

# Siting charging stations and identifying safe and convenient routes for environmentally sustainable e-scooter systems

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## ABSTRACT

E-scooters are considered a new type of micromobility that promotes sustainable transportation modes by shifting the private car mode to a Mobility as a Service. Irregular parking and high life cycle global warming impacts of e-scooters due to dockless operating system cause a tendency from dockless systems to charging stations. This article presents one of the first comprehensive spatial analysis studies aiming to develop a novel GIS-based multi-criteria decision support model for: (1) siting optimum e-scooter charging station locations that will integrate e-scooter system with the existing public transportation systems and point of interests, and (2) finding the most secure and convenient road network to connect the charging stations. Identifying the optimum road network for connecting the charging stations and developing a raster based spatial method for this purpose distinguish this study from the previous studies. The developed model was implemented by performing a case study in Karsiyaka, Izmir, Turkey. 35 suitable locations were determined for siting e-scooter charging stations and the optimal connectivity network connecting each station with its neighboring stations were identified. The model can be reproduced for other locations and used to develop innovative policies and plans for environmentally more sustainable and operationally effective shared e-scooter systems.

## 1. Introduction

Shared e-scooters are considered a new type of micromobility that promotes sustainable transportation modes by shifting the private car mode to a Mobility as a Service, and marketed as an environmentally preferable transportation mode (green mobility option) (Bozzi & Aguilera, 2021; Fazio et al., 2021; Shaheen & Cohen, 2019). Integration of e-scooters with public transportation is considered an important solution to improve its accessibility and usage (DuPuis et al., 2019), fulfill the last mile problem for short distances (Baek et al., 2021; Hosseinza-deh et al., 2021a; Mathew et al., 2019; Oeschger et al., 2020), and reduce the traffic congestion along the public transportation corridors, especially rail transit lines (Fazio et al., 2021; Luo et al., 2019; Oeschger et al., 2020; Sanders et al., 2020). Although shared e-scooters are promoted as an environmentally sustainable transportation mode, investigations on their environmental impacts have recently started (Bozzi & Aguilera, 2021). Early studies indicate their high life cycle global warming impacts (Hollingsworth et al., 2019).

The reason for the growing popularity of shared e-scooters is their advantages over other micromobility modes (Sanders et al., 2020). The

main advantage is that while public administration promotes the bike sharing system, e-scooters have been encouraged by private companies making them rapidly spread in cities (Badia & Jenelius, 2021). Secondly, no physical effort is necessary, it is electrically powered; and has a higher speed than bikes. Thirdly, a dockless system is employed, providing drop off flexibility. The working principle is that users can readily borrow or return the e-scooters at any location within the service area using mobile applications (Baek et al., 2021).

The increase in modal share of e-scooters in cities also causes some negative consequences. One of the main issues is irregular parking of e-scooters due to dockless operating system. Irregular parking causes undesired occupation of urban spaces, and threatens pedestrian safety and comfort (Guo et al., 2020; Zou et al., 2020). Another issue is that e-scooters are ridden on sidewalks or major arterials with a high volume of vehicular traffic since there has not been any dedicated lane or route for e-scooters. Lastly, environmental sustainability of dockless e-scooter systems is debatable (Bozzi & Aguilera, 2021; Markvica et al., 2020). The main concern is that daily collection and distribution of e-scooters for charging and rebalancing requires long travel distances, which is not environmentally sustainable. Hollingsworth et al. (2019) stated that

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43% of life cycle carbon emissions are due to daily collection for charging. Their results showed that dockless e-scooters result in higher life cycle global warming impacts compared to bus use.

The establishment of the dockless e-scooter system started in Izmir, Turkey in 2020, under the context of the sustainable urban mobility plan. Today, several companies are operating in the city. The rapid increase in shared e-scooter systems in Izmir also resulted in safety and environmental concerns, as in many cities in the world. Illegal parking on sidewalks and cycleways (see Fig. 1), insecure and inconvenient routes for travel, and the challenge of daily battery collection are the most significant problems. We consider charging stations at suitable locations, where e-scooters can be parked and charged at the same time, and secure and convenient routes or e-scooter lanes connecting charging stations as an alternative solution.

The literature on shared e-scooter systems to determine the drop off/charging station locations and to find the road network connecting these stations is limited. This article presents one of the first comprehensive spatial analysis studies aim to develop a novel GIS-based multi-criteria decision support model for: (1) siting optimum e-scooter charging station locations that will integrate e-scooter systems with the existing public transportation systems and point of interests, and (2) finding the most secure and convenient road network to connect the charging stations. Although there are not many studies on siting e-scooter stations or drop off locations, there are plenty of similar spatial suitability/site selection studies in the literature. Extending the study with identification of optimum road network for connecting the charging stations and developing a raster based spatial method for this purpose distinguish this study from the previous studies. The developed GIS-based multi-criteria decision support model was implemented in Karsiyaka District of Izmir, Turkey to promote an environmentally more sustainable and operationally effective shared e-scooter system. Several explanatory decision criteria were selected and the weights were determined via Analytical Hierarchy Process (AHP). The model can be reproduced for other locations and the results may be beneficial for policymakers and planners.

The paper is organized as follows: A comprehensive literature review on the factors affecting the e-scooter trip frequency and selection of suitable station locations are presented in Section 2. Section 3 describes the study area. Section 4, materials and methods, introduces the GIS-based multi-criteria decision support model. Section 5 presents the results and discussions. Conclusions, together with the limitations and possible future research directions are provided in Section 6.

## 2. Literature review

The literature review consists of two parts. The first part addresses the factors affecting the trip frequency of e-scooters and the second part investigates the literature on the siting suitable station locations and determination of routes for e-scooters, especially the methods and criteria used. In the end, the research gap in the literature and the contribution of the present study are discussed.

### 2.1. Effective factors for e-scooter trip frequency

National Association of City Transportation Officials (NACTO, 2019) reported that e-scooters were the most desirable among the micro-mobility modes in the USA with 38.5 million trips in 2018. The Portland Bureau of Transportation reported 40% of its residents prefer e-scooters instead of private cars for short trips (PBOT, 2020), while this range was 34% in 2018 (PBOT, 2019).

The effect of built environment, socioeconomic factors and public transportation facilities, such as land use, population density, employment density, proximity to city centers, bicycle infrastructure, etc., on the trip frequencies have been scrutinized via surveys, regression models or geographically weighted regression (GWR). Markvica et al. (2020) collected the data from 147 e-scooter users via an online survey in Vienna, Austria. Most of the users responded that the lack of separate lanes was the main barrier (65%) followed by the higher traffic density on major arterials to discourage the e-scooter usage. The survey results also indicated that streets with narrow sidewalks and high pedestrian flows threaten the use of e-scooters. Caspi et al. (2020) examined the spatial factors associated with e-scooter trips in Austin, Texas. They aimed to develop a spatial model describing e-scooter usage and underlying influential factors for trip frequency. The results indicated that bicycle lanes, bus stops and high employment regions are the most influential parameters. Bai & Jiao (2020) were conducted a similar study in Austin, TX. Proximity to city center, accessibility to public transportation, high population density regions, and recreational areas were determined as positively correlated variables with e-scooter trip frequency, while industrial regions were negatively correlated. Reck et al. (2020) reported that schools and bus stops were the most favorable locations for e-scooter trips in Louisville, Kentucky. Hosseinzadeh et al. (2021a,b) found that age distribution, distance to transit stations, walkability areas, and high commercial areas were the main factors in e-scooter trip frequency in Louisville, Kentucky via GWR model. Lower trips were observed in areas with inadequate public transportation

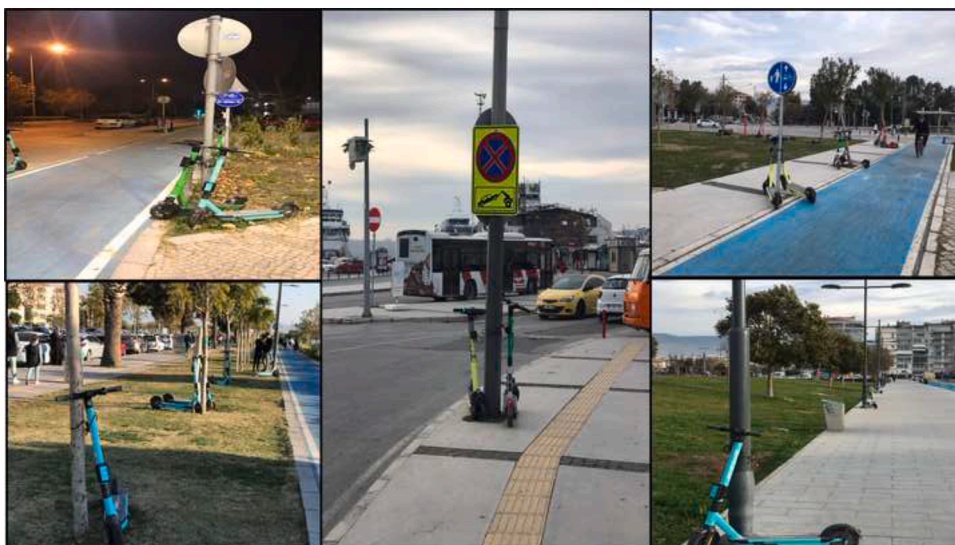


Fig. 1. Pictures for illegal parking of e-scooters in Izmir, Turkey. Too many e-scooters, but not when and where they are needed.

facilities as a result of a network analysis performed by Smith & Schwieterman (2018) in Chicago. Huo et al. (2021) performed a more comprehensive study to generalize the most influential factors in e-scooter trip frequency by analyzing data from Austin, Minneapolis, Kansas City, Louisville, and Portland. Population density, employment density and bus stop density were found positively correlated variables. Unlike the findings in Bai & Jiao (2020), proximity to city center was negatively correlated with trip frequency. In general, population density, points of interest such as schools and parks, employment regions, and public transportation stations were defined as the factors that positively affect e-scooter use, while lack of separate lanes, higher traffic density, and industrial regions were defined negatively correlated with e-scooter use.

## 2.2. Suitable station locations and routes for e-scooters

GIS-based multi-criteria decision support models are extensively used to site suitable station locations and plan safe routes for bike share systems. Eren & Katanalp (2022) proposed a hybrid approach combining Fuzzy logic-based GIS with AHP for the selection of bike share stations in Izmir, Turkey. 21 criteria were selected, including land use patterns, transportation network, and point of interests. The results concluded the most suitable locations. Fazio et al. (2021b) developed a multi-criteria GIS-based method to find the most suitable bike share station locations in Catania, Italy. Socio-economic information (employee index, place index), public transportation accessibility, and point of interests were selected as the main criteria. Guler & Yomralioglu (2021) employed the best worst method in GIS to identify the suitable station locations for bike sharing system in Istanbul, Turkey. Among the decision criteria, proximity to transportation stations gained the most weight, followed by proximity to cycling infrastructure after AHP analysis. A similar study was conducted by Kabak et al. (2018). AHP and multi-objective optimization by ratio analysis (MOORA) techniques were used with GIS to identify the locations of new bike share stations. Moshref Javadi et al. (2013) combined multi-criteria decision techniques with mathematical programming to determine the best areas for stations in Isfahan, Iran. de Cássia Martinelli Guerreiro et al. (2018) proposed a bicycle network for the city of Sao Carlos, Brazil by using the origin-destination survey. The bicycle network was derived based on bicyclists' most frequently used routes. Saplıoğlu & Aydın (2018) combined AHP with GIS to determine the safe and suitable bicycle routes around the public transportation systems. Accident-prone areas, road-side parking, road grade, bicycle parks, traffic capacity, and separated bike lanes were selected as decision criteria and their relative weights were determined via AHP.

As for e-scooter related studies, there are limited studies on siting e-scooter stations/drop off locations or identification of safe routes for e-scooters. Fang et al. (2018) reported that 72% of e-scooters were parked on sidewalks in California, USA, in which 20% of them hindered pedestrian movement. James et al. (2019) found improper parking rate of 16% among 606 observations in Virginia, USA. For this purpose, Sandoval et al. (2021) proposed a data-driven method to find suitable station locations for e-scooters in Nashville, Tennessee, USA. Station locations were determined based on sidewalk width, pedestrian density, and a high number of trip destinations. However, important parameters such as integration of public transportation, land use patterns and proximity to bicycle lanes were not taken into account. Masoud et al. (2019) suggested suitable charging stations based on the average travel distances using linear programming approach. Losapio et al. (2021) reported the need for a large operational effort to efficiently manage e-scooter fleets due to imbalanced distribution and charging. Their solution involves monetary incentives to encourage users for accepting alternative pick-up or drop-off points. Zou et al. (2020) suggested a semi-dockless system for the areas where high vehicular traffic and pedestrian movements existed. Recently, a pilot project has been started in Paris to determine suitable locations for 150 e-scooter stations aimed

at preventing environmental clutter and decreasing theft (Casey, 2021).

As for studies related to identification of safe and convenient e-scooter routes, PBOT (2020) reported that traveling on the sidewalk is the primary safety concern in Poland. On the other hand, traveling on major arterials poses a great safety risk for e-scooter users. To overcome this problem, PBOT (2020) suggested separate lanes for e-scooters on major arterials, and Zou et al. (2020) proposed safer bikeways in which e-scooter users can also be utilized. Suitability of bikeways was determined by identifying the risk-prone accident locations using five-year bike crash data in Washington D.C. Fazio et al. (2021a) presented a multi-criteria spatial approach for planning suitable routes in which proximity to public transportation, number of accidents, number of employees and traffic flow related parameters were used. Two indices were defined (priority and safety) for each road segment which were later used to determine suitable routes for e-scooters.

The model share of e-scooters among the other transportation modes is expected to increase in the near future. Such an increase in e-scooter usage will bring above mentioned safety and environmental concerns that have not been completely handled in the literature. Most of the recent studies focused on investigating the travel behavior and trip frequencies of e-scooters. Recent studies have revealed a tendency from dockless systems to charging stations for an environmentally more sustainable and operationally effective shared e-scooter system. However, these studies are rather limited. To our knowledge, none of these studies performed a comprehensive spatial analysis to determine both suitable charging station locations and the most secure and convenient road network connecting these charging stations which is one of the main focuses of this study.

Secondly, e-scooters travel along the major arterials and sidewalks since they do not have dedicated routes and lanes. An increase in this mode will also threaten vehicular traffic and pedestrian safety, causing e-scooter-vehicle, e-scooter-pedestrian conflict. Although some of the earlier studies (Fazio et al., 2021; Zou et al., 2020) emphasized the importance of separate routes for e-scooters, their decision criteria were very limited and GIS-based spatial analysis has not been performed. Hence, a GIS-based multi-criteria decision support model was developed to connect charging stations via secure and convenient e-scooter routes by performing raster-based operations which distinguish the present study from the previous studies.

## 3. Study area

The study area encompasses Karsiyaka District in Izmir, Turkey. Karsiyaka was chosen as the study area because it is one of the few municipalities that has started and regulated e-scooter operations in Turkey (Izmir Metropolitan Municipality, 2021c). Karsiyaka encompasses an area of approximately 24 km<sup>2</sup> located in the west of Turkey along the Gulf of Izmir in the Aegean Sea. It is the 4th most populous district of Izmir with a population of 350,100 as of 2020 (Turkish Statistical Institute, 2021). Karsiyaka is one of the signatories of the Covenant of Mayors for Climate & Energy with an emission reduction target of 35%. It has approximately 16 km of separate bike road, most of which are located along the coast, which has to be used as the primary route for e-scooters (Izmir Metropolitan Municipality, 2021c). There are 11 bike share stations, 2 ferry ports, 6 train stations, and 12 tram stations in the study area. Most of these are located on or near the coast where the population is the highest. On the east, there is a pedestrian street shown in black and red lines where there are many shops and restaurants located. On the west, there are 3 shopping malls that serve not just Karsiyaka but are popular in the entire city. The majority of the parks are located on the coast with separated cycleways. There are 4 hospitals, 48 elementary, middle and high schools within the study area. The majority of the parking lots are located on the west near the shopping malls. There are 17 municipal buildings in the study area including the town hall, theaters, libraries, cultural centers, and the courthouse. The operation center for bicycle and recently started e-scooter services are

located 15 min or 6 km north of the nearest bike share station. Train line and a highway prohibited for e-scooter ride were defined as barrier. The location, transportation elements and point of interests of the study area (Karsiyaka) are presented in Fig. 2.

#### 4. Materials and methods

The methodology splits into 2 sections: (1) siting optimum e-scooter charging station locations that will integrate the e-scooter system with the existing public transportation systems and point of interests, and (2) finding the most secure and convenient road network for e-scooters. Since both sections involve spatial problems, a novel GIS-based solution approach was developed in the methodology. The stepwise methodology is presented in Fig. 3.

##### 4.1. Data collection and geodatabase generation

The first step of the analyses is data collection and geodatabase generation. Road network, shopping malls, parking lots, schools, hospitals, and municipal buildings data were downloaded from the OpenStreetMap (OSM). Parks and separated cycleways were also obtained from the OSM, but with major changes in line with municipal data (Izmir Metropolitan Municipality, 2021d,b). Bus stops, ferry stations, train stations, and tram stations were obtained from the municipal open data portal (Izmir Metropolitan Municipality, 2021a). Slope was derived from the elevation data obtained from NASA's Shuttle Radar Topography Mission (SRTM). Administrative boundaries were downloaded from the General Directorate of Mapping (General Directorate of Mapping, 2021). Neighborhood centers were manually digitized as point vector data, and associated with the population data (Turkish Statistical Institute, 2021). Bus lines were also manually digitized in accordance with the municipal data (Izmir Metropolitan Municipality, 2021a). The locations of traffic accidents between 2017 and 2019 were obtained from the Izmir General Directorate of Security and digitized. Speed limits were adjusted based on the limits established by the General Directorate of Highways (General Directorate of Highways, 2022). Barriers were created on Anadolu St. in the north, and the trainway. A restricted road was also created on a pedestrian way in the southeast.

All the georeferenced data were collected in vector formats except elevation data was in raster format. Since the major analyses performed

in this study require raster operations, projected coordinate system was used to maintain the integrity of raster operations. Therefore, all georeferenced data were transformed to the World Geodetic System 1984 (WGS 1984) Universal Transverse Mercator (UTM) Zone 35 projected coordinate system. The data arrangements and spatial analyses were performed with the ArcGIS software version 10.

##### 4.2. Siting optimum e-scooter charging station locations

The purpose of this section is to identify the optimum locations for e-scooter charging stations that will serve the maximum number of people, and integrate the public transportation stations and point of interests. Siting optimum e-scooter charging station locations can be considered as spatial suitability modeling, which is one of the most fundamental spatial analyses. It is often constituted of three consecutive raster operations; exclusion analysis, preference analysis, and generation of the land suitability map (Yalcinkaya & Kirtiloglu, 2021). Raster operations in spatial analyses are performed on same sized cells that define the entire study area. Each cell contains a value, such as slope, population, or distance to a specific feature (distance to cycleway). Mathematical functions can be performed on single or multiple rasters, which provides a great use for spatial suitability modeling. In this way, the suitability of the entire study area can be evaluated cell by cell, not just a few predefined locations. Rasters with 5 m cell sizes were created and used in this study considering the e-scooter charging station area requirements. Mathematical raster operations in the preference analysis were performed on 5 m cells that define the entire study area. First, each criterion was derived from the base data as a map layer. Then, each criterion was transformed to a common scale using linear fuzzy membership functions. Thus, spatial suitability of each cell in the study area was determined for each criterion. Then, weights based on the relative importance of each criterion were determined using AHP. Finally, cell by cell weighted sum operation was performed using transformed criteria map layers and AHP weights to create the final land suitability map. Cell values, ranging between 0 and 1, were defined as the suitability index.

Exclusion analysis is used to exclude limited use areas, such as environmental conservation areas, military bases, and cultural heritage areas. Exclusion analysis was not performed in this study, since the area require for e-scooter charging stations was not considerably large and

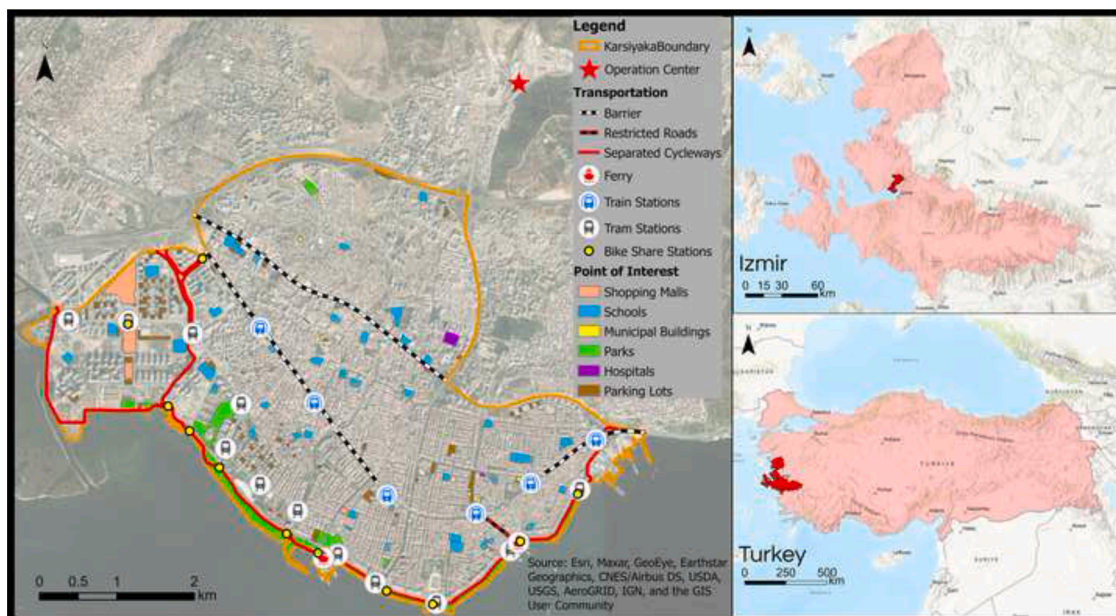


Fig. 2. The location of the study area including the existing transportation system, and point of interests.

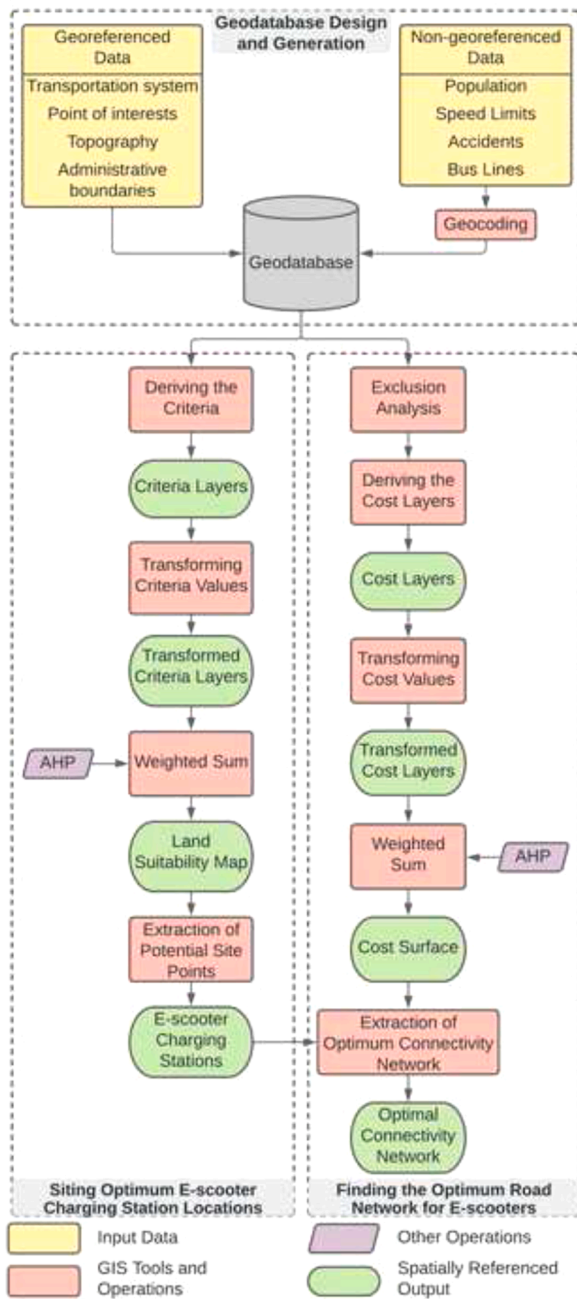


Fig. 3. Stepwise methodology.

the optimal locations found at the end were snapped onto the road network.

Preference analysis ranks every single cell within the study area based on its spatial suitability for each criterion. Identifying the criteria is crucial in preference analysis. Based on the purpose of this suitability, a detailed literature review, and data availability, the criteria were identified (Table 1). The Transportation Department of Izmir Metropolitan Municipality and Karsiyaka District Municipality were also involved in identifying the criteria, pairwise comparison in the AHP, and determination of fuzzy membership parameters. The pairwise comparison was conducted with 8 participants including the authors after identifying the criteria. Two of the participants are civil engineers operating the municipality’s e-scooter system, one of the authors is a civil engineer with expertise in transportation engineering and the other author is an environmental engineer with expertise in environmental spatio-temporal and network analyses. The remaining 4 participants are

Table 1

Preference criteria, minimum and maximum parameters of linear fuzzy membership functions, and AHP weights.

Base data	Derived criteria	Min, m	Max, m	Weight
Ferry stations	Distance to ferry stations	500	0	0.107
Bus stops	Distance to bus stops	500	0	0.095
Train stations	Distance to train stations	500	0	0.095
Tram stations	Distance to tram stations	500	0	0.095
Separated cycleway	Distance to separated cycleway	100	0	0.083
Bike share stations	Distance to bike share stations	100	0	0.083
Neighborhood populations	Population density	min	max	0.071
Road network	Distance to roads	100	0	0.071
Shopping malls	Distance to shopping malls	500	0	0.060
Parks	Distance to parks	500	0	0.060
Municipal buildings	Distance to municipal buildings	500	0	0.060
Elevation	Slope	15 deg	0	0.048
Parking lots	Distance to parking lots	500	0	0.036
Schools	Distance to schools	500	0	0.024
Hospitals	Distance to hospitals	500	0	0.012

students who are residents of Karsiyaka and frequently ride e-scooters. Participants were asked to score each criterion using Saaty’s comparison scale between 1 and 9 depending on the relative importance of each criterion (Saaty, 1980). The criteria were gathered under the following categories:

- distance to point of interests: shopping malls, parks, municipal buildings, schools, hospitals, and parking lots;
- integration of public transportation stations: distances to ferry stations, bus stops, train stations and tram stations;
- bicycle infrastructure: existence of bike sharing stations, closeness to the cycleway;
- population density, and
- topography (slope).

The criteria layers/maps were derived from base data. For example, slope criterion was derived from elevation data, or distance to train station criterion was derived from train station data using the Euclidean Distance method. Then, each criterion was transformed into a common scale (0-1) using the linear fuzzy membership function, since each criterion may have different scales and units. The minimum and maximum parameters of fuzzy membership functions for each criterion are shown in Table 1. Higher values (distances) were defined for the minimum parameters, since the spatial membership degrees are decreased as moving away from the criteria. For example; spatial membership degree is 1 right next to a ferry station and decreases as moving away from the station. Spatial membership degree is 0 (minimum) at 500 m away from the station. Locations further than 500 m from the station are not suitable for this criterion (distance to ferry stations), therefore receive 0 for spatial membership degree. The resulting spatial membership degree maps/transformed criteria layers can be compared and combined. A maximum distance of 100 m from roads and cycleways was assigned to keep the distance to road short (Guler & Yomralioglu, 2021a). Distances from public transportation stations and point of interests were limited up to 500 m (Guler & Yomralioglu, 2021a). More than 500 m walking distance is considered unsuitable. Only the areas with a slope between 0 and 15° were considered suitable for riding e-scooters by evaluating the technical specifications of e-scooter brands used in Izmir (Papuççayan, 2020).

Some criteria may be more important than others. Therefore, AHP was used to weight the criteria between 0 and 1 (the sum of weights is

equal to 1) based on their relative importance in the suitability model. AHP is a multi-criteria decision analysis (MCDA) method used to quantify the weights of criteria through pairwise comparisons (Saaty, 1980). Calculations to determine the weights were conducted by the authors after receiving pairwise comparisons from the participants. First, the comparison scores for each criterion were averaged and rounded to the nearest integer. Pairwise comparison matrix was built using the average comparison scores. The matrix was normalized by dividing each entry in each column by its column sum. Then, each row on the normalized matrix was averaged to calculate the AHP weights. Finally, consistency ratio was calculated and degree of consistency was measured. The consistency ratios for both AHP were calculated as less than 0.1, therefore the pairwise comparison was consistent enough. The weights calculated for each criterion are shown in Table 1 (evaluated in the results and discussion). Each spatial membership degree map was multiplied with its AHP weight and combined to create the final land suitability map, which is indexed between 0 and 1 based on the suitability of a cell/area for being an e-scooter charging station location. Suitability index of 1 on the final land suitability map corresponds to a perfect location for e-scooter charging station, while suitability index of 0 indicates an unsuitable location.

One e-scooter charging station was allocated to every ferry, train, tram, and bike share station to contribute to integration of public transportation. In addition to these 26 stations defined as the existing e-scooter charging stations in the model, additional station locations were extracted from the land suitability map with a minimum suitability index of 0.5. Threshold for suitability index was decided based on the existing stations' statistics, where a normal distribution was observed with a mean of 0.65 and standard deviation of 0.17. A minimum suitability index of 0.5, which corresponds to approximately one standard deviation from the mean, was taken. Distance between e-scooter charging stations was set to be maximum of 800 m and minimum of 400 m in the extraction process. It should be noted that the appropriate distance between stations was not explicitly presented in the literature (Wang et al., 2018; Zhou, 2015). While some studies suggested a minimum distance of 250 m (Eren & Katanalp, 2022; Kabak et al., 2018), some studies preferred to take a minimum of 300 m (Banerjee et al., 2020; Griffin & Sener, 2016). On the other hand, NACTO (2015) stated that the minimum distance for bike sharing stations should be within a walkable distance. The report did not suggest any threshold limit. We decided to take a minimum of 400 m and a maximum of 800 m for being a reasonable walking distance. The resulting e-scooter charging stations were ranked based on their suitability index.

#### 4.3. Finding the optimum road network for e-scooters

Although there are not many studies on siting e-scooter station or drop off location, there are plenty of similar spatial suitability/site selection studies in the literature. Extending the study with identification of optimum road network for connecting the charging stations to each other determined in the previous section and developing a raster based spatial method for this purpose distinguish this study from the previous studies in transportation. Therefore, a more detailed methodology will be presented in this section.

The purpose of this section is to identify the most secure and convenient road network for connecting e-scooter charging stations to each other. First, restricted roads were excluded from the road network of the study area. Path, footway, pedestrian and step road types of OSM, and roads with maximum speed greater than 50 km/h were removed as they were restricted by law (Ministry of Transport and Infrastructure et al., 2021). The maximum allowable speed for e-scooters is 25 km/h in Izmir. Then, a multi-criteria cost surface map was created for the remaining road network using a procedure similar to the previous section. Creating a multi-criteria cost surface is the reverse of suitability modeling. The preferred criteria are assigned lower costs, while undesirable criteria are assigned higher costs. The cost surface map

determines the cost of moving through cells. The cost value of each cell for each criterion was classified on a scale of 0-10, where 0 refers to the least cost cells to move through and 10 is the highest cost cells in terms of security and convenience. Separated cycleways, accident locations and accident density, traffic speed, road slope, intersections, and bus lines were considered as influencing criteria, listed by significance (Fazio et al., 2021; Guler & Yomralioglu, 2021b; Kabak et al., 2018; Saphloğlu & Aydın, 2018). Separated cycleways were considered the most significant criterion in creating the cost surface map because it is mandatory by the regulation to ride e-scooters on separated cycleways if available (Izmir Metropolitan Municipality, 2021c). It is also considered the most secure and convenient road to ride an e-scooter. Therefore, separated cycleways were scored 0, while the remaining road network was scored 10 for separated cycleways cost layer. Similarly, roads with bus lines were scored as 10, while others were 0, since roads with bus lines cause more frequent stops and mostly have more traffic (Saphloğlu & Aydın, 2018). Accident locations were converted into a 5 by 5 meter cell size raster map, and multiplied by 10 for each accident to score the cost. Thus, not just the accident locations, but also the densities at each accident location were taken into account. Linear fuzzy membership function was used to score costs for traffic speed and road slope. The cost increases from 0 to 10 as the traffic speed increases between 0 and 50 km/h, and road slope increases from 0° to maximum. Intersections were also converted to a 5 by 5 meter cell size raster map. Only the cells that coincide with intersections receive a cost of 10, while all other cells along the road network have 0 costs. Once the cost layers for each criterion were created, and weights were calculated by AHP based on their relative importance in identifying the most secure and convenient e-scooter road network, cost layers were multiplied with AHP weights and combined into one single raster map named as the cost surface map. Cost layers, minimum and maximum costs and AHP weights are presented in Table 2.

Finally, the optimum network of least cost paths to connect e-scooter charging stations determined in the previous section was identified using the multi-criteria cost surface map. First, e-scooter stations were introduced into the model. The least cost region for each station was calculated using the Thiessen Polygons method. Thiessen Polygons method divides the study area into polygons based on cost distances of the input points from each other. The shape of a Thiessen Polygon is calculated such that any location within the polygon is less costly to the point where the polygon was produced than other input points (Yamada, 2016). The least cost paths from each station to its neighboring cost regions were calculated to determine the optimum network connecting the e-scooter charging stations (Optimal Connectivity Network). Then, the stations were converted to vertices and their least cost paths were converted to edges to evaluate the pairwise relationships through graph theory. The costs of the least cost paths were considered as the weight for the edges. The minimum spanning tree, which connects all vertices without any cycle and with the minimum total edge weight as possible, was used to determine the optimum path (Optimal Path).

The advantage of raster based spatial method developed in this study from the vector based methods used in previous studies is the higher resolution. Higher accuracy can be achieved with raster based methodology compared to vector based methods. For example, slope is calculated as the elevation difference between the endpoints of a road

**Table 2**  
Cost criteria, minimum and maximum costs, and AHP weights.

Cost Criteria	Min cost	Max cost	Weight
Separated cycleways	0	10	0.25000
Accident locations and density	0	Accident*10	0.21875
Traffic speed	0 for 0 km/h	10 for 50 km/h	0.18750
Road slope	0 for 0°	10 for max	0.15625
Intersections	0	10	0.12500
Bus lines	0	10	0.06250

vector data divided by the length of road section. This road section may be kilometers long. However, slope is calculated for each cell for raster based road data. Assume that 30 m SRTM elevation data was used in slope calculation, a slope value for every 30 m of the road will be calculated. Another example can be given for point data such as traffic accidents. Traffic accidents are defined to the entire road section in vector based method, while it is defined only to the related cell in raster based method (in our case it is a 5m road section). If a station or stop is located before the accident location on an accident defined road section, it will be punished in vector based method, while it will not be in the raster based method.

## 5. Results and discussion

In line with the methodological steps described in the previous section, the results of the GIS-based multi-criteria decision support model for siting the optimum e-scooter charging station locations, and determining the most secure and convenient road network to connect the charging stations are presented in the following two subsections, respectively.

### 5.1. Part A: siting and ranking of potential E-scooter charging stations

The suitability of the charging station locations for the study area was evaluated for each criterion separately via linear fuzzy membership functions as detailed in the previous chapter. Fifteen spatial membership degree maps were created after the fuzzification process with the normalized values of [0, 1] as shown in Fig. 4. The value of 1 was colored green, indicating the most suitable locations (100%), whereas red color presents the unsuitable areas (0%). Overall, the study area showed higher suitability for the slope, distance to roads, distance to parking lots, distance to bus stops and distance to schools since these criteria are spatially more distributed and frequent. Fewer suitable areas for distance to ferry station criterion were observed. This is expected since there are only two ferry stations inside the study area, providing the connection between the southern and the northern shores of the city. Therefore, ferry stations in the study are vital for multimodal connectivity. Additionally, the southern part of the study area was found to be more suitable considering the distance to tram stations, distance to cycleways, bike share stations and distance to parks.

The highest importance was assigned to distance to ferry station criterion since a free pass from ferry to other public transportation is allowed. Integration of public transportation stations received the highest rankings in the pairwise comparison (Table 1). It is obvious that charging stations near public transportation not only increase the accessibility of e-scooters but also promote the use of public transportation systems, leading to a more sustainable urban development. Bicycle infrastructure related criterion had the second highest weight; closeness to cycleways contributes to the safe movement of e-scooters as also reported in previous studies (Caspi et al., 2020; Zou et al., 2020). Population density and distance to road network are the next, as they are considered the most influential factors in e-scooter accessibility and usage (Bai & Jiao, 2020; Caspi et al., 2020; Hosseinzadeh et al., 2021a,b; Huo et al., 2021). Distance to point of interests and slope were received the lowest weights.

AHP weights and spatial membership degree map of each criterion were jointly used in weighted sum analysis to create the final land suitability map, shown in Fig. 5. In addition to the 26 charging stations allocated to every ferry, train, tram, and bike share station, 9 new charging stations were proposed with suitability indices greater than 0.5. Overall, the southern shore of the study area, where majority of public transportation facilities coincide with separated cycleways and parks, was found as the most suitable area. On the other hand, suitability index of the northern part of the study area was rather low because of high slope and low population density, indicating unsuitable locations for e-scooter charging stations.

Criteria and corresponding spatial membership degrees for the 9 new charging stations are presented in Table 3. As for the suitability index of 9 new charging stations, it ranges from 0.504 to 0.574 which are very close to each other. S-1 (station 1) has the highest suitability index of 0.57. Compared to S-1, slightly lower suitability indices were calculated for S-3 and S-9 with a value of 0.56. Population density and shopping mall proximity seem to be distinctive criteria for S-3. S-2 is the fourth most suitable location with a suitability index of 0.54 followed by S-4, S-6, S-7 and S-8 with a suitability index of 0.52. Distance to separated cycleways, bus stops, and distance to roads are the most influential criteria overall. Distance to ferry, distance to train stations, distance to tram stations and distance to bike share stations criteria have no or low impacts. This is an expected result since one e-scooter charging station was initially assigned to every one of these locations.

### 5.2. Part B: optimum network for connecting E-scooter charging stations

A raster based spatial method was developed to identify the most secure and convenient road network for connecting e-scooter charging stations to each other in this part. Cost layers for each criterion are presented in Fig. 6. The lowest cost roads were calculated along the seaside, where separated cycleways are located, since separated cycleways were scored 0 costs. All other roads were scored as 10. Traffic accidents have distributed all over the study area, but they are more concentrated along the primary and some secondary arterials. Especially the primary arterial by the separated cycleway has more frequent accident locations. There are several high-density accident locations shown in pink, orange and red. Speed limit cost scores range from 0 to 50. Higher scores were calculated for primary and secondary arterials, as shown in red. Collector roads, which had a speed limit of 30 km/h, were scored as 6 after transforming cost values via the linear fuzzy membership function. Road slope cost ranges between 0 and 8.74. The roads on the north resulted in high costs as they have high road slopes. Cost for bus lines resulted in a similar map to traffic, except for the northern part. High costs were calculated along the primary arterial by the seaside when considering the accident locations, traffic speed and bus lines cost criteria. Although this road is located right next to the cycleway, they are separated roads. Some accident locations coincided with intersections which resulted in higher cost scores.

The influence of cost criteria determined via AHP revealed that separated cycleways are the most important criterion (0.25 weight) followed by the accident locations with a weight of 0.22. The weight of traffic speed was determined as 0.19. Road slope was ranked as the fourth most influential criterion (0.16). The weights for intersections and bus lines were calculated as 0.13 and 0.06, respectively. Among these six criteria, separated cycleways, accident locations and traffic speed were the most influential criteria based on the AHP results which are consistent with the literature (Fazio et al., 2021; Zou et al., 2020).

AHP weight and cost layer of each criterion were jointly used to create the final cost surface map, as shown in Fig. 7. The final cost surface ranges between 0.19 and 19.45. Lower cost values, shown in green, indicate secure and convenient roads for e-scooters, while red lines indicate less secure and inconvenient roads with higher cost values. Minimum costs were calculated for the separated cycleways, which makes it the most secure and convenient road as it must be. The collector roads, shown in yellow, could also be regarded as safe and convenient for riding e-scooters due to their lower traffic speed, appropriate road slope, and not having bus lines. On the other hand, the primary and secondary arterials were found the most insecure and inconvenient roads due to higher traffic speed, higher accident density, and existence of bus lines.

The optimal connectivity network to connect e-scooter charging stations was identified using the cost surface map and locations of potential e-scooter charging stations determined earlier. The least cost paths from each station to its neighboring stations were calculated and resulting optimal connectivity network is mapped in Fig. 8 (b). This

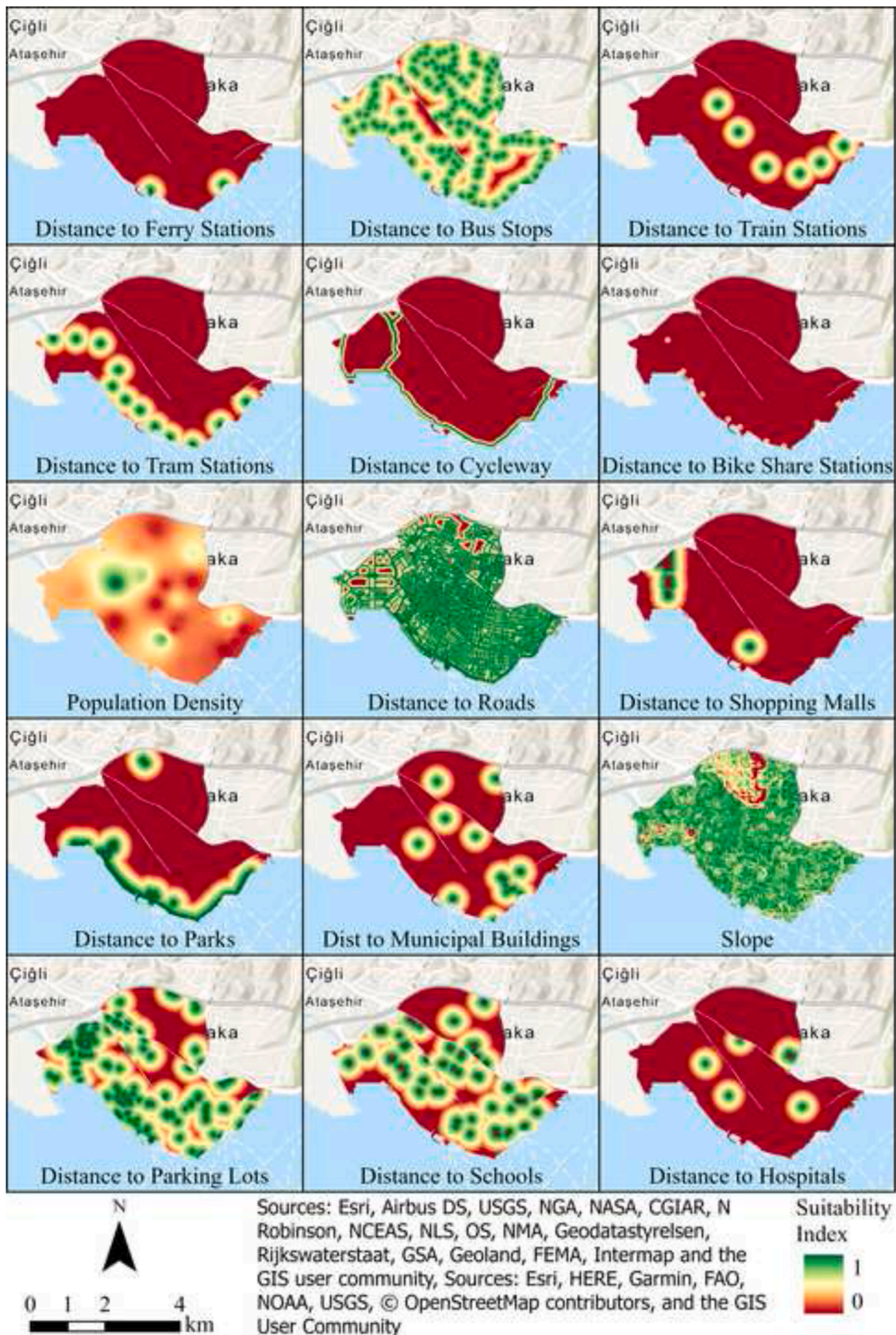


Fig. 4. Spatial membership degree map/transformed criteria layer for each criterion.

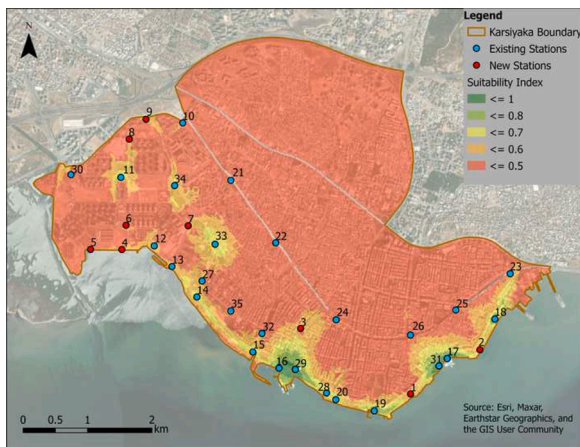


Fig. 5. Land suitability map and potential sites for e-scooter charging stations.

network provides the most secure and convenient paths that will integrate the e-scooter system with the existing public transportation systems and point of interests. This network together with suitable e-scooter charging station locations will provide an operationally more efficient and environmentally more sustainable e-scooter system compared to dockless systems, while still satisfying user needs. The optimal path connecting all e-scooter stations together without any cycle and with the minimum total cost is presented in Fig. 8 (a). This can be regarded as the initial step if a policy will be created for separating e-scooter lines or regulating the e-scooter routes. Later, that initial e-scooter transportation network can be expanded to the optimal connectivity network that connects each station to its neighboring station. It can be concluded that:

- Separated cycleways constituted a significant part of the e-scooter road network providing e-scooter safety by separating them from vehicular and pedestrian traffic, as also reported in previous studies (Caspi et al., 2020; Zou et al., 2020).
- None of the primary and secondary arterials were used. The safety of the vehicular traffic and e-scooters were maintained; thus, the network serves as convenient transportation for e-scooters.
- All charging stations are well-connected, meaning that integration of the e-scooters with public transportation facilities is also achieved.

6. Conclusions and recommendations

This study proposes a novel GIS-based multi-criteria decision support model for (1) siting optimum e-scooter charging station locations that

will integrate e-scooter system with the existing public transportation systems and point of interests, and (2) finding the most secure and convenient road network to connect the charging stations. 15 influential criteria were selected considering the previous studies and data availability: (1) public transportation facilities, (2) bicycle infrastructure, (3) population, (4) point of interests, (5) topography, and (6) road network. Spatial membership degree of each criterion in the study area defined by 5 × 5 m cells was calculated using linear fuzzy membership functions. The relative importance of each criterion was determined via AHP. Spatial membership degree of each criterion and AHP weights were multiplied and summed for each cell and the final land suitability map of the study area was created. 9 charging stations were located with suitability indices greater than 0.5 in addition to 26 stations allocated to each ferry, tram and train stations. As a result, daily collection and distribution of the e-scooters for charging would not be required for the case study. Hence, a significant part of carbon emissions would be minimized, contributing to environmental sustainability. Also, illegal parking would be prevented, providing clear urban space.

E-scooters often use the existing infrastructure; they can travel either with vehicular traffic or pedestrian sidewalks, causing safety problems. Introducing safe and convenient routes for e-scooters is inevitable in the near future since its modal share is expected to increase. The second GIS-based multi-criteria decision model was developed to connect the charging stations via safe and convenient routes. A raster based spatial method for this purpose distinguish this study from the previous studies in transportation. 6 criteria were considered and a similar procedure to the station siting was performed to create the cost surface map of the study area. The least cost path connecting each station with its neighboring stations (Optimal Connectivity Network) was identified from the cost surface map. The results indicated that separated cycleways constitute a significant part of the e-scooter road network and all charging stations are well-connected. The raster based spatial method has limitations as it has advantages over the vector based methods used in the previous studies. We had difficulties in using elevation data. Some areas may require data preprocessing due to high features such as tall buildings. Resolution of the raster data is important. For example, 30 m by 30 m cell sized raster data was used for elevation. Resampling techniques were performed to decrease the cell size to 5 meter. Routing in terms of time and distance requires vector based network dataset. Vector based routing can be performed on the raster based network solution.

We believe that environmentally more sustainable and operationally more effective shared e-scooter systems can be achieved with proper siting of charging stations and connecting them via secure and convenient road networks. High life cycle global warming impacts of e-scooters and irregular parking problems can be alleviated by shifting

Table 3  
Criteria and corresponding spatial membership degrees for the 9 new charging stations.

Criteria	Spatial Membership Degree								
	S-1	S-2	S-3	S-4	S-5	S-6	S-7	S-8	S-9
Distance to ferry stations	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Distance to bus stops	0.12	0.11	0.13	0.06	0.09	0.14	0.13	0.14	0.12
Distance to train stations	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Distance to tram stations	0.01	0.00	0.01	0.00	0.00	0.00	0.03	0.01	0.00
Distance to separated cycleway	0.11	0.10	0.00	0.13	0.13	0.00	0.00	0.00	0.11
Distance to bike share stations	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Population density	0.02	0.01	0.07	0.03	0.03	0.03	0.06	0.04	0.04
Distance to roads	0.11	0.11	0.10	0.11	0.11	0.11	0.11	0.11	0.10
Distance to shopping malls	0.00	0.00	0.09	0.03	0.00	0.08	0.00	0.09	0.05
Distance to parks	0.09	0.09	0.04	0.09	0.04	0.05	0.04	0.00	0.00
Slope	0.05	0.03	0.05	0.03	0.07	0.05	0.06	0.05	0.06
Distance to municipal buildings	0.02	0.01	0.01	0.00	0.00	0.00	0.01	0.00	0.00
Distance to parking lots	0.03	0.05	0.03	0.04	0.03	0.05	0.04	0.05	0.05
Distance to schools	0.01	0.02	0.03	0.00	0.00	0.00	0.04	0.03	0.03
Distance to hospitals	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00
Suitability index	0.57	0.54	0.56	0.52	0.50	0.52	0.52	0.52	0.56

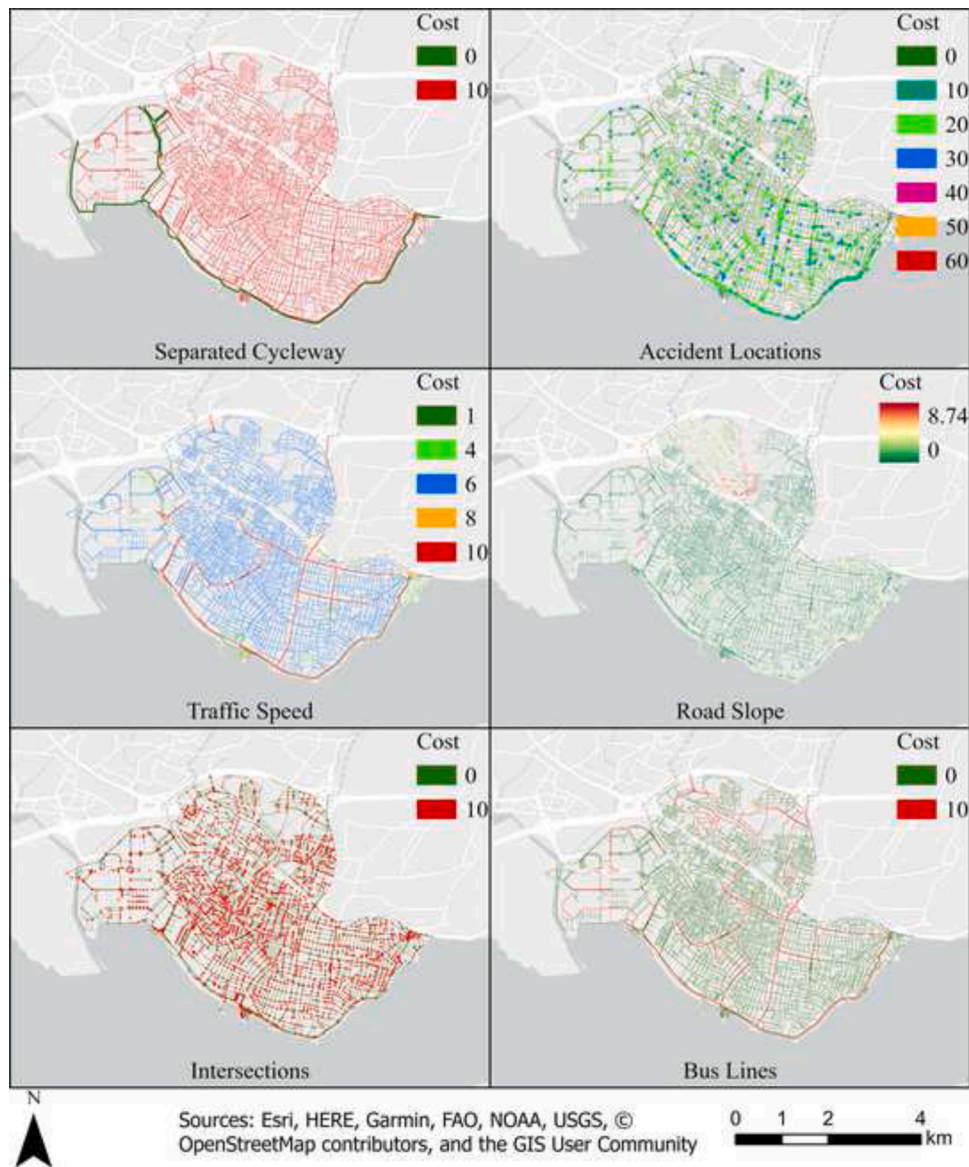


Fig. 6. Cost layer for each criterion.

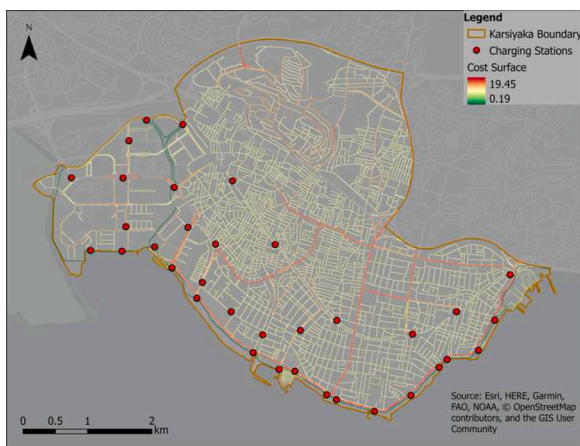


Fig. 7. The final cost surface map (please zoom in for a better view).

from dockless to charging systems. More research is needed to reach that conclusion, especially on life cycle assessment of environmental impacts of shared e-scooters with charging stations, and operational efficiency. User satisfaction is also another aspect to be investigated. Age, gender, education level, land use patterns (including commercial areas, residential areas, industrial regions, etc.), high employment regions, and bus stop density were also identified as influential factors affecting trip frequency of e-scooters in the literature. One of the limitations of this model is not considering these parameters in the GIS-based model development process. The collection of such information requires supplementary data that can be collected via surveys or collaboration of local authorities. The GIS-based decision support model can be extended by considering these factors in future studies. This study investigated the suitable charging locations and road network connecting them; however, extending the present study to estimate the number of charging units in each station can be a motivation for future studies. This study establishes an important step into siting suitable e-scooter charging stations locations and identifying road networks connecting the stations, which lays a foundation for further research. This study can be utilized by urban planners and policymakers to develop innovative policies and plans for environmentally more sustainable and operationally effective

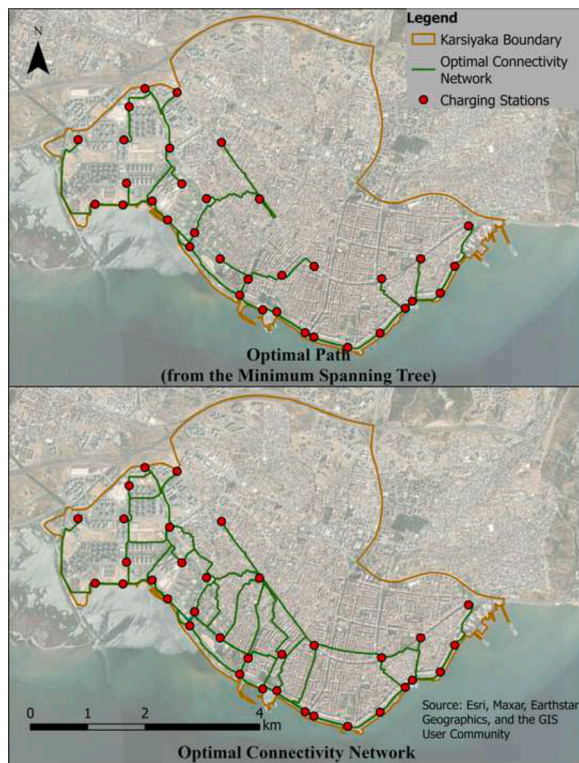


Fig. 8. Optimum road network connecting e-scooter charging stations.

shared e-scooter systems.

#### 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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