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Identification of required stations for autonomous vehicles using AHP and TOPSIS method with GIS approach

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ABSTRACT

Autonomous vehicles (AVs) equipped with new technologies that replace the human driver and operate essential functions without human input. Current stations have simple structures that need to be re-evaluated for the use of AVs in future sustainable cities. As the aim of this study is to identify appropriate locations of stations for AVs, 53 existing stations were evaluated in Mashhad, Iran. The combination of Analytical Hierarchy Process (AHP) analysis and Geographic Information System (GIS) software confirmed 15 of them based on considered criteria of accident rate, street width, population, traffic congestion, distances from stations and station density. Additionally, the mentioned criteria were ranked using TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method, and their weight were determined with the aid of AHP analysis. Finally, 9 Decision-Making Units (DMUs) were proposed for the construction of new AVs stations, and GIS maps indicated that these 9 stations meet the criteria more than others. In addition, the sensitivity analysis was specifically conducted using the Export Choice software to evaluate the robustness and stability of the model's results and to ensure their accuracy under different conditions.

1. Introduction

All technological innovations have the potential to improve the lives of people. These days, AVs have been a particular interest, and they can reshape the transportation system and the daily lives of those who wish to live healthier and longer. As the most important aim of AVs is to reduce the number of accidents, they must be smart enough to consider all road conditions and pick up and drop off passengers in stations flawlessly. Technically, through the use of intelligent algorithms, AVs select more efficient routes and avoid causing traffic congestion and blockages at stations. To this end, "the output of localization and environment perception is sent to the AV path planner to decide on what actions to take, and they are sent to the AV motion control" ([1], p.1).

One of the most important issues in AVs is route selection and station detection which the new concept of a Virtual Vehicle (VV) on the Internet of Vehicles (IoV) tries to solve the related problems [2]. Vehicles in IoV are so smart and must possess advanced communication technologies, multi-sensor platforms, computation units and efficient connectivity to the Internet [3]. Thus, these vehicles must be able to sense all the information about the environment to find stations and best routes. For this reason, some available sensors or systems such as LIDAR, RADAR, etc. are used in AVs. It is worth mentioning that each of these sensors has its own limitations and may be affected by some environmental variations. Therefore, appropriate combinations of electrical devices are suggested by AVs researchers to compensate their limitations. As the fundamental phase towards implementing AVs is to design an appropriate controller, a variety of different control approaches, software and hardware were introduced to manage these vehicles to find their routes and stations. Thus, appropriate design of electronic control units, internal communications, data processors, vehicle buses, mechanical actuators and electromechanical actuators should be applied [4]. Moreover, AVs stations should be designed to incorporate advanced technologies that optimize their functionality. These stations could include features such as automated ticketing systems, smart sensors for monitoring traffic and air quality, and real-time tracking systems to better manage passenger flow. These technologies can reduce waiting times for passengers and help manage traffic around the stations more effectively.

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As current stations have been built for human drivers, reconstructing them or making new stations for AVs should be included in the future programs. In fact, this new technology requires smart and developed infrastructure which is not ready yet. It is worth noting that many problems such as disorders in trip distribution, air pollution, travel time, energy consumption and human errors in accidents can be solved or decreased by using AVs. Thus, the identification of suitable locations for autonomous vehicle (AV) stations based on traffic criteria such as accidents, street width, population, traffic, distance from the stations, etc. is a critical issue in encouraging and convincing people to use these vehicles. All urban transportation systems around the world need stations in order to provide safe movement for road users. The number of stations should be balanced; more stations boost ridership and also increase travel time, while fewer stations can decrease ridership [5]. In this regard, the combination of theory and practice in choosing the location of stations should be considered.

In the present work, the issue of AVs and their stations is investigated with the aim of taking some effective actions in transportation system. Mashhad was selected as the case study because this historical and religious city, as the spiritual capital of Iran, experiences an influx of millions of domestic and international pilgrims every year, especially during peak pilgrimage seasons. This leads to significant pressure on its transportation infrastructure, resulting in common urban issues such as traffic congestion, overcrowded public transportation systems, air pollution, and delays in the movement of people. These issues are magnified by the sheer volume of visitors, many of whom rely on public transportation or taxis to travel to and from religious sites. The scale of these problems during high-demand periods is far more intense compared to other major cities in the country. Hence, the specific characteristics of this city, such as its high population density, large number of pilgrims, and traffic challenges, make it an ideal location to study and analyze the transportation challenges and the potential use of AVs. As these challenges are not unique to Mashhad and are shared by many cities in Iran and other countries around the world, the findings and conclusions of this research can be significantly generalized and applied to other similar cities. Thus, the condition of this city makes it the representative of many cities in developing countries [6]. Also, the AHP (Analytic Hierarchy Process) and TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) methods were used in this study to offer robust frameworks for decision-making and identifying optimal locations for AVs stations. These methods help prioritize factors such as accessibility, traffic conditions, environmental impact, and infrastructure readiness, all of which are critical in optimizing the placement of transportation systems, especially AVs stations. Cities facing high congestion, pollution, and infrastructure constraints can apply these methods to assess and choose locations that would maximize the effectiveness of AV stations, improve traffic flow, reduce pollution, and enhance public transportation access. By using them, urban planners can also make more informed decisions regarding the integration of AVs into the existing transportation network. For example, selecting locations that are already experiencing high traffic volumes but lack sufficient public transportation could encourage users to switch from traditional vehicles to AVs, alleviating congestion and pollution. Moreover, the use of AVs in underdeveloped or underserved areas could improve access to transportation and reduce regional inequalities.

2. LITERATURE review

The first attempt at driverless vehicles dates back to many years ago, and the evolution in them has been started in the 1920s [7]. The operation of these vehicles is based on a design with three phases called ‘‘sense-plan-act’’, which is the fundamental presumption of multitude robotic systems [8]. Unfortunately, many people have been partially or entirely excluded from participating in public life because of some mobility restrictions or disabilities [9]. AVs have their own advantages that can provide new mobility opportunities for the mentioned group of people [10]. AVs offer significant benefits in creating a happier life for road users and increasing safety [11]. In fact, advances in this technology can take control from a driver who is impaired in some abilities [12]. As driving includes different interactions with road users such as vehicles, pedestrians and bicyclists, it is more complicated than flying an airplane. In fact, there is a need to provide vehicles to have human-like driving efficiency, so the aim of AVs designers is to move toward actuality [13]. Also, based on the readiness of people, countries must select a proper management model for AVs since they need on-time implementation [14]. It should be noted that the intention of people to use AVs may be affected by legal concerns, ethical issues and trust in this new technology [15].

In recent years, various studies have been conducted on the conceptualization, development and implementation of AVs. Transportation engineers are interested in investigating its traffic efficiency [16,17], safety aspects [18,19], economic benefits [20–22], environmental issues [23,24], demand forecasting [25] and its accessibility for elderly and disabled people [26,27]. Civil engineers have studied the integration of this technology with existing infrastructure [28], the development of new passenger stations [29], the construction of charging stations [30] and the implementation of real pilot programs. They are concerned about the details of roadways, intersections, and signage for safe and effective navigation of AVs. Existing road infrastructure has been built for human drivers, and it is not ready for the integration of AVs [31]. So, based on the needs of AVs, existing road infrastructure must be upgraded [32]. Urban planners have carried out research on the best policies and strategies [33] for the use of AVs technology and its effect on land use [34]. Public engagement, education, transit integration, regulations, insurance and liability are other aspects that need further investigation. Sensors [35], algorithms for training of AV systems [36,37], artificial intelligence [38], robotics [39] and automotive engineering are additional topics for investigation. In this paper, passenger stations for AVs are investigated.

Generally, there are two patterns of AVs ownership: “private” one refers to private vehicles with private use, while “shared” is about shared uses that can be with or without any vehicle ownership. Shared Autonomous Vehicles (SAVs) are a form of self-driving transportation that can provide on-demand services and transport multiple passengers from the same station or pick-up location to the same station or drop-off destination with the same vehicle [40]. Consequently, the number of vehicles on the roads and traffic congestion will decrease. Also, SAVs have potential to reduce energy, emissions and vehicle travel [41]. Car sharing, personal vehicle sharing, ride-sharing and on-demand ride services are some models of shared transportation [42]. In car sharing, multiple people use the same vehicle at different times without ownership, allowing for either station-based or free-floating models. The other system is personal vehicle sharing, in which vehicle owners turn their personal cars into a shared vehicles and rent them out to others. Recently, various studies have been conducted on SAVs [43–46]. Hence, it is crucial to identify suitable stations for these types of vehicles.

The space of the stations affects the performance of the transportation system [47]. They found that by improving facilities in stations, the stopping time would be reduced. As a matter of fact, stations should be located appropriately, without causing any blockages for other road users [48]. The distance from stations is another issue; residents near stations prefer to use them more than people who live far from them [49]. Minimizing travel time and waiting time for stations are two important issues and benefits of AVs [50]. These parameters can be considered for AVs, as well. The decision-making process can help to find appropriate locations for AVs stations. AHP and TOPSIS are extensively used as decision-making tools in transportation studies such as dangerous goods transportation [51,52], transportation logistics [53,54], urban public transit [55], site selection for transportation subjects [56], transportation supply chain parameters [57], optimal route selection [58,59], site selection for emergency centers in Silk Road [60], and selecting the best strategies for transportation systems [61–63].

Transportation researchers utilize GIS in decision-making studies [64–66].

3. Materials and methods

This study has been carried out in two phases: analyzing the current stations and then, determining the locations of new stations for AVs.

3.1. Study area

Mashhad as the capital of Razavi Khorasan province, is located in Northeast Iran, covering an area of 204 square kilometers, with a population of over 3 million people. It is the second-largest metropolis in Iran, known for its striking urban journeys. The city as a tourist center, is positioned along longitude 59 degrees 15 min to 60 degrees 36 min and latitude 35 degrees 43 min to 37 degrees 8 min, with an altitude of 985 m above the sea. This city has the potential to develop in a sustainable manner. As shown in (Fig. 1), the locations of current taxi stations do not have a homogenous distribution; they were established based on previous experiences. In this figure, 53 stations are displayed with yellow point symbols on satellite images of Mashhad.

3.2. Data collection

The data utilized was carefully selected from several reputable and authoritative sources, ensuring its reliability and accuracy. These key organizations involved in transportation management and urban planning in Mashhad. These sources include Mashhad Traffic Control Center, Mashhad Transport Organization and Statistical Center of Iran, and additional information was obtained from the Traffic Police (see Table 1). It is worth mentioning that the data collected from these centers is regularly updated and provides accurate, high-quality and time-sensitive information. For the purposes of this study, the data from these sources were harmonized and standardized before analysis. This process involved addressing any potential inconsistencies between datasets and ensuring that all data points were compatible with the research methodology employed. Also, a combination of technologies and methodologies such as Traffic Counters, Surveillance Cameras, Annual Statistics, Accident Data and Street Width Measurements were utilized to collect the required data. In order to ensure the reliability and validity of the collected data, several validation measures including Regular Reviews, Cross-Checking with Other Sources and Comparison with Historical Data were employed.

Table 1
Required spatial data.

Format	Saving method	Data source	Scale	Data name
Shape File	Vector	Mashhad Transport Organization	1.43056	Streets
Shape File	Vector	Mashhad Traffic Control Center	1.43056	Stations
Excel File	Report	Mashhad Traffic Control Center	1.43056	Traffic
Excel File	Report	Statistical Center of Iran	1.43056	Population
Excel File	Report	Traffic police	1.43056	Traffic reports

3.3. Analysis method

Generally, the combination of AHP and TOPSIS methods effectively contributed to choosing the best locations for AVs stations in the present work. AHP scientifically and transparently assigned weights to criteria, while TOPSIS, using similarity analysis, identified the optimal stations among various alternatives. At the first step, the AHP and GIS software were integrated to analyze the 53 existing stations. Then 15 suitable AVs stations were selected. After that, they were ranked using the TOPSIS method. Finally, the best location for each station was proposed with the

Fig. 1. Location of taxi stations on satellite images of Mashhad.

aid of GIS software.

4. Results and discussion

The abilities of a site will differ based on its considered concepts, so functional indicators should be combined with the criteria, to assess the locations for stations.

4.1. Analytic hierarchy process (AHP)

AHP is a well-established and credible method, particularly effective in multi-criteria decision-making, where various criteria need to be considered simultaneously. This method assigns accurate weights to various criteria, such as air pollution, traffic, and infrastructure quality, and determines the significance of each criterion in the final decision-making process. AHP consists of three levels: goals, criteria, and alternatives, making it a useful tool for addressing complex economic problems, especially in developing countries [67]. This method simplifies the decision-making process by evaluating and assigning weights to multiple criteria [68]. Moreover, AHP is particularly effective in reducing human errors and accelerating the evaluation of options with minimal economic costs [69].

In this study, by assuming n alternatives and m criteria, there were six parameters: Staccdense, Stwiddense, Stpopdense, Sttrfdense, Ststdense, Stdistdense. The first one referred to accident density, the second one was street width density, the next one was population density, the other one was traffic density, and the fifth one referred to station density, and the last parameter was distance from station density. All of these parameters have been weighted, and the results are shown as the following matrix. In this matrix, the rows indicate parameters and the columns show the weights of parameters. The steps of analysis are as follows:

1. Comparing criteria with respect to the target

$$\begin{bmatrix} 1 & \frac{9}{7} & \frac{9}{6} & \frac{9}{8} & \frac{9}{4} & \frac{9}{5} \\ \frac{7}{9} & 1 & \frac{7}{6} & \frac{7}{8} & \frac{7}{4} & \frac{7}{5} \\ \frac{6}{9} & \frac{6}{7} & 1 & \frac{6}{8} & \frac{6}{4} & \frac{6}{5} \\ \frac{8}{9} & \frac{8}{7} & \frac{8}{6} & 1 & \frac{8}{4} & \frac{8}{5} \\ \frac{4}{9} & \frac{4}{7} & \frac{4}{6} & \frac{4}{8} & 1 & \frac{4}{5} \\ \frac{5}{9} & \frac{5}{7} & \frac{5}{6} & \frac{5}{8} & \frac{5}{4} & 1 \end{bmatrix}$$

After normalization:

2. Matrix weights by using arithmetic mean

$$\begin{bmatrix} 0.23 & 0.23 & 0.23 & 0.23 & 0.23 \\ 0.18 & 0.18 & 0.18 & 0.18 & 0.18 \\ 0.15 & 0.15 & 0.15 & 0.15 & 0.15 \\ 0.21 & 0.21 & 0.21 & 0.21 & 0.21 \\ 0.1 & 0.1 & 0.1 & 0.1 & 0.1 \\ 0.13 & 0.13 & 0.13 & 0.13 & 0.13 \end{bmatrix}$$

Finally, the weight of each parameter is as follows:

Accident density: 0.23, Street width density: 0.18, Population density: 0.15, Traffic density: 0.21, Station density: 0.1 and Distance from station density: 0.13.

These coefficients were entered in ArcGIS software, and the outcomes are shown in (Fig. 2).

Six criteria were analyzed by AHP and the weight of each of them was entered into GIS software. Dark spots in this figure indicate the best stations (Fig. 2). The color spectrum shows that number 1 has the lowest value, while number 9 contains the highest value. Also, there are several dots that overlap each other. This means that the place and its surroundings are suitable for the location of stations.

To verify the accuracy of the results and assess how changes in the weights might affect the final outcomes, sensitivity analysis was also conducted. This analysis was performed using the Export Choice software, and its purpose was to examine the impact of changes in the weights of the criteria on the final rankings of alternatives. By conducting this analysis, we evaluated the effects of weight changes on the results and assessed the flexibility of the model in response to various changes. The output of the sensitivity analysis is presented in the form of diagrams (Fig. 3), which show how variations in weights can significantly influence the final results.

As it shows, the accident parameter has the highest fluctuation compared to other criteria and it is the most effective parameter in determining the locations of stations.

4.2. Running technique for order preference by similarity to ideal solution (TOPSIS) method

TOPSIS is a widely used and effective method for prioritizing alternatives, capable of quickly ranking various options and selecting the best ones. This method evaluates alternatives by comparing them to the ideal and the worst possible solutions, ranking them based on their proximity to the ideal solution. This method provides high accuracy, greater stability in final results, and rapid data processing, which facilitates the decision-making process and yields reliable and valid results [70,71]. It is one of the Multi Criteria Decision-Making methods (MCDM) that is able to specify the effect of any criterion according to the station's situation. The following steps are required to implement TOPSIS:

1. Making a decision matrix in which the rows are the alternatives (stations) and the columns are effective criteria.

$$A_{ij} = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ a_{m1} & a_{m2} & \dots & a_{mn} \end{bmatrix} \quad (1)$$

2. Standardized decision matrix elements and create a standard matrix using the following equation.

$$r_{ij} = \frac{a_{ij}}{\sqrt{\sum_{k=1}^{m} a_{kj}^2}} \quad (2)$$

3. Determine the weight vector of each of the criterion (W_i) subject to the unbiased condition $\left(\sum_{i=1}^{n} W_i = 1\right)$. In this regard, the most important indicators are higher in weight. Then, in order to achieve the standard Matrix (V), standard values are multiplied to the equivalent weight per criterion.

$$V_{ij} = \begin{bmatrix} w_1 r_{11} & w_2 r_{12} & \dots & w_n r_{1n} \\ w_1 r_{21} & w_2 r_{22} & \dots & w_n r_{2n} \\ \vdots & \vdots & \dots & \vdots \\ w_1 r_{m1} & w_2 r_{m2} & \dots & w_n r_{mn} \end{bmatrix} \quad (3)$$

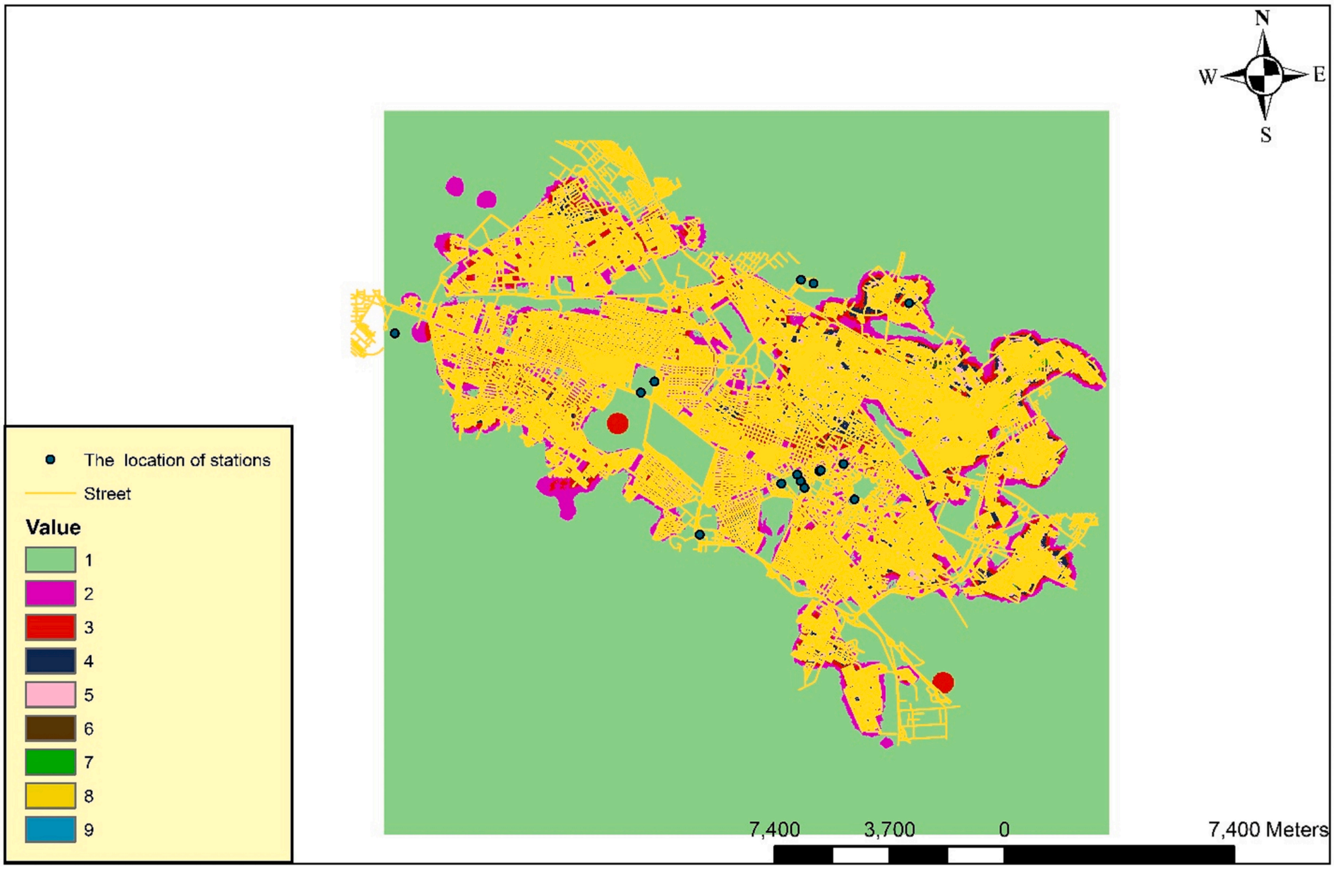

Fig. 2. Location of stations in GIS software.

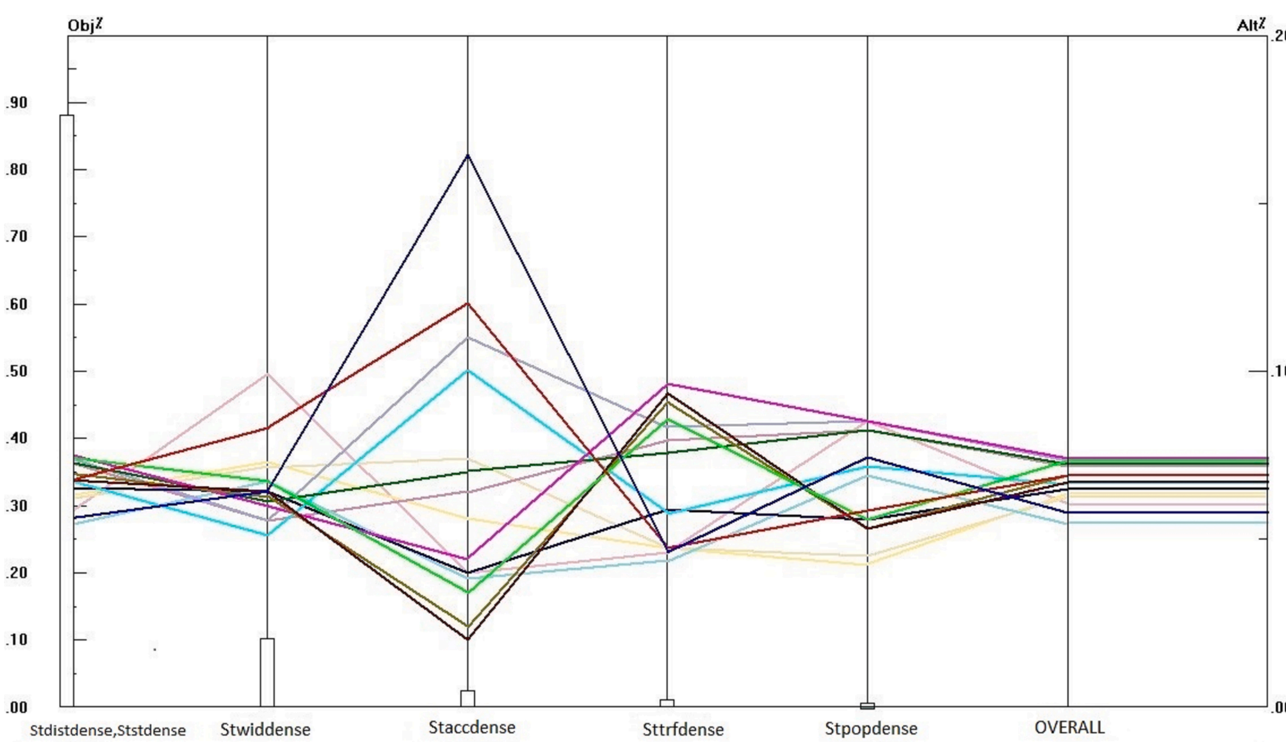

Fig. 3. The output of the sensitivity analysis.

4. Calculate the distance of i th alternative from the ideal alternative (the highest performance of any criteria) that is shown by (A^*).

$$A^* = \{(\max v_{ij}|j\varepsilon J)(\min v_{ij}|j\varepsilon J\} \tag{4}$$

$$A^* = \{v_1^*, v_2^*, ..., v_n^*\} \tag{5}$$

In the above equation v_{ij} represents the weighted standard matrix element, i is the number of columns and j is the number of rows.

5. Estimate of i th minimum option distance (the lowest performance indicators) that is shown by (A^-).

$$A^- = \{(\min v_{ij}|j\varepsilon J), (\max v_{ij}|j\varepsilon J\} \tag{6}$$

$$A^- = \{v_1^-, v_2^-, ..., v_n^-\} \tag{7}$$

6. Estimate the distance of each option (S_i^*) from the ideal and anti-ideal options (S_i^-)

$$S_i^* = \sqrt{\sum_{j=1}^{n}\left(v_{ij} - v_j^*\right)^2} \tag{8}$$

$$S_i^- = \sqrt{\sum_{j=1}^{n}\left(v_{ij} - v_j^-\right)^2} \tag{9}$$

7. Determine indicator C_i for each item and ranking the options according to it.

$$C_i^* = \frac{S_i^-}{S_i^- + S_i^*} \tag{10}$$

The parameter range is varied in $0 \leq C_i^* \leq 1$ so that $C_i^* = 1$ represents the top and $C_i^* = 0$ represents the lowest ranks.

TOPSIS method was performed in accordance with the above steps and, considering accident density, street width, population density, traffic density, station density, and density of distance from the stations, these results are provided (see Table 2).

In this table, station (17) located at Hemmat Highway bridge in the Resalat, with a score of 0.599378782, was in the best situation, while station (40) located at Mousavi Ghouchani and Gharani intersection, with a score of 0.172045327, was not efficient in terms of performance.

Table 2
Results of TOPSIS method in ranking the stations.

DMU	RANK	CL
17	1	0.59938
19	3	0.54785
21	8	0.35705
23	9	0.35078
24	10	0.34772
25	6	0.42208
30	5	0.42387
31	4	0.44138
34	14	0.21367
37	2	0.58672
40	15	0.17205
42	7	0.41247
48	12	0.32575
50	13	0.25868
52	11	0.33861

4.3. Suggested location for the best stations

Choosing the best location for stations is affected by a variety of criteria, including accident density, street width, population density, traffic density, station density and density of distance from the stations. For this purpose, and according to the location measures, evaluation and analysis, preparing maps, tables and graphs on their spatial patterns showed that the existing stations in Mashhad are not enough to cover the entire city. By using AHP in combination with GIS capabilities and considering the weight and efficacy of each criterion, it revealed that some AVs stations can be located in areas different from existing stations. Therefore, (Fig. 3) was proposed in the software output for locating the best stations.

The color spectrum in (Fig. 4) illustrates that brown areas are the best and final sites for construction of AVs stations. According to this figure, a couple of locations are recommended for building AVs stations (see Table 3).

The software output indicated that these 9 areas in Mashhad city are appropriate for building AVs stations, and they meet the considered criteria. In fact, the traditional model of stations needs to be modernized for AVs in some regions of this city. It is worth mentioning that more than half of the current range of the city is outside the standard coverage radius and requires new stations in order to cover the entire city. Besides, findings indicated that AVs stations must be located in streets with balanced widths because narrow roads may create traffic congestion and accidents consequently. In addition, the space of stations for picking up and dropping off passengers must be considered, since some stations are usable for both human drivers and AVs simultaneously, and the general satisfaction of these two groups is important. Thus, policymakers and experts can use the outcome of present study to promote the transportation system of this city by implementing AVs; however, before implementation, the infrastructure, such as the best location of stations, design of streets, and culture of using them, must be provided.

To enhance the reliability of the proposed station locations, additional sources of validation were utilized. These included reviewing similar projects globally, where AV infrastructure has been implemented, and incorporating expert opinions from urban planners, transportation experts, and other stakeholders with specialized knowledge. By comparing the results of this work with successful case studies and gathering insights from professionals who have hands-on experience in AV infrastructure projects, it was revealed that the proposed locations align with proven practices and lessons learned from other cities.

While analytical methods and expert reviews provide valuable insights, real-world testing and simulation models are essential for assessing the practicality of the proposed station locations in a dynamic urban environment. Future trials, such as pilot projects or small-scale implementations, could allow for observing how the stations perform in real-life conditions. These trials would enable the assessment of factors like actual traffic patterns, passenger flow, safety measures, and public acceptance. By simulating how AVs interact with the infrastructure and testing the system in real-time scenarios, the potential challenges that might not have been captured through theoretical models can be identified.

Additionally, simulations using traffic management software or dynamic urban modeling tools could be conducted to assess how these proposed stations interact with other aspects of the city's infrastructure, such as roads, public transportation systems, and existing traffic signals. These simulations would provide valuable data on potential congestion points, user behavior, and the integration of AVs into the broader urban transport ecosystem.

By combining the current analytical results of this research with these additional validation methods, including future pilot trials and simulation studies, the effectiveness and reliability of the proposed station locations will be confirmed. These validation processes will ensure that the findings of the present study can be confidently applied in real-world applications and contribute to the successful integration of

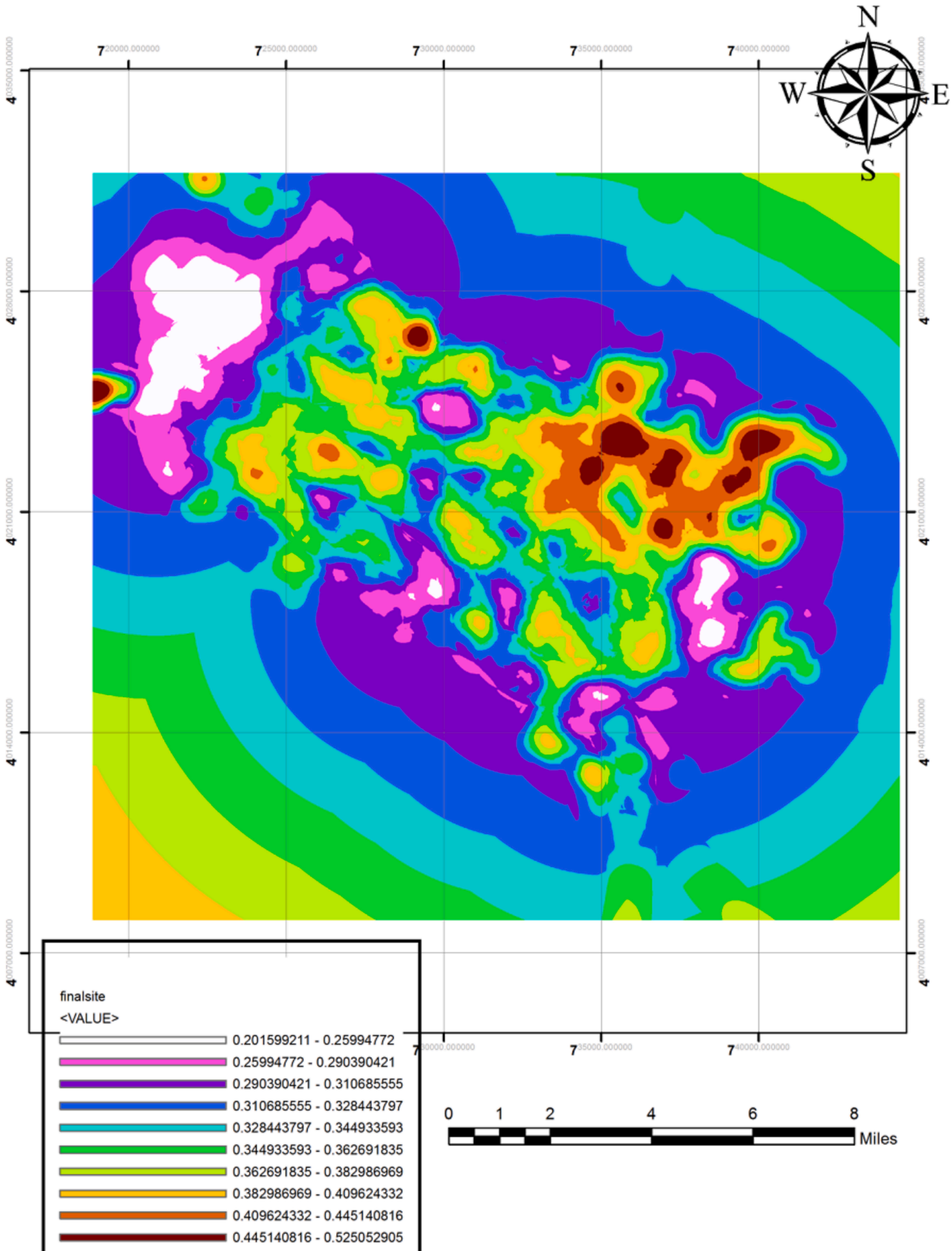

Fig. 4. The software output for locating the best station.

Table 3
Suggested location for the construction of AVs stations.

No.	Area	Between	
1	Sajjad Boulevard	Khayyam intersection	Palestinian three-way
2	Samarkand (Martyr Ebadi)	Railway intersection	Gaz intersection
3	100 Metri Boulevard	Imam Hosein Square	Aboutaleb Boulevard
4	100 Metri Boulevard	Barnoqan Square	Imam Hosein Square
5	Hejazi Hospital	Martyr Quchani Boulevard	Bou-Ali Square
6	Imam Reza Boulevard	Kalantar intersection	Beitolmoqadas Square
7	Imam Reza	Zed Square	Bargh Square
8	Airport Boulevard	Hafez Square	Parvin Etesami
9	Fadaian Islam	Emdadi intersection	Bargh Square

AVs into urban transportation systems.

Ultimately, by drawing on a combination of advanced analytical techniques, expert input, and real-world testing, the proposed AVs station locations are both practical and beneficial for the future of urban transportation. These steps will help ensure that the implementation of AVs infrastructure is effective, efficient, and widely accepted by the public.

5. Conclusion

These days, one of the important topics related to the transportation system is Autonomous Vehicles (AVs), which will drive people without any direct control by humans. Limitations such as driver tiredness, overspeeding and ignoring traffic rules do not apply to AVs since these cars can detect obstacles and avoid them. These existing problems will increase in the future with a growing population and increasing migration to urban areas in many countries. For this purpose, using AVs as a safer and more efficient type of transportation system has been proposed to improve mobility for the disabled, elderly, and also young people.

In the transportation system, stations are fixed locations for road users, determined by experts. Unfortunately, in the city of Mashhad, the stations that have been built up to date, are based on experimental models and management comments, and there is no certain mathematical model concerning traffic to determine their locations. As a result, construction of stations in inappropriate locations causes obstructions, accidents and pollution. So, examining the problem and offering suitable solutions will be particularly important in Mashhad. Therefore, in this paper, existing stations' locations were evaluated through a comprehensive review, and appropriate sites based on effective factors were suggested to develop new AVs stations. To this end, using new technologies and information analysis technology played a significant and indispensable role in managing and deciding the exact locations of stations. Using GIS and AHP indicated that accident density, with the highest weight of 0.23, and traffic, with a weight of 0.21, are two affective criteria in determining the locations of stations. In fact, accident rates and traffic congestion will reduce if an appropriate location of station is identified. As expected, station density, with a weight of 0.1, has the lowest influence on the locations of stations. Also, from the 15 selected stations, three-30 (Janbaz Boulevard), 37 (Khayyam Boulevard) and 52 (Ahmadabad Boulevard)- have some technical problems due to the lack of taxi station signs. These stations were designed according to managerial comments and economic considerations without adhering to the rules and regulations governing station locations. Thus, traffic signs, as a momentous topic, should be developed in existing stations, and they must be assimilated into both existing stations and new stations of AVs.

It is clear that the implementation of AVs will take several decades, so both manual driving and these new vehicles may coexist on the roads simultaneously. Thus, smart stations equipped with rigorous routing technologies, high-speed internet, standard traffic signs and advanced optical fibers can facilitate travel for both AVs and human drivers. Also, waiting times for passengers will be minimized in smart stations since they include real-time tracking systems, automated ticketing systems and various smart sensors to control traffic. Furthermore, the existing stations should be upgraded and standardized to connect AVs and stations, receive and send real-time information, announce arrival and departure times, reduce errors and improve the passenger experience. In fact, for the integration of AVs, some structural changes and updates to the station designs are necessary.

Air quality is another significant factor in determining optimal locations for new AV stations. The negative environmental impacts of existing transportation systems can be decreased by considering the Air Quality Index (AQI) during the location analysis of new stations. Unfortunately, picking up or dropping off passengers in stations creates traffic congestion, slows down the flow of traffic, and increases air and noise pollution. As a result, those areas with better air quality and lower pollution levels were prioritized in the present study.

The successful implementation of AVs and the use of their stations require the satisfaction and acceptance of road users. In this research, the feedback and opinions of road users were taken into account in selecting the station locations and designing them. Factors such as accessibility to stations, time-saving, enhanced travel experience, aesthetic and modern station design, adaptation to various weather conditions and infrastructure improvement should be considered. Road users expect to access stations easily and process of boarding and alighting from AVs to be fast and efficient. Additionally, the design should also harmonize with the urban environment, providing a positive impression that motivates users to use these stations. Stations should be suitable for all weather conditions, including rain, snow, or extreme heat. Based on the opinion of road users, various transportation infrastructure such as traffic signs, road markings, mapping systems, and other physical equipment need to be updated.

Moreover, public advertising, raising awareness, and educating road users on how to use AVs and smart stations, especially during the early stages of technology adoption, are crucial. Different public awareness campaigns and collaborations with community groups can increase acceptance and help overcome any skepticism regarding the adoption of AVs.

Considering the construction of smart stations for these vehicles, initial assessments suggest that the required budget for these projects is significantly lower compared to traditional transportation infrastructure. This makes the construction of AVs stations economically feasible, allowing policymakers to consider it as a viable option for future urban development.

The findings of this research provide valuable insights for organizations such as urban planning authorities and public transportation agencies. These insights can guide them in shaping future transportation policies, infrastructure investments, and projects. Involving urban planners, transportation authorities, local government agencies, and community representatives ensures that all perspectives are considered, and the project aligns with the broader goals of the city or region. Their input can help identify potential challenges or concerns, such as infrastructure readiness, user acceptance, and regulatory hurdles. By involving these groups early on, the research findings can be applied more effectively, ensuring the success and sustainability of the AV systems.

In summary, these vehicles and smart stations can remarkably improve the current transportation system in Mashhad and many large cities around the world that face similar challenges. The proposed new stations feature distinct and optimized characteristics. These stations are strategically located in less congested areas to avoid creating problems. Constructing stations equipped with smart technologies can reduce pollution, alleviate traffic, enhance the quality of transportation services, and make travel easier for all road users. Considering these explanations, it can be concluded that the proposed new stations not only address existing problems but also contribute significantly to the greater acceptance of AVs and provide a positive user experience.

CRediT authorship contribution statement

Alireza Hoveidafard: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sina Fard Moradinia:** Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Babak Golchin:** Validation, Methodology, Data curation. **Ali Ghaffari:** Software, Methodology.

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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Hereby, the authors claim that this paper is a presentation of their original research work.

Data availability

The data that has been used is confidential.

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