Implementation of Mutually Exclusive Pedestrian Accessibility Zones of the Metro on the Example of a Megalopolis

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Abstract. The article presents a novel method for assessing pedestrian accessibility zones around metro stations through the integration of isochrones and Voronoi polygons. The proposed method unfolds in four main stages: constructing isochrones, creating Voronoi polygons, adjusting isochrones to fit within Voronoi boundaries, and merging trimmed and remaining isochrones. Conducted experimental research utilizing the Moscow metro system as a case study validates the method's effectiveness. It outperforms traditional buffer zone approaches by offering improved explanatory capability and reduced prediction errors. The paper also explores how this method can be further improved by tailoring it to the unique characteristics of various metro stations. Implementing this advanced method for determining the influence zones of metro stations promises to significantly improve urban planning and transport management accuracy.

Keywords: Transit attraction zones · Isochrones and Voronoi polygons · Metro planning

1 Introduction

Forecasting metro passenger flow is a crucial aspect of planning and developing the urban infrastructure of major cities. It facilitates the optimization of metro operations, including scheduling train movements, allocating necessary resources such as trains and personnel at each station, and implementing strategies to maintain comfort in crowded stations. Such measures help to prevent overcrowding and service shortages that could disrupt the operation of a complex transportation system.

Traditional time series forecasting methods fail to account for the interaction between spatial and temporal dynamics, limiting their effectiveness primarily to short-term traffic flow predictions under typical conditions. These methods falter under anomalous circumstances [1]. For example, the development of new residential areas or the opening of the new metro stations can abruptly change passenger volumes. Consequently, long-term forecasting requires the use of techniques that incorporate spatial variations.

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Furthermore, this analysis aids in forecasting the necessity for future network expansion. Accurate predictions of potential passenger numbers are essential for deciding where new stations should be constructed. By estimating the prospective number of passengers, it's possible to identify areas that could benefit from new transportation infrastructure. Most often, analysis in forecasting is based on identifying factors influencing passenger flow. Typically, the most important factors are the population residing near metro stations and land use. Transit attraction zones are fundamental in assessing these factors, as several potential factors related to usage are usually measured based on the size of the station's catchment area [2, 3].

For instance, transit attraction zones define areas where potential passengers might reside or work and use the metro for transportation. Analysis of these zones helps to predict transit service demand and estimate passenger flow volumes at specific stations [4].

Transit attraction zones can be categorized into different types depending on the mode of access to transit stations. Specifically, access modes can be pedestrian, bicycle, bus, and automobile. The pedestrian access mode is often considered the most prevalent for various transit systems, such as urban metros. Therefore, there is a general agreement among researchers that the size of transit attraction zones should be determined considering pedestrian access (referred to as pedestrian catchment zones) [5, 6].

The rapid development of megacity transportation systems results in an expanding sphere of influence, characterized by a growing number of metro stations and an increased availability of stations withing the walking distance for passengers.

Therefore, people generally tend to use only the nearest station, even when multiple options exist within the catchment areas [7]. This leads to an increasing overlap of station catchment areas. Hence, developing methods for accurately determining catchment zones where the population concentrates is of critical importance. This article presents a new method for generating pedestrian catchment zones around metro stations. Government officials involved in urban management can apply this method both for forecasting—as the population increases in areas with high-density metro stations, the method can help determine which station is expected to experience a higher passenger flow—and for designing metro entrances that can regulate passenger flow at stations by more precisely defining their accessibility. It is also possible to determine the optimal distance between construction sites of stations to minimize overlapping zones. By applying this method, we are able to demonstrate how zones differ depending on the destination and how they change after the construction of new stations, opening of new exits, or the development of road networks.

2 Literature Review

The concept of a pedestrian influence zone is based on the assumption that there is a certain maximum time that most people are willing to spend to reach metro station entrances [8]. In contemporary studies of passenger flows, two main methods of zone delineation are commonly used: buffer based [9, 10] and Voronoi (or Thiessen) polygon construction [11]. However, both approaches have their drawbacks. For example, when using buffers, potential zone overlap is not considered. On the other hand, Voronoi

polygons may create zones where the distance to the nearest point is too large, which does not accurately reflect pedestrian accessibility.

To overcome these issues, a modification method has been developed based on constructing buffers using trimmed Voronoi polygons. This method has been actively employed in many studies [12, 13]. It has helped avoid the problem of zone overlap, but it has not completely resolved the issue of accounting for pedestrian accessibility levels. The Euclidean method, based on using buffers, typically overestimates the size of real influence zones because it does not account for road networks and natural barriers (such as rivers) and allows for straight-line distances.

To avoid fixed boundaries for influence zones, Mengyang Liu, Yuxuan Liu, and Yu Ye proposed a method, which relies on data from public bicycle usage [14]. This method involves analyzing trip information provided by bike-sharing services. This data enables the identification of the starting and ending points of users' routes for each station, thereby determining the influence zone around it. However, this method may not be suitable for determining influence zones in winter period when bicycle usage decreases and may be inapplicable in car-oriented cities lacking developed cycling infrastructure. Another attempt to avoid using buffers was the construction of isochrones in the work of Diao Lin, Ruoxin Zhu, Jian Yang and Liqiu Meng. However, as the authors themselves claim in the conclusions, the created zones may overlap with each other [15]. This means that the selected parameters (such as population and land use type) can be accounted for in both the first and second station attraction zones. As a result, we cannot accurately determine how many people will use each station, which also affects multicollinearity between variables when attempting to forecast passenger flow.

Additionally, in most studies, station centroids are utilized [9, 10, 12, 13]. Using station centroids as focal points for assessing influence zones introduces additional complexities. Centroids fail to accurately represent the actual access points for pedestrians, who mainly enter and exit stations through designated entrances and exits. This discrepancy becomes particularly evident in large, complex metro stations featuring multiple access points over wide areas. Consequently, relying on centroids may therefore misrepresent the true catchment area, resulting in a misinterpretation of pedestrian accessibility and, by extension, the station's effective service area.

The main goal of this research is to develop a method for determining pedestrian accessibility zones around metro stations that will address the shortcomings of previous approaches. This method will take into account: 1) the location of station entrances and their role as transfer hubs (in cases where multiple stations share common entrances); 2) pedestrian access influenced by the street-road network and natural obstacles; 3) the exclusion of overlapping zones.

3 Method

3.1 Method Description

Exclusion zones in pedestrian accessibility for metro stations denote areas where the nearby stations' service coverage competes without overlapping due to their deliberate division. Particularly in areas with high station density, these zones are delineated to ensure that each station exclusively serves its designated territory, avoiding overlap with

neighboring stations. The proposed method for determining zones is based on generating isochrones and Voronoi polygons. The method's scheme is presented in Fig. 1.

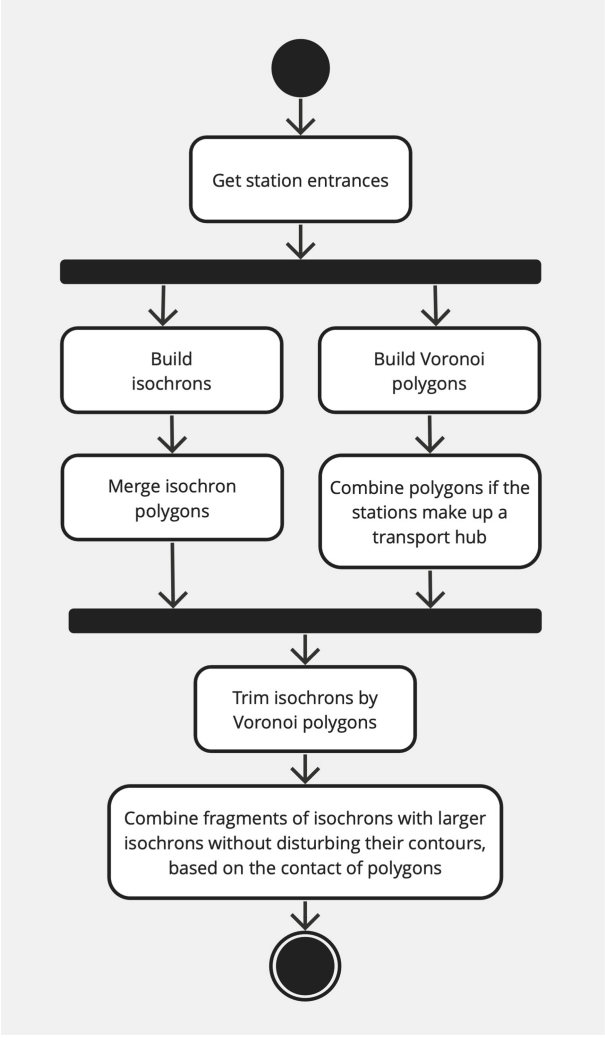


Fig. 1. Block diagram of the generation of zones of influence.

The generation method consists of four main parts: isochrone construction, Voronoi polygon construction, clipping isochrones to Voronoi polygons, and adding small sections of the original isochrones that were trimmed by Voronoi polygons. Figure 2 illustrates an example of the main stages of the method in action.

In the initial stage, isochrone generation takes place. Isochrones represent lines of equal travel time and are constructed for each entrance of the metro station. If generation is being done for the exits of a future metro station where infrastructure is not yet

developed and road networks are not established, it is advisable to construct a single buffer at 0.7 of the selected distance from the centroid of the station. This area, on average, corresponds to the area of an isochrone.

In the second stage, Voronoi polygons are constructed for each metro station entrance. These polygons define geometric areas where any point within a polygon is closer to its respective station entrance than to any other station entrance, effectively delineating the local influence zone of each entrance. The entrance polygons of metro stations belonging to the same transport interchange hub are merged into a single polygon. This decision is justified by the common scenario, when one station can be accessed from several entrances belonging to other stations, facilitating transfers.

In the third stage, the original isochrone zones are trimmed according to the boundaries of Voronoi polygons. Segments that do not intersect with the trimmed zones are transferred to a separate geolayer. This is crucial for preserving potential small areas where populations reside within walking distance of metro stations.

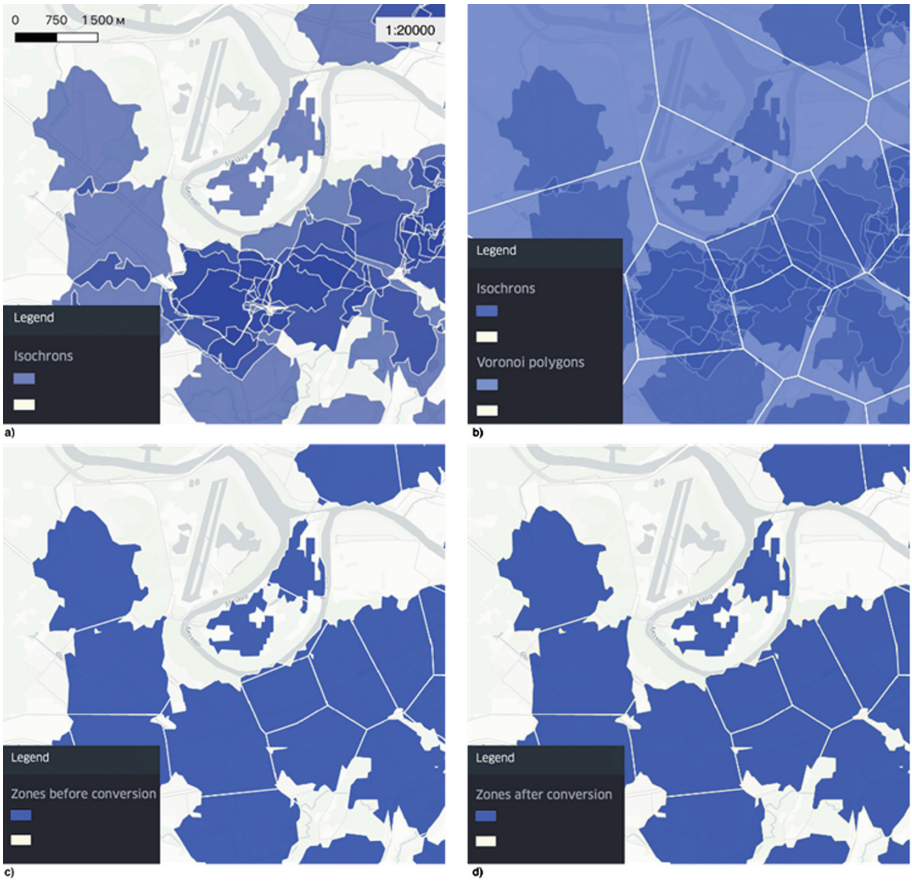


Fig. 2. The method consists of several stages: (a) isochrone generation, (b) Voronoi polygon construction, (c) clipping based on Voronoi polygons, and (d) joining clipped isochrones.

At the final stage, these zones are merged with the remaining isochrones. More details about the process are described in Sect. 3.2.

3.2 Restoration of Parts of the Original Isochrons Cut Off by Voronoi Polygons

During the trimming process based on Voronoi diagrams, a problem with mismatches between isochrones and polygon volumes emerged. This is particularly noticeable outside central areas due to lower station densities. Consequently, there are pieces of isochrones that end up inside polygons of other stations, even though they shouldn't belong to them (see Fig. 3a). To address this issue, it was decided to split the multipolygon layer into individual polygons. Two types of zones emerged: those touching entrance points and those not touching. The latter, accounting for approximately 2 to 5% of the population, introduced significant inaccuracies into the modeling results when misallocated. Therefore, in the proposed method, these fragments are merged with zones they connect with. If polygons have multiple touch points, the maximum distance from the selected ones is determined before merging (see Fig. 3b–d). This is explained by the peculiarities of isochrone construction observed at most stations with a similar situation. A larger touch size typically indicates that small fragments previously belonged to the influence zones of one transport interchange hub before trimming according to Voronoi



Fig. 3. Merging by polygon contact zone.

polygons. Additionally, the distance to station entrances for such fragments is usually shorter for polygons with a larger touch boundary.

This approach allows even small areas on the map that might have been missed or overlooked to be considered. This is helpful in determining station influence zones, which is crucial for accurate accessibility analysis and urban development planning.

4 Experimental Research of the Method

4.1 Study Area

The method was investigated in Moscow, Russia. Geodata was obtained for metro stations, the Moscow Central Circle (MCC), Moscow Central Diameters (MCD), railway stations (anticipated to integrate into new MCD lines) within the Moscow Ring Road (MKAD). Voronoi polygon boundaries were determined for construction purposes. Population data for Moscow covering both residents and employees were gathered for polygonal objects, specifically buildings, to support the analysis.

4.2 Data for Research

The initial dataset comprised point geodata of station entrances, obtained from the 2GIS platform. An online service designed for map creation, Mapbox, was employed to construct isochrones. Additionally, data regarding the annual passenger flow of stations and population density were acquired from the Moscow Department of Transport.

4.3 Building Accessibility Zones for Metro Stations

Pedestrian isochrones, covering areas within a 15-min (approximately equivalent to 1200 m) walk, were created for 1685 entrances of 351 metro stations. The selection of the threshold value is based on regional urban planning standards in the city of Moscow [16] and studies that determine the walking distance within a 15-min timeframe [17]. After trimming these zones in line with Voronoi polygons and merging polygons based on identifiers for status of transport interchange hubs, the number of zones was reduced from 1685 to 219 (see Fig. 4).

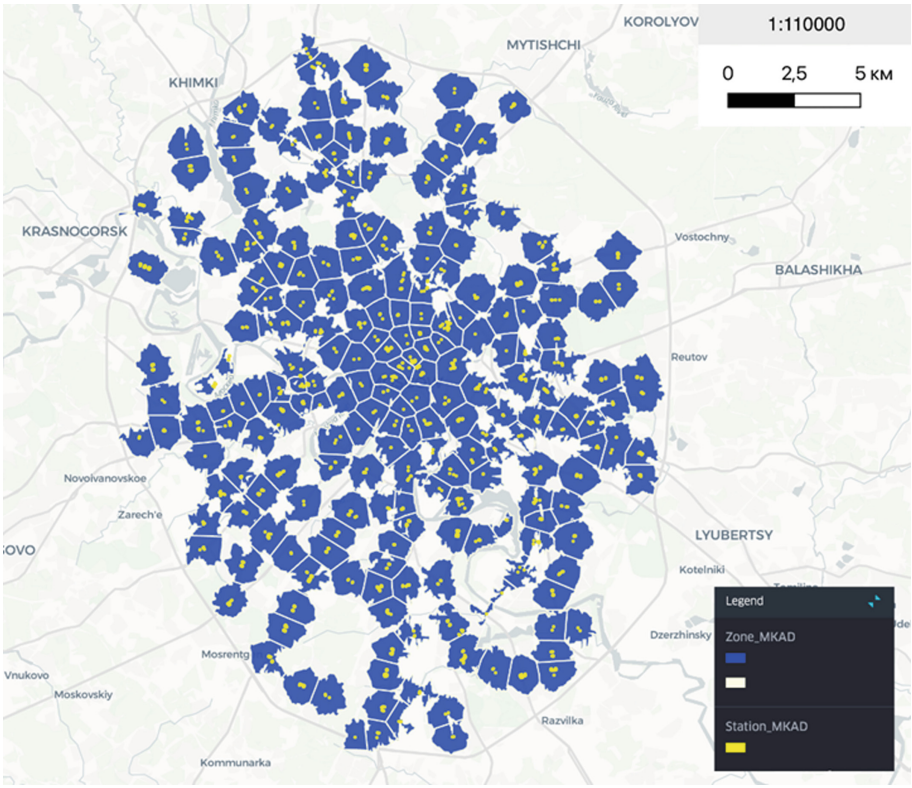


Fig. 4. Building accessibility zones for metro stations for the city of Moscow, Russia (blue – influence zones, yellow – station entrances). (Color figure online)

4.4 Evaluation of the Method

To avoid counting the population multiple times within each zone, buildings from which stations could not be accessed within the buffer zone were excluded. Consequently, the total number of people residing within a 15-min accessibility zone was reduced by 1.457.158 individuals, from 9.850.119 to 8.392.961. An illustrative case is the recently opened "Terekhovo" metro station, which is located in a former village and was until recently an uninhabited area of Moscow (see Fig. 5).

To evaluate the methodology, a passenger flow prediction was undertaken for metro stations along the Kalininskaya line within the Moscow Ring Road (MKAD), identifying a total of 7 such stations. The catchment areas of 6 stations were combined with those of other metro, MCC (Moscow Central Circle), and MCD (Moscow Central Diameters) stations to form unified transport interchange hub polygons. An Ordinary Least Squares (OLS) multiple regression model was employed, with the dependent variable being the 2023 passenger flow at the metro stations and transport interchange hubs. The choice of this model is motivated by its wide application for passenger flow forecasting [9, 10, 18]. Prior studies indicated that metro passenger flow is impacted by population density [19, 20] and land use structure [21]. Accordingly, independent variables in the analysis

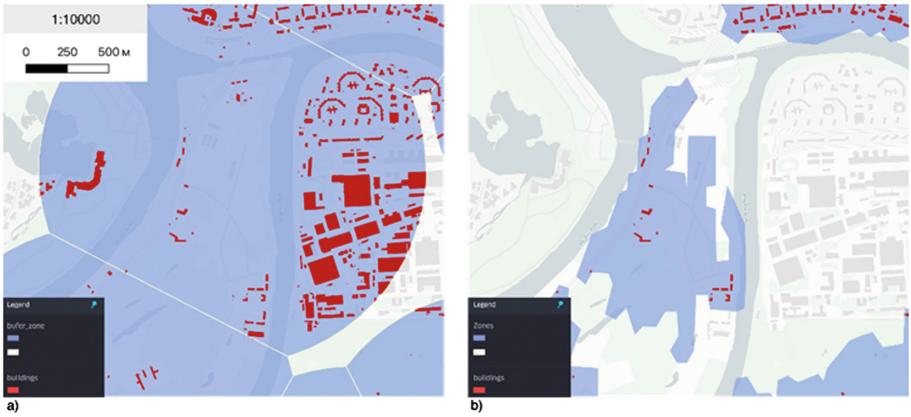


Fig. 5. The influence zone of the "Terekhovo" metro station (a – conventional method using buffers, b – proposed method).

included land use types and population density in the specified zones (see Fig. 6, input data for modeling: a, b, c – buffer method, d, e, f – proposed method). Initially, land use types such as commercial, green areas, industrial, railway, and residential zones considered.

However, in both cases, the variables "commercial," "grass," "industrial," and "residential" zones were found to be statistically insignificant, failing to meet the 0.05 significance threshold. Additionally, "commercial," "industrial," and "residential" zones exhibited high Variance Inflation Factor (VIF) values (exceeding 10), indicating high multicollinearity. It is assumed that this is related to the discrepancy between the designated land use types and their actual conditions. Currently, there are renovation zones where panel buildings are being demolished (which has been a practice in Moscow since 2017), however, these zones are classified as "residential". Additionally, there are residential complexes that have already been put into operation, and their residents were taken into account when determining population density, yet they are not classified as "residential". The same issue applies to lands classified as "industrial" - some of them have been adapted for public spaces, yet they are still marked as industrial sites. Some studies employ a different approach to land use determination – through point extraction and classification [13]. Additionally, incorporating new categories for specific uses such as administrative buildings, schools, or offices might refine land use assessments and could be explored in future studies.

The model characteristics using the proposed method are presented in Table 1. The model characteristics using the conventional method through buffers are presented in Table 2.

From Table 1 it is evident that the model based on the proposed method demonstrates a higher coefficient of determination (R-squared) of 0.929, in contrast to 0.838 achieved by the model using the conventional method (Table 2). This indicates that the proposed method better explains the variation in metro station passenger flow data. Furthermore, the Mean Absolute Error (MAE) and Mean Absolute Percentage Error (MAPE) for the proposed method are also lower, suggesting more accurate passenger

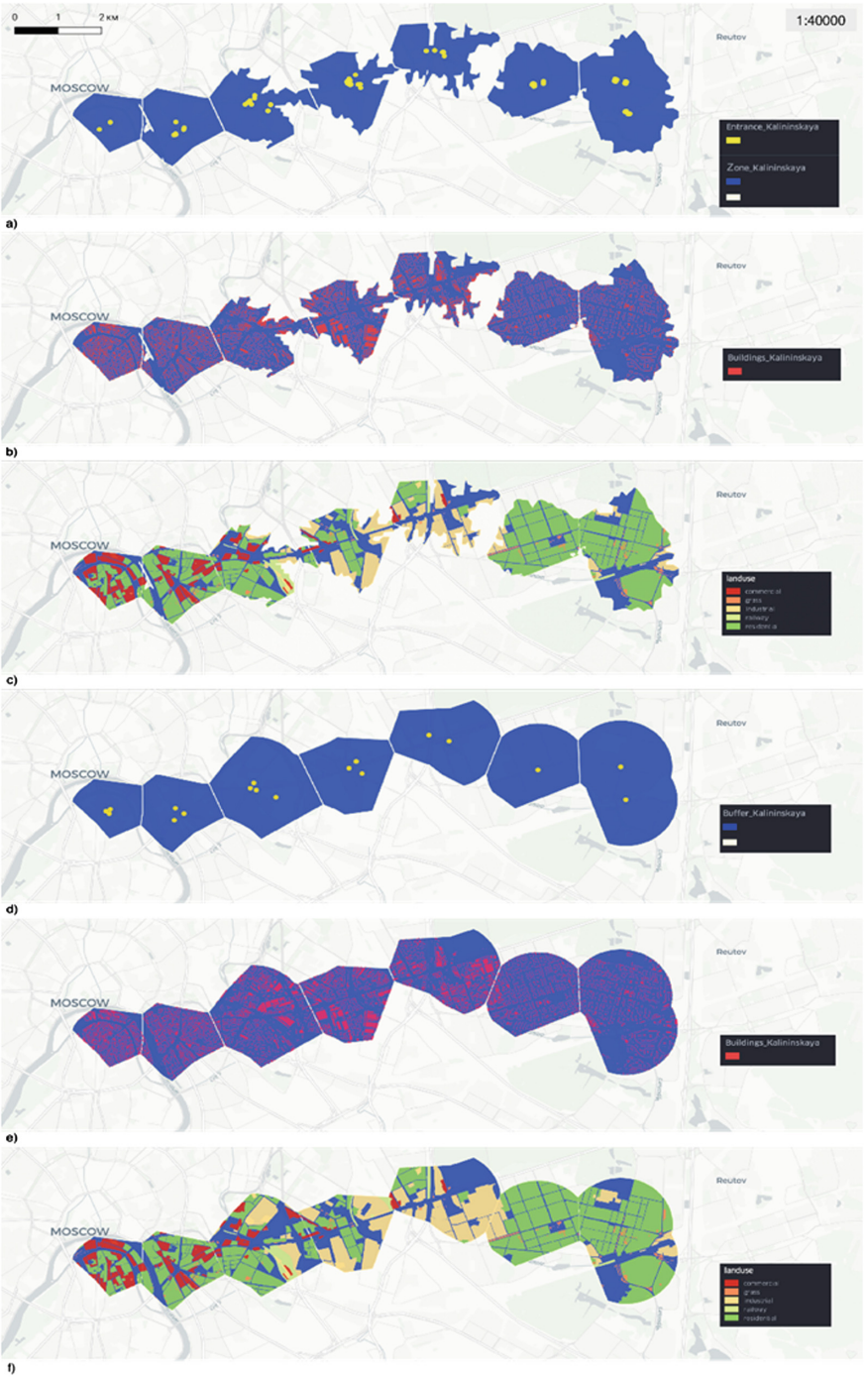


Fig. 6. Areas of influence of the Kalinskaya metro line.

Table 1. Characteristics of the model based on the proposed method of generating zones of influence of stations.

	coef	std err	t	P > |t|	[0.025	0.975]	VIF
const	0.533	0.543	0.982	0.382	-0.974	2.040	9.478
railway	0.327	0.045	7.217	0.002	0.201	0.453	1.111
populations	72.722	25.405	2.862	0.046	2.185	143.259	1.111
R-squared:	0.929	Adj. R-squared:	0.894	F-statistic	26.23	Prob (F-statistic)	0.005
MAE:	0.266			MAPE:	0.107		

Table 2. Characteristics of the model based on the generally accepted method through buffers.

	coef	std err	t	P > |t|	[0.025	0.975]	VIF
const	0.713	0.814	0.876	0.431	-1.548	2.974	9.325
railway	0.473	0.104	4.547	0.010	0.184	0.761	1.276
populations	83.106	40.223	2.066	0.108	-28.570	194.782	1.276
R-squared:	0.838	Adj. R-squared:	0.757	F-statistic	10.34	Prob (F-statistic)	0.026
MAE:	0.453			MAPE:	0.169		

flow predictions compared to the conventional method. Notably, in the model using the conventional method, the population density indicator has a p-value of 0.108 and is statistically insignificant at a significance level of 0.05.

Therefore, given the data presented, it is concluded that the proposed method of generating metro station influence zones suppresses the conventional method through buffers.

The methodology holds potential for future development, taking into account the unique significance and locations of different stations. A logical step forward would be to use Voronoi diagrams based on polygons. Station points can be replaced with polygons, the size of which would be regulated by centrality indicators or station type [22].

5 Conclusion

In conclusion, it is important to emphasize that the proposed method for determining the influence zones of the metro based on isochrones and Voronoi polygons offers a systematic and effective strategy. By utilizing these spatial analysis techniques, it is possible to accurately delineate the influence zones specific to each station entrance, thereby enhancing urban planning and transport management efforts.

By minimizing population duplication and prioritizing accessibility within walking reach, the proposed method optimizes zone delineation, leading to more accurate passenger flow forecasts. The effectiveness of this method was evaluated through experimental research conducted on the Moscow metro (Russia). Statistical analysis confirms the superiority of the proposed method, exhibiting higher explanatory power and lower forecasting errors compared to conventional buffer-based methods.

There are opportunities for further refinement and adaptation of the methodology, especially when considering the specific characteristics and requirements of various stations. Implementing centrality indicators or station types may offer additional insights and optimizations, thereby enhancing the effectiveness of metro station influence zone determination.

Disclosure of Interests. The authors have no competing interests to declare that are relevant to the content of this article.

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