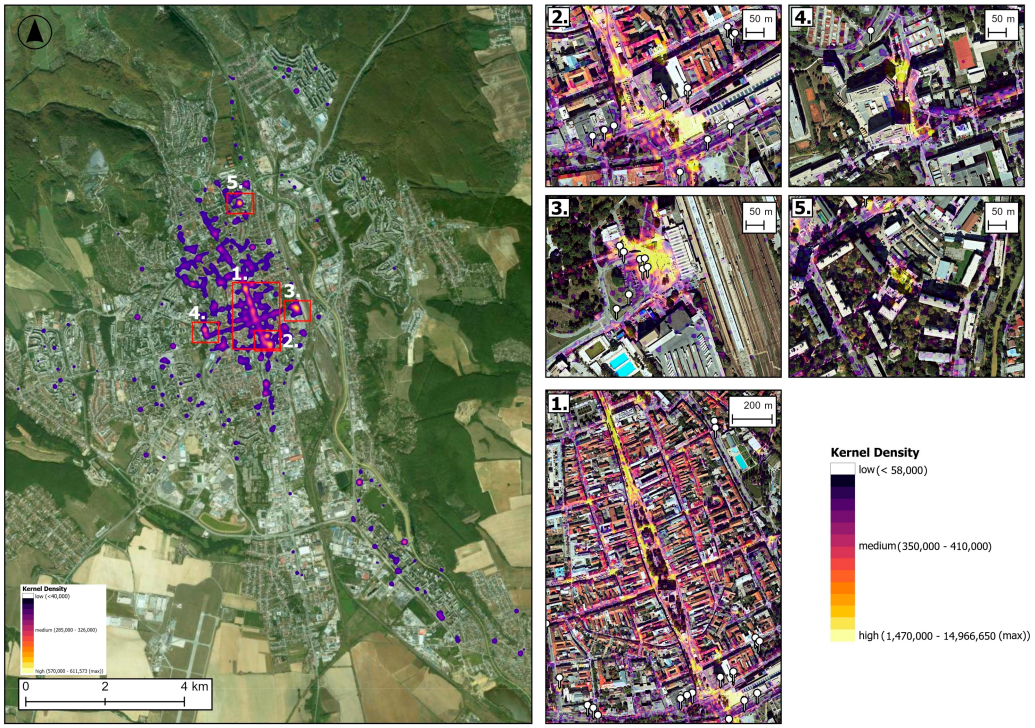


Figure 6. KDE of destination points in Košice (2019–2022).

While the KDE analysis at the city-wide level provides fundamental trends and identifies the main POI, the high-resolution localized visualization (with a radius of 2.64 m) (Figure 6) reveals detailed spatial characteristics and offers a more precise view of specific locations with high micromobility usage intensity. These maps also enable better identification of specific factors and spatial characteristics that support or influence its utilization. Location 1, particularly in the southern part, as well as Locations 2 and 3, show a significant concentration of clusters near urban and regional public transport stops, and in the case of Location 3, also long-distance and international public transport stops. These clusters mostly fill spaces directly at or in close proximity to the stops. This phenomenon suggests a strong connection between shared micromobility and public transport systems, which may contribute to addressing the FLMTP.

In contrast, Locations 4 and 5 exhibit a different pattern—clusters are clearly concentrated in areas in front of building entrances, with only weak or negligible concentrations near the nearest bus stops. This difference may indicate that micromobility is important in connecting work or commercial areas to larger public transport hubs rather than the nearest stops. Another factor that may contribute to the higher intensity of micromobility usage in these locations is the issue of parking. These areas are characterized by a high concentration of businesses and services, increasing the demand for car parking spaces. Shared micromobility offers a more flexible alternative, allowing vehicles to be left near building entrances. This aspect enhances the attractiveness of micromobility in areas with limited parking options.

All the analyzed locations also serve as centers for services, commerce, and important transportation hubs for both urban and regional transit. The presence of sufficiently large open spaces in these locations allows users to conveniently leave their shared vehicles, which supports their further use and maintains an efficient rotation of vehicles within the shared service.

Changes in the volume and modal structure of trips justify examining spatial patterns at annual intervals. This enables capturing the differences and regularities in development in the spatial distribution of the most significant POI (Figure 7). Throughout all periods,

three locations stand out prominently: Cluster A—the main train and bus station area (Staničné námestie square), Cluster B—the area around Námestie osloboditeľov square, and Cluster C—the main pedestrian zone (Hlavná ulica street).

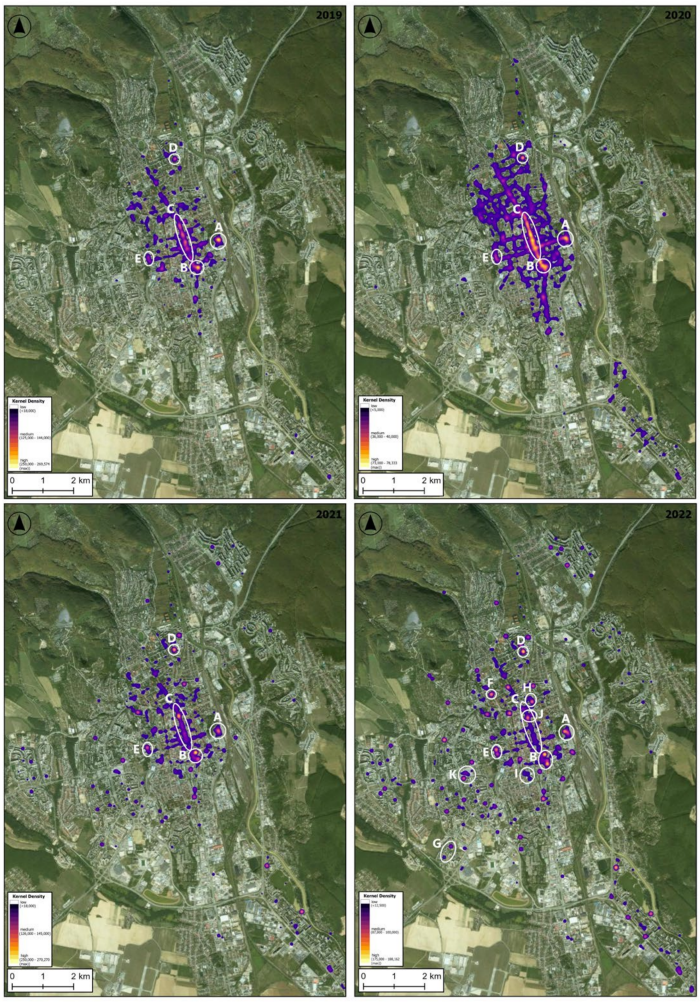


Figure 7. KDE of destination clusters separately for each year in the 2019–2022 period.

Cluster A (Figure 7; also shown as cluster 3 in Figure 6) is a typical transport hub in the city, housing both a railway and a bus station. It also serves as an important node for intra-city transportation, where tram and bus networks intersect. This expansive area is well-equipped with infrastructure for parking shared transportation vehicles. While this cluster is not directly connected to a network of bike lanes [85], it is linked to the city center and bike lanes via wide sidewalks commonly used by cyclists and scooter riders. The combination of good accessibility, connections to intra-city and inter-city transport routes, and the amenities available in the area make it an attractive hub for micromobility throughout the observed period. This hub effectively addresses the FLMTP, despite lacking a dedicated cycle path network.

Although regional bus stops are also located in this area, Cluster B (Figure 7; also shown as cluster 2 in Figure 6) primarily serves as a hub for urban public transportation. Additionally, it serves as an entry point to the main pedestrian zone and is home to one of the largest shopping centers in the broader city center. There is a noticeable change over time in this area. In 2019 and 2020, one prominent cluster is located there. In 2021 and 2022, another cluster appears near this one but is positioned slightly to the north. The southern cluster is served by public transport running from west to east, while the northern cluster is served by public transport running from east to west. The later appearance of the northern

cluster may be explained by the fact that in 2019 and 2020, shared micromobility was almost exclusively carried out by bicycles, which face no restrictions in the central pedestrian zone. Additionally, in 2020, strict COVID-19-related restrictions were imposed on dining and shopping establishments located in the shopping center and central pedestrian zone, significantly reducing the need to linger in these areas. By 2021, these restrictions were much more relaxed. Moreover, e-scooters have come to the forefront of shared micromobility, with their speed in the central zone automatically limited to 10 km/hour. Therefore, while in 2019 and 2020 destination trips in this area were mainly linked to city public transport, the second cluster that appears in 2021 and 2022 likely relates more to access to the central pedestrian zone, where it makes sense, given the speed limit, to leave or pick up an e-scooter.

Cluster C (Figure 7; also shown as cluster 1 in Figure 6) has a linear character and covers the entire main pedestrian zone, along which two cycle paths also run. This cluster stands out prominently in all observed years, except for 2022 when the KDE intensity reaches lower but still significant values. The pedestrian zone serves as both an origin and destination for many short trips related to cultural activities, shopping, dining, financial and insurance services, nightlife, religious ceremonies, tourism, and others. The demand for alternative modes of transportation is evidently driven by the ban on car traffic and the lack of public transport service in the pedestrian zone. The decrease in the concentration of destination trips for shared micromobility in 2022 may be explained by the growing preference for e-scooters, which automatically have their speed limited to 10 km/hour in this zone. This likely led to the formation of several more or less distinct clusters around the central pedestrian zone.

In addition to the prominent POI listed above, there are also others that occur every year. One of them is the headquarters of Antik (Cluster D) (Figure 7), where employees benefit from discounted rides and where there is an extensive infrastructure, including shelters and charging stations. Another prominent location is Cluster E (Figure 7) near the Cassovar business center. Until 2020, approximately 2500 employees of the IT company T-Systems (Deutsche Telekom) worked there. Besides its location on the outskirts of the flat part of the city and its good accessibility from Clusters A to C, active promotion of shared micromobility by T-Systems may have motivated its employees to use shared micromobility. Another incentive could be related to parking policies, specifically issues with availability and fees for parking spaces in the area. This assumption can generally be applied to the use of alternative micromobility resources in the city, as we observe some other less prominent POI in several locations with problematic parking or parking limitations in the central part of the city.

Overall, the spatial distribution of clusters in 2019 and 2020 shows a very similar pattern, with a strong concentration of destination locations mainly in the central part of the city.

The introduction of e-bikes and particularly e-scooters (in 2021), has indeed altered spatial patterns. The concentration of destination locations remains predominantly near the central pedestrian zone. Presumably, due to the automatic speed restriction of e-scooters in the pedestrian zone and adjacent streets, the attractiveness of surrounding areas as micromobility POI has increased. However, the most significant difference compared to the first two years is the emergence of new clusters in some peripheral parts of the city.

The establishment of motorized modes of transport led to their utilization in parts of the city characterized by more varied topography, especially in the western and eastern outskirts. Apart from terrain characteristics, interpreting the results also involves considering the cycling infrastructure, including established cycle paths or bike lanes. In this context, good transport connectivity can be explained, particularly for neighborhoods like

Nad jazerom (southeastern part), Západ and Sídlisko KVP (western part), and the southern part of neighborhood Sever (northern part). Although some of these areas are at a higher elevation then the central part of the city, their main transport routes and bike lanes traverse flat terrain and are mostly led along the elevation lines.

In addition to the above-mentioned POI, new ones appeared in the housing estates in the eastern, hilly part of the city, which is further away from the city center and separated by a river, railway line, and expressway. The more prominent POI are in Sídlisko Ťahanovce (north-east), which is hilly, but the street network is partially led along contour lines. Much less prominent POI are in Sídlisko Dargovských hrdinov (east), where the entire road network is sloping.

The area surrounding the campus of the Technical University of Košice (TUKE), represented by cluster F (Figure 7), also shows significant micromobility activity. TUKE, the university with the largest number of students in Košice, is situated in a well-connected area with access to public transport stops, cycle paths, and nearby commercial and service centers. While this cluster is less pronounced compared to others, it highlights the role of micromobility in connecting the university to surrounding amenities and public transportation hubs. It is possible to assume that students likely use micromobility not only for commuting between classes and nearby facilities but also for broader mobility needs within the city.

In addition to cluster F, micromobility activity is evident around the dormitories of the major universities in Košice, represented by cluster G (Figure 7). These dormitories are located at a higher elevation and a relatively greater distance from the universities. However, the elevation difference and distance appear to pose no significant challenge for e-scooter users. It is likely that the introduction of motorized modes, along with the resumption of in-person classes at universities after the lifting of COVID-19 restrictions, contributed to the emergence of clusters around the dormitories. Moreover, students likely use micromobility for purposes beyond commuting between their accommodation and university, highlighting its flexibility and appeal.

Clusters near centers of culture, arts, and creativity (such as Tabačka Kulturfabrik—cluster H, Kasárne Kulturpark—cluster I, and Kino Úsmev—cluster J) are also noteworthy (Figure 7). These locations, situated in or near the city center with relatively flat terrain, may see demand for shared micromobility due to better environmental awareness and a greater inclination of visitors to these centers to use new forms of transportation. In addition to these, there is also a prominent cluster K (Figure 7) located near a significant shopping center with good access to intra-city transport stops and bike lanes (Galéria Shopping Košice).

4. Discussion

The methodological approach of this study, based on a combination of Near analysis, ANN, and KDE, enables the identification of spatial patterns at both macro and micro levels with high precision. The Near analysis statistically confirmed that the spatial distribution of origin and destination points is nearly identical. Therefore, we identified the most significant spatial clusters indicating key POI for destinations. The locations of destination points in a dockless system are perceived as the result of user preferences and decisions. This confirms the findings of Bai and Jiao [86] and Zhao et al. [75], who consider destinations highly suitable tools for exploring, understanding, and explaining the spatial patterns of micromobility.

The overall use of different transport modes is influenced by multiple factors, including temporal, spatial, weather-related, system-related, and user-related aspects, which significantly affect the choice of transport mode within the micromobility category [9,87–89].

During the observed period, we noted the highest number of rides in the warmer spring and summer months. Conversely, the number of rides drops to a minimum in the winter months. This confirms the significant impact of weather on micromobility [90,91] and justifies Antik's seasonal suspension of shared micromobility services, which typically occurs from late December to early spring, depending on the weather. The number of trips during this time would be minimal anyway. Seasonality in shared micromobility is also evident in other medium-sized cities, though its intensity depends on climate characteristics. In oceanic climates with mild winters, such as in a British mid-sized city, summer demand for micromobility is about three times higher than in winter [16], whereas in Košice, with its continental climate and cold winters, winter demand is almost negligible. This raises the question of whether shared micromobility can be a sustainable urban transportation solution, especially in a city like Košice, where air pollution poses the most significant challenge during the winter months.

Minimal use of shared micromobility during the winter months presents a challenge for transport policy, particularly in relation to reducing air pollution. Encouraging users to opt for public transport instead of private cars during this period could help address this issue. The negative impacts of individual car transportation are most pronounced in the broader city center of Košice. Our results suggest that policies restricting private car use can positively stimulate the adoption of shared micromobility. A study [92] indicates that offering discounts for shared micromobility services significantly encourages users to reduce their reliance on personal vehicles. Since the city of Košice has taken over the management of parking policies in recent years and has introduced measures to calm car traffic in the central part of the city, an effective tool for this strategy could be incentivized car parking —providing discounts for shared micromobility when parking a car in designated parking areas. This policy could also help mitigate the negative impacts of the increasing volume of car commuting into the city [81].

The gradual introduction of new types of shared micromobility modes also confirmed that each type of vehicle operates differently [93]. Introducing new shared vehicles led to changes in spatial patterns for the distribution of destination POI. With the introduction of motorized vehicles, more distant and topographically challenging locations have become attractive for shared micromobility. In line with Fishman et al. [94] and Liu [95], our study in Košice also confirms that topography, elevation differences, and slope negatively affect the use of human-powered transportation. However, electric shared vehicles significantly help users overcome these barriers.

From an overall perspective, the spatial distribution of micromobility usage in cities exhibits a highly similar pattern. These patterns predominantly include areas such as city centers [35]; locations near train and bus stations, metro systems, and other public transportation hubs [16,34,51]; areas surrounding schools and workplaces; and zones with commercial activities and services [33,96,97]. Zhao et al. [75], who used a 100 m search radius KDE, found that drop-off points are predominantly concentrated around transportation hubs and some commercial areas. These findings align with the results of our KDE analysis, which demonstrated that during the observed period, the most prominent destination POI in Košice were located in the central urban area, near the main bus and train stations, close to major urban, regional, and long-distance public transportation hubs, near large shopping centers, in proximity to certain employment zones, schools, and cultural and service centers within the city.

An interesting finding is that while the number of trips in the shared micromobility system varies from year to year, the location of key points of interest remains unchanged. The only exception was in 2020 when pandemic-related restrictions limited the operation of shops, essential services, and dining establishments. During this period, clusters of

destinations around shopping centers and at entry points to the central pedestrian zone (an area where shops, restaurants, pubs, clubs, and social life in general are concentrated) were less pronounced.

The decline in the number of trips and minor changes in spatial patterns of micromobility during the period of the strictest restrictions aligns with findings from studies conducted during this phase in Beijing [98] and Austin, Texas [99]. However, our study from Košice, conducted with a time gap, confirms the indications from Beijing and Austin that the COVID-19 pandemic did not lead to a long-term decline in the number of trips, nor to a disruption of spatial patterns in shared micromobility. The location of significant destination clusters around public transportation hubs and important stops demonstrates the close connection between shared micromobility and other forms of public transport, making these hubs and stops significant micromobility POI. It also highlights the key role of integrating different transport modes, which is integral to smart solutions in urban transport planning. In this context, our results are consistent with the idea of the positive impact of micromobility on public transport systems and the complementarity and substitutability of both forms, as discussed by Kostrzewska and Macikowski [100] and Moinse and L'Hostis [101]. In this context, we can also confirm that micromobility addresses the FLMTP [36,54]. Micromobility often emerges as an important component of urban mobility while simultaneously being associated with sustainability issues [14]. The results of this study raise the question of whether the several-month winter period without micromobility operations, particularly in climate zones with long winters, truly allows shared micromobility to be considered a key solution for sustainability, or merely a seasonal contribution to it. A challenge for future research will be to explore in greater detail the seasonality of micromobility and its relationship with the use of other forms of transport in the city.

The availability of bike lanes and infrastructure significantly supports the adoption of micromobility [102]. However, well-developed infrastructure does not always directly translate to increased micromobility usage at the expense of individual car transportation [16]. This pattern is also evident in our case study. Major clusters are located near or directly connected to bike lanes. Nevertheless, a key challenge identified in the city's urban mobility strategy [28] is the fragmentation of cycling infrastructure. The lack of connectivity between individual cycling paths increases the risk of conflicts between different road users, particularly as micromobility adoption continues to grow. This issue is pronounced in the city's main public transportation hub, near the central railway and bus stations (Figure 6-3). While this area has dedicated static infrastructure, such as micromobility shelters and charging stations, it lacks direct connections to the city's bike lane network. As a result, shared micromobility trips primarily occur on pedestrian sidewalks, which are sufficiently wide to accommodate bicycles and scooters. However, as the volume of micromobility increases, this infrastructure gap may lead to a higher risk of collisions between pedestrians and micromobility users. A similar pattern is observed at other high-usage micromobility POI such as the business center (Figure 6-4) or the shared micromobility provider headquarters (Figure 6-5). These locations lack direct cycling infrastructure but still exhibit high micromobility activity. Despite this, factors such as car parking problems, employer support, and the concentration of young, educated individuals may help offset the lack of proper infrastructure. Addressing the infrastructure gap through better network integration could further enhance micromobility accessibility and safety. To improve the sustainability of shared micromobility, urban policies should focus on integrating micromobility with existing transport networks. This includes ensuring seamless connectivity between key micromobility hubs and cycling paths to minimize conflicts with pedestrians while maintaining accessibility in high-demand POI.

Differences in the adoption of shared micromobility in more distant neighborhoods in the flat area south of the city center highlight the importance of adequate infrastructure. Neighborhoods to the southeast (Nad jazeromand Krásna) have relatively well-developed cycling paths, and POI in shared micromobility tend to form along them. In contrast, neighborhoods to the southwest (Pereš, Poľov, Lorinčík, Šaca) are connected to the city center by a high-speed road for cars but lack a safe route for cyclists. There were no POI identified in these areas. This suggests that adequate infrastructure is especially crucial when using shared micromobility for longer distances.

Another factor affecting the implementation of micromobility, especially in the central urban area, is parking policy and parking issues. The use of shared transportation frees users from the need to find parking, as they can leave the vehicle almost anywhere [103]. This is even more relevant in the central pedestrian zone, which is completely closed to both car and public transportation but not to micromobility vehicles. However, due to the automatic speed limit on e-scooters, the central pedestrian zone is particularly attractive for bicycles.

Mattson & Godavarthy [104] emphasize the significant role of students in shaping micromobility patterns in medium-sized cities, while Scott & Ciuro [105] highlight the strong local demand from residents as a crucial factor. Reck and Axhausen [106] suggest that micromobility services are primarily used by young people, individuals with higher educational attainment, those without cars, and those without children. In line with these findings, our study shows that high micromobility demand is concentrated in areas where younger, educated individuals reside, such as clusters around dormitories and campuses in Košice, emphasizing the importance of universities in shaping micromobility's spatial patterns [16]. These population groups also contribute to the formation of POI around cultural hubs and, particularly, business centers, where younger and more educated employees are concentrated. Conversely, no POI are formed in industrial zones and manufacturing areas. This contrast highlights the significant role of the post-socialist transformation in the city, from an industrial economy to one based on IT, smart technologies, and knowledge-intensive services, in shaping the adoption and spatial distribution of shared micromobility.

5. Conclusions

Based on the shared micromobility data, this study identifies micromobility places of interest expressed by clusters of destination (drop-off) points of micromobility trips, using the case study of Košice, Slovakia. The analysis is based on data from the largest provider of shared micromobility in Košice—ANTIK Telecom—both in terms of fleet size, trip volume, and overall market presence, covering the period from 2019 to 2022. Using a script developed in RStudio, we extracted the origin and destination locations for each trip from this data. For the analysis of the distance between origin and destination points, we used the Near tool and the Average Nearest Distance (NNR) function to calculate the observed and expected mean distance. This function also confirmed that the locations of destination points tend to form strong clusters, despite the city operating a dockless shared micromobility system. For visualization, we employed the Kernel Density method to create maps displaying clusters of destination locations at the city-wide level as well as high-resolution, localized views.

The results confirm the expected strong seasonality of shared micromobility in temperate continental climate zones. The number of rides peaks in the warm summer months and late spring, while it drops to near zero in winter, prompting operational downtime for maintenance by the operator. This sharp decline raises the question of whether shared micromobility can be a true contributor to reducing environmental burdens and enhancing

transportation sustainability in cities with cold winters, where air pollution issues are most severe during this time. While spatial patterns suggest potential, the seasonal drop challenges the year-round effectiveness of this transportation mode and underscores the need for targeted policies. These policies should include the integration of shared benefits between car parking, city public transportation, and the shared micromobility system to help reduce the increased reliance on individual car transportation during the winter months. Nonetheless, more moderate fluctuations in a similarly sized city in an oceanic temperate climate suggest that the specific climate conditions of a city may determine the viability of shared micromobility as an ecological and sustainable urban mobility solution.

Given the extensive body of literature indicating a strong impact of current weather conditions on micromobility [68,69,90,107,108], as well as our study results demonstrating a significant influence of weather on the annual cycle of micromobility usage in Košice, a key challenge for further research is to explore the daily rhythms of shared micromobility and effect of real-time weather conditions on micromobility usage.

As the range of transportation modes expanded gradually, we identified a shift from bicycles to e-scooters, which by the end of the study period became the most utilized shared micromobility mode. The widespread adoption of e-scooters as self-propelled vehicles contributed to the emergence of new clusters, covering areas with more varied terrain and at greater distances from the city center.

The study also confirmed only insignificant differences between origin and destination points. We identified several clusters that were prominent each year from 2019 to 2022. These included clusters near important nodes of intra-city, regional, and even national and international transportation located close to the city center. Significant clusters also formed at access points to the central pedestrian zone, while the zone itself constitutes a linear cluster where individual automobile and public transport are excluded, but not micromobility. The introduction of self-propelled modes (e-scooters) also led to clusters in locations farther from the city center or with more varied terrain. These locations include business centers, cultural and creative institutions, and university dormitories. Conversely, the significance of the linear cluster in the central pedestrian zone decreased toward the end of the study period, likely due to the automatic speed limit imposed on e-scooters, which became the most widely used mode of shared micromobility in 2022.

Spatial patterns of demand for shared micromobility also indicate that user preferences are significantly influenced by established infrastructure, especially bike lanes and cycle paths, restrictions on automobile traffic, and obstacles such as problematic or paid parking. On the other hand, certain significant points of interest suggest that barriers to accessibility via public or private car transportation, as well as problematic parking, when combined with factors such as employer support and an increased frequency of movement of young, educated individuals, can help compensate for insufficient cycling infrastructure.

While the study is limited by the absence of information on user demographics and social characteristics, certain features can be inferred from spatial patterns. Prominent clusters in areas around business centers suggest usage by users with higher educational attainment. Prominent clusters around business centers suggest usage by users with higher educational attainment, reflecting the broader economic transition of the city towards knowledge-based industries. Age demographics are evident in clusters near universities and student dormitories. These user groups clearly contribute significantly to overall shared micromobility in the city.

This study also underscores the role of shared micromobility in complementing existing public transportation systems, particularly in addressing the first/last mile transport problem. Generally, most shared micromobility vehicles are green modes, whose use, especially as alternatives to individual automobile transportation, can contribute to reduc-

ing environmental burden, traffic congestion, and thereby promoting urban sustainability. Understanding the regularities and patterns of spatial demand for micromobility can also significantly contribute to improving the efficiency of shared micromobility service provision, locating docking stations, and deploying vehicles. Understanding these spatial patterns can contribute to more effective infrastructure development by local authorities.

The data structure provided by Antik creates a unique opportunity to explore spatial patterns of different transportation modes, and insights from this research could be partially transferable to places where similar structured data is not available. Besides scientific purposes, shared micromobility data also demonstrates significant potential in practical applications across various forms of urban planning and local development. Integrating micromobility data with other datasets on urban mobility could further provide a comprehensive view of the dynamics and nature of urban transportation in selected cities.

This study fills a gap in the research on spatial patterns of shared micromobility in a medium-sized Central European city with a transforming economy and creates potential for comparative studies. With the expansion of Antik's shared micromobility services into additional towns and villages, there is an opportunity to compare spatial demand patterns for micromobility across various settlement sizes. This will facilitate international comparisons and enable future exploration of spatial patterns of similar micromobility systems in cities and towns of different sizes within a single country or region.

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