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Research Article

Optimization of urban spatial planning considering isochrones of transport accessibility: The case of Aktobe city, Kazakhstan

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Abstract

The development of large cities has a significant influence on surrounding settlements. Urban areas are characterized by diversity and variability, depending on their size, function, combination of elements, and the spatial distribution of industrial and transport infrastructure. Over the past decade, due to population resettlement, urban settlements have undergone substantial transformations. However, spontaneous processes often accompany urban development, and land use efficiency remains suboptimal. The relevance of this study is determined by the necessity of analyzing urban territories as an integral part of the city. This paper presents an analysis of the structure and dynamics of suburban development in the vicinity of Aktobe. The expansion of these areas plays a crucial role in shaping the city's economic landscape and determining its growth trajectories. The study employs statistical, comparative-analytical, and isochrone methods. From a geodemographic perspective, the suburban zone of Aktobe is of particular interest due to its formation characteristics and specific spatial dimensions. The most active and attractive development occurs within a 15–30 km radius from the city center, corresponding to 40-minute and 90-minute isochrones. In recent years, Aktobe has been experiencing rapid urban growth, necessitating the resolution of key planning issues such as functional zoning, urban regulation, development of major transport infrastructure, preservation of recreational areas, and the establishment of green spaces. A SWOT analysis of the settlements surrounding Aktobe was conducted as part of the study. One of the identified strengths is the favorable transport and logistics situation. Additionally, the study evaluates other strengths and weaknesses, as well as potential opportunities and existing constraints for suburban development.

Key words: Functional zoning, geodemography, land use, regional development, settlement dynamics, sustainable development, urbanization

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1. Introduction

Currently, the differentiation of territories within the urban core and the city itself has become one of the pressing issues in economic-geographical research. Cities serve as centers of economic growth and social development, and their formation is largely associated with the transformation of adjacent

areas surrounding the urban center. Enhancing the economic efficiency of suburban zones contributes to their comprehensive development. The integration of urban and rural areas, as one of the key directions of contemporary urbanization, can serve as a foundation for addressing industrial and agro-industrial challenges, as well as for the more efficient utilization of territorial, resource, and social potential. The migration of urban residents to suburban areas is gaining increasing significance in both economic and social aspects. These areas harmoniously combine elements of urban and rural lifestyles, fostering the development of new economic links (Udahogora et al. 2021). The spontaneous expansion of large urban agglomerations highlights the analytical challenge of identifying the "real city" and improving urban planning mechanisms beyond the administrative boundaries of the city. Ensuring spatial harmony in the face of global socio-economic challenges has become a priority area of urban planning policy (Hudalah and Firman 2012). Modern cities face numerous challenges related to population growth, increasing urban density, and the need for improved transportation systems. In this context, spatial planning plays a crucial role in creating a comfortable, accessible, and sustainable urban environment. One of the promising tools in this process is the analysis of transport accessibility isochrones, which allows for the assessment of travel time across the city using different modes of transportation (Seliverstov et al. 2020). Transport accessibility determines how quickly and conveniently residents can reach key urban infrastructure facilities such as schools, hospitals, workplaces, shopping centers, and recreational areas. Uneven urban development often leads to inadequate service provision in certain districts, which can contribute to social isolation and a decline in quality of life. It is widely recognized that optimizing transport planning based on isochrone analysis can help mitigate these imbalances. Furthermore, the strategic development of transport infrastructure facilitates travel time reduction, alleviates highway congestion, and decreases traffic bottlenecks (Petrova and Grunin 2024). Amid rapid urbanization and population growth, it is essential to prioritize the efficient use of urban land, the preservation of natural areas, and the creation of a comfortable urban environment. A key focus area is the development of smart city technologies, including digital solutions for monitoring migration flows, optimizing transportation networks, and ensuring environmental control (Masoumi and Van Genderen 2024).

The use of isochrone maps enables an objective assessment of transport accessibility across different urban districts and helps identify problem areas. For instance, pedestrian accessibility analysis determines how conveniently residents can reach public transport stops and social infrastructure without relying on private vehicles. Simultaneously, the calculation of isochrones for both private and public transport allows for an evaluation of the road network's efficiency and the overall functionality of the transportation system (Śleszyński et al. 2023). Integrating such data into spatial planning helps address several critical issues: optimization of infrastructure placement—facilitating the construction of hospitals, schools, and shopping centers in locations where these facilities are most needed; balancing transport flows—redistributing traffic load across road networks and public transport to reduce congestion on specific routes; development of a polycentric urban structure—fostering multiple equally significant business and residential centers instead of excessive concentra-

tion in a single district; encouraging alternative modes of transport—promoting cycling and pedestrian infrastructure, thereby enhancing the environmental sustainability of the urban environment (Liu and Zhou 2021). By leveraging isochrone-based transport analysis, urban planning can become more strategic, leading to a more balanced, efficient, and sustainable city development. A comprehensive approach to spatial planning based on isochrone analysis enhances the efficiency of the transportation system, improves access to urban infrastructure, and increases the quality of life for the population (Forsch et al. 2021). With technological advancements, transport accessibility analysis has become more accurate and widely accessible. Geographic Information Systems (GIS), artificial intelligence, and big data processing technologies enable the modeling of various urban development scenarios, the prediction of transportation policy outcomes, and the creation of convenient, efficient, and sustainable urban environments (Yin et al. 2020). Considering isochrones of transport accessibility is an essential component of modern spatial planning. This approach not only facilitates the rational allocation of resources and enhances urban livability but also lays the foundation for the cities of the future—environmentally sustainable, livable, and functionally balanced (Cebrián Abellán et al. 2023).

At the regional level, the city's role as a regional development center is manifested in the improvement of spatial economic organization and settlement systems. This contributes to the dynamic growth of small and medium-sized cities, strengthens territorial and economic integration, and fosters the development of a modern infrastructure network. At the macro level, the city functions as a hub of interregional cooperation, facilitating integration into the global economy and international relations. It promotes economic collaboration, expands foreign economic activities, and leverages favorable territorial conditions for sustainable growth. The urban system represents an efficient form of spatial economic organization, exerting a significant influence on various economic sectors and administrative-territorial structures.

Urban spatial planning is a fundamental task of urban development, aimed at creating an efficient and sustainable urban environment. One of the critical aspects of such planning is transport accessibility, which directly influences residents' quality of life and the economic activity of urban areas. In recent years, the use of transport accessibility isochrones for optimizing territorial development has been actively discussed in scientific literature. Classical works on urban planning (Järv et al. 2018; Biazzo et al. 2019) emphasize the importance of spatial organization in ensuring sustainable urban development. Contemporary studies (Mohíno et al. 2016) focus on the integration of transport systems and spatial zoning, which helps minimize transportation costs and enhance urban connectivity. The concept of transport accessibility is extensively explored in the works of Dubovik (2013) and Cirtautas (2015), where accessibility is defined as a combination of time, distance, and the quality of transport services. Within the framework of the Transit-Oriented Development (TOD) concept (Papa and Bertolini 2015; Xu et al. 2017), urban planning policies are proposed to be centered around public transport hubs, reducing dependence on private vehicles. This approach promotes sustainable urban mobility and fosters the development of more compact, walkable, and well-connected urban environments. Isochrones (lines of equal travel time) are one of the key

tools for analyzing transport accessibility. Several studies (Sá Marques et al. 2020; Fu et al. 2022) have explored various models for calculating isochrones, ranging from simple Euclidean approaches to complex graph-based algorithms that account for real street networks and transport constraints. Contemporary research (Bhellar et al. 2023; Singh et al. 2024) demonstrates that the use of isochrones enables a more accurate assessment of access to employment opportunities, social facilities, and commercial infrastructure.

The application of transport accessibility isochrones in urban planning has been actively developing over the past decade. Studies by Vîlcea et al. (2024) illustrate how transport isochrone analysis can assist in adjusting zoning regulations and optimizing the placement of key infrastructure. Research by Phua et al. (2024) provides examples of integrating isochrones into GIS to support urban planning decisions. Isochrone analysis is a multifaceted tool that not only enhances mobility but also addresses critical urban challenges, including social inequality, traffic congestion, environmental concerns, and the development of sustainable transport systems (O'Sullivan et al. 2000). An ideal urban transport system should ensure one-hour transport accessibility to the city center from all settlements within its structure, aiming to minimize the average travel distance. The transport framework should establish an optimal grid-network structure of settlements, facilitating access to service infrastructure, enabling rapid mobility between cities and towns, and ensuring efficient territorial management (Nefedova and Treivish 2015; Makhrova et al. 2016). The most effective approach to urban transport planning today is recognized as the TOD concept, which enables residents to comfortably utilize all modes of transportation: pedestrian and bicycle networks within residential areas, private automobiles for suburban and intercity travel, and public transport for commuting to the city center. Substituting private vehicles with public transport enhances the efficiency of road network utilization by a factor of two to three (Ibraeva et al. 2020).

As a rule, the transport infrastructure of Kazakhstani cities is not designed to accommodate modern traffic intensity. Therefore, territorial planning must address several key challenges: formation of an optimal road network, ensuring minimal construction costs for new roads; improvement of the public transport system to enhance mobility and accessibility; reduction of transport load on the city center, including strategies to decrease commuter migration; development of modern, year-round external agglomeration transport links to support regional connectivity (Abilov et al. 2023; Kenespayeva et al. 2023; Sakhatbekovna et al. 2024).

The analysis of urban agglomerations is based on several key criteria, including: the presence of a central city with a defined population size; urban population density levels; intensity of commuter migration and the distance traveled between the central city and surrounding settlements; the proportion of the working-age population not engaged in agriculture; the percentage of the workforce employed outside their place of residence; the number of small towns and the degree of their functional connections with the central city; the existence of stable economic and industrial linkages; the development of a unified infrastructure system and other relevant indicators (Krzysztofik et al. 2017). These criteria enable an objective assessment of the level of integration of settlements within the agglomeration and help identify the spatial and economic characteristics of its structure. Scientific literature indicates that incorporating

transport accessibility into spatial planning enhances urban efficiency, reduces transportation costs, and balances infrastructure development. The integration of isochrone analysis into urban planning is a crucial step toward creating a comfortable, accessible, and environmentally sustainable urban environment.

2. Materials and methods

2.1. Case study area

Aktobe is one of the largest industrial hubs in the Western Kazakhstan region and serves as the administrative center of the Aktobe region. The city is situated on the banks of the Ilek River, a left tributary of the Ural River, in the central part of the Pre-Ural Ridge, with elevations ranging from 250 to 400 meters. Historically, Aktobe originated on the site of the Ak-Tobe fortress, founded in 1869 (Nurlankyzy and Beknazarov 2022). The city exhibits a complex spatial structure, comprising an old district located on the slopes of the Aktobe hill, where residential and public buildings are concentrated, and a new northwestern district, which has been undergoing rapid development over the past decades (Sergeyeva et al. 2021).

According to statistical data from 2011, the population of Aktobe exceeded 400,000 people, raising the issue of territorial division of the city into districts like those in Astana and Almaty (Fig. 1). Additionally, the Orenburg–Tashkent

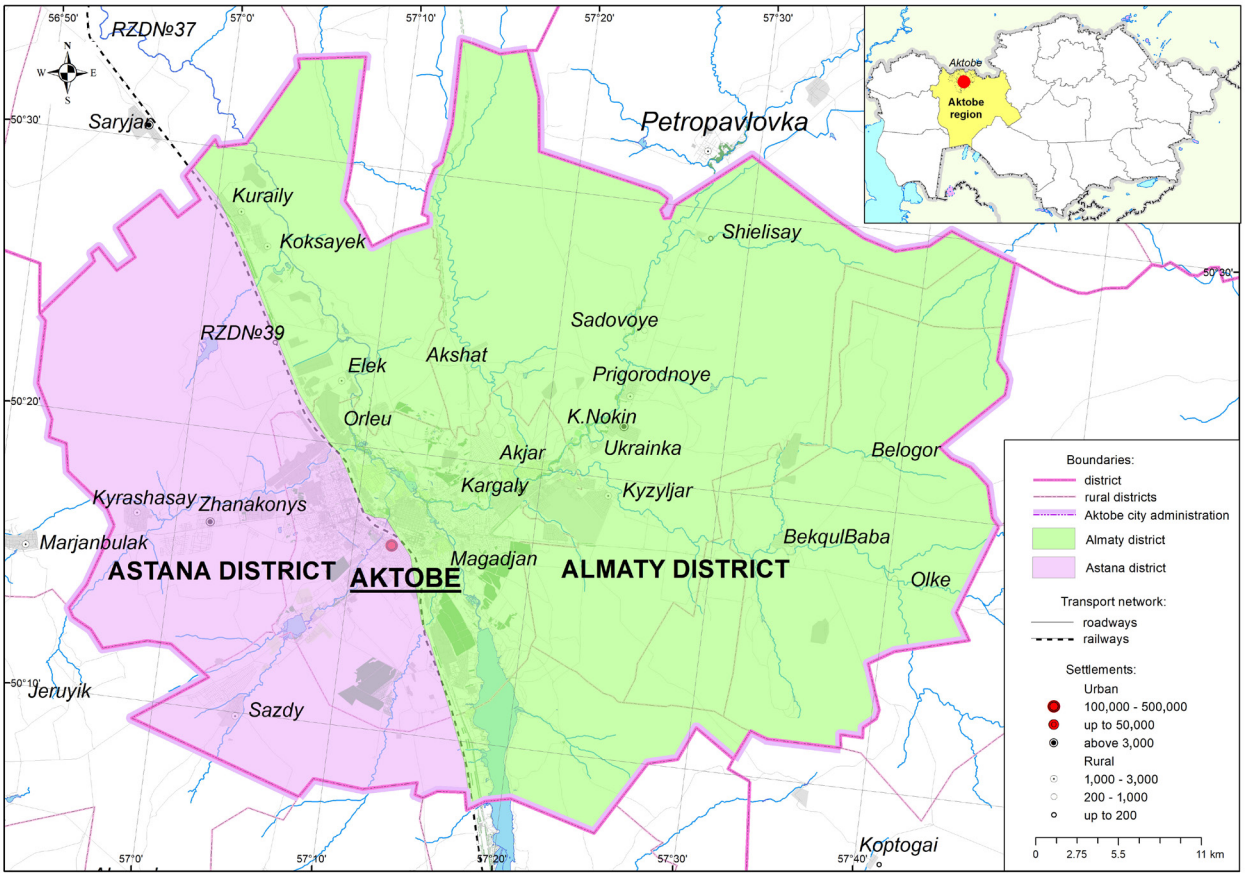


Figure 1. Case study area.

railway corridor has a significant impact on the spatial organization of the city, dividing its territory into several functional zones. The Astana District is in the western part of Aktobe. Its eastern boundary borders the Almaty District, while the northern boundary adjoins the Martuk District of the Aktobe region. The southwestern, western, and northwestern boundaries border the Alga District of the Aktobe region. The Almaty District is in the eastern part of Aktobe. Its western boundary borders the Astana District, while the northern boundary adjoins the Martuk District of the Aktobe region. The northeastern boundary borders Kargaly District of the Aktobe region, while the eastern and southeastern boundaries adjoin Khromtau District of the Aktobe region. The southern boundary borders the Alga District of the Aktobe region.

Aktobe's favorable geographical location at the intersection of key transport corridors, such as Orenburg–Tashkent and Atyrau–Aktobe, has played a decisive role in its economic development and the formation of the urban agglomeration. Initially, the city served strategic and commercial functions; however, over time, it has transformed into a major industrial and administrative center, consolidating financial flows, labor resources, and material assets within the region. Aktobe plays a pivotal role in the economic and logistical development of the region, functioning as both a transportation hub and an industrial center. Further integration of Aktobe into international economic networks through the expansion of transit corridors and the establishment of new industrial clusters will be a key driver of its future growth. A key factor that has had a decisive influence on the regional economy and its spatial development was the decision to construct a metallurgical plant in Aktobe. As a result, the city has transformed into a major industrial hub, accumulating substantial material, labor, and financial resources.

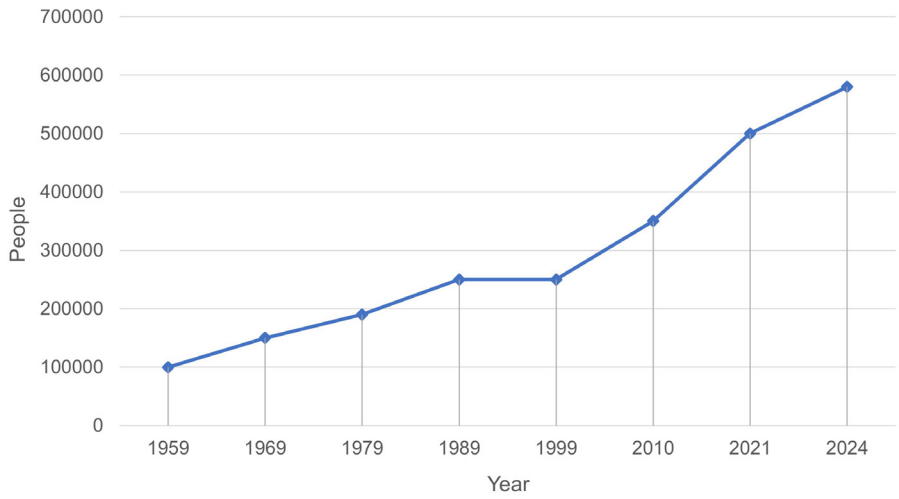


Figure 2. Population of the city of Aktobe.

Moreover, Aktobe has become a center of scientific and technological progress in the field of industrial production, further enhancing its economic potential (Official Information Source of the Prime Minister of the Republic of Kazakhstan 2018). Over the past two decades, the urban population has increased by 1.5 times, while the rural population has doubled. The average annual population growth in the city and rural districts is 9,400 people, of which

8,600 are accounted for by urban areas and 800 by rural areas. Most of this growth (70%) is driven by natural population increase, while the remaining 30% results from migration processes. The population dynamics of Aktobe and its adjacent territories are illustrated in Fig. 2. Statistical data for the period 1959–2024 were processed based on information provided by the National Bureau of Statistics (2025) of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan.

2.2. Data and methodology

The objective of this study is to identify the factors that determine the spatial dynamics of urban territories in Aktobe. To achieve this goal, the isochrone method of transport accessibility is employed to delineate the city's boundaries. The research is conducted in several stages, including identification of the potential city center, characterized by a population exceeding 100,000 inhabitants, and determination of the potential and established zone of agglomeration influence, along with an assessment of its socio-economic development. Modern cities face numerous challenges, including uneven infrastructure distribution, congestion on major transport arteries, and limited access to public transportation. In the context of urbanization and population growth, one of the primary tasks of urban planning is to develop solutions that create a convenient, efficient, and accessible urban environment.

One promising approach is the use of isochrone-based transport accessibility analysis, which evaluates how quickly residents can reach key locations within the city. This method enables optimized spatial planning, making cities more connected, livable, and functionally efficient. The method of determining city boundaries based on transport accessibility has been widely applied in scientific research since the mid-20th century (Vandenbulcke et al. 2009). Under a planned economy, the isochrone method was used to define agglomeration boundaries, considering the accessibility of the central city by private and public transport, including automobile and railway transport, within 1, 1.5, and 2 hours (Dorofeeva 2016). In international practice, a widely used method is based on statistical analysis of population size and the dynamics of commuter migration between the central city and suburban settlements. This approach defines urban agglomeration boundaries based on the smallest administrative-territorial units for which statistical data are available (Nefedova and Treivish 2021).

Isochrones are lines on a map that connect points reachable within the same travel time. They help define accessibility boundaries for different urban districts, considering travel speeds across various transportation modes. Various methods are used to determine transport accessibility isochrones, including spatial analysis, transport modeling, and GIS. Modern GIS tools, such as ArcGIS and Google Maps API, enable the visualization of isochrones and the analysis of their impact on the urban environment (Miller and Bridwell 2009). To develop a detailed transport accessibility model for Aktobe using isochrones, several key analytical stages must be followed.

The first stage involves data collection and preparation. It is essential to gather information on the city's road network, utilizing open sources such as OpenStreetMap. These data are then integrated into a GIS platform, where they undergo preliminary processing and preparation for further modeling. The next

stage involves defining transport characteristics. At this stage, each segment of the road network is assigned attributes such as speed and surface type, allowing for a more accurate representation of real travel conditions. Additionally, existing traffic restrictions, such as one-way streets and prohibited turns, are incorporated into the analysis, making it more precise and realistic. During the transport accessibility modeling stage, network analysis tools in GIS are utilized to generate isochrones—lines representing zones that can be reached within equal travel time from a given point. The time intervals for isochrones are selected based on the research objectives, enabling the evaluation of accessibility to key infrastructure facilities.

In the context of increasing urbanization and rising traffic density, it has become essential to consider not only distance but also road congestion levels when planning transportation routes. To achieve a more accurate assessment of transport accessibility, the Bureau of Public Roads (BPR) model is utilized, allowing for the evaluation of traffic impact on travel time. The BPR model is employed to estimate road congestion and is represented by the following equation (1):

$$T = T_0 \times \left(1 + \alpha \left(\frac{V}{C}\right)^{\beta}\right) \quad \text{(eq. 1)}$$

Where:

T_0 – the base travel time in the absence of congestion,

V – traffic volume (number of vehicles),

C – road capacity.

α, β – empirical coefficients (typically α = 0.15, β = 4).

This model enables the prediction of increased travel time as road congestion intensifies. Calculations based on the BPR model indicate that travel time increases compared to baseline estimates due to the incorporation of congestion effects. Over short distances (up to 20 km), the difference between calculated and adjusted travel time is minimal, increasing by only 1–2 minutes. Over medium distances (20–40 km), the difference becomes more pronounced, with an average increase of 5–7%. Over longer distances (exceeding 40 km), congestion effects become most significant, leading to a difference of up to 10–15%. The type of road infrastructure significantly influences travel time increases: minor roads (serving settlements within a 10–20 km radius) exhibit the highest increase in travel time due to their low capacity (800 vehicles per hour) and high traffic density; medium-sized roads (spanning 20–40 km) experience moderate congestion, yet still exhibit an increase in travel time due to traffic flow; major roads (40+ km) with high capacity (3,000 vehicles per hour) demonstrate a relatively smaller increase in travel time. However, congestion effects become noticeable as traffic volume rises.

Following Clause 73, Chapter 10 of the Traffic Rules of the Republic of Kazakhstan, the maximum permitted speed limit in populated areas, including Aktobe, is 40–60 km/h (Regulatory Legal Acts of the Republic of Kazakhstan 2010). However, the actual average speed may be lower due to factors such as road conditions, traffic intensity, the presence of traffic lights and pedestrian crossings, and weather conditions. The application of this formula allows for the assessment of transport accessibility across different districts of Aktobe. The final stage involves the analysis and visualization of the collected data.

Isochrone zones are examined in terms of their territorial coverage, and areas with insufficient transport accessibility are identified. Based on these findings, decisions can be made regarding the modernization of the transport network, the development of new public transport routes, or the improvement of existing infrastructure. Thus, the proposed approach provides a comprehensive assessment of transport accessibility across various districts of Aktobe, enabling data-driven decision-making to optimize urban infrastructure and enhance mobility convenience for residents.

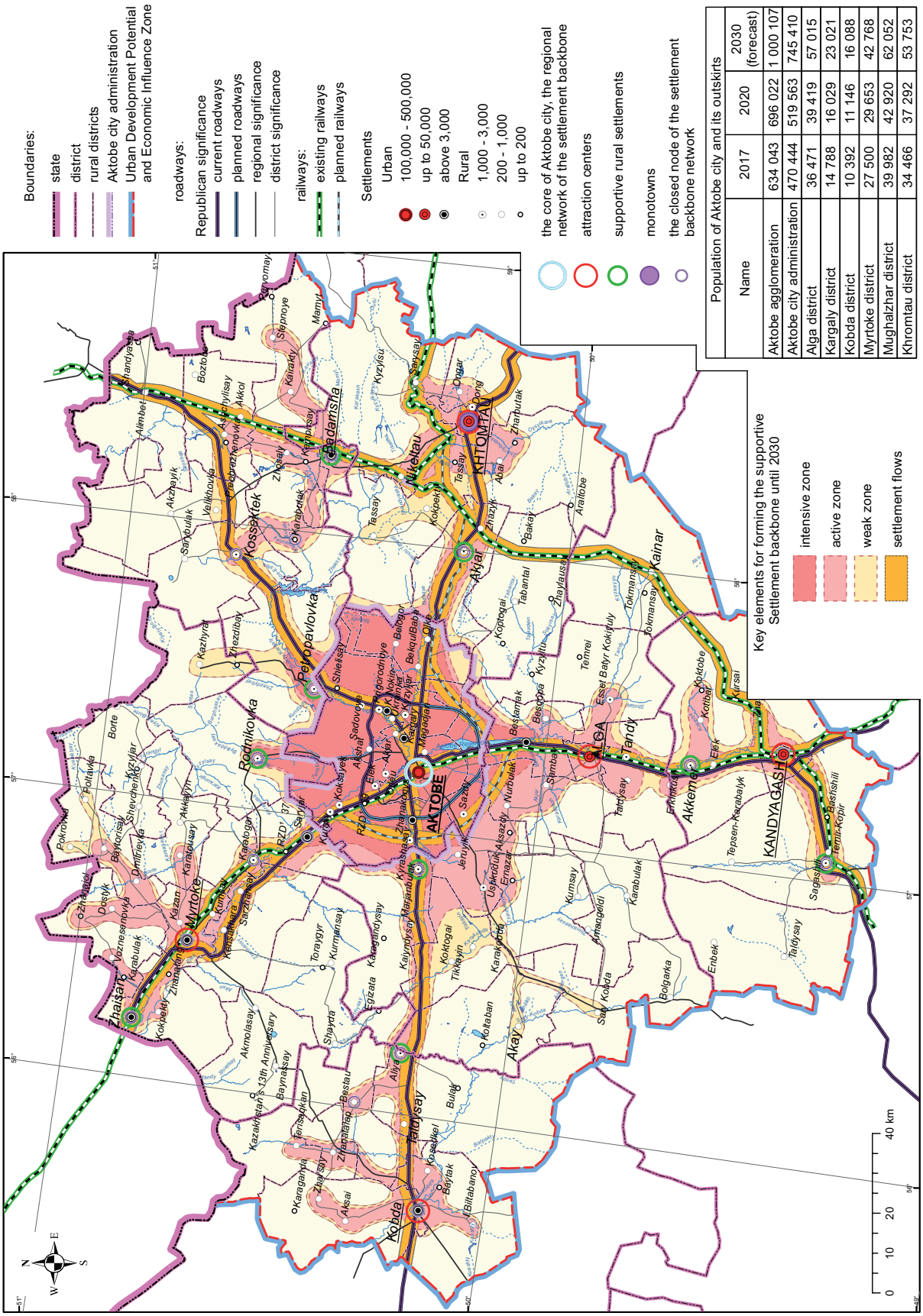
3. Results

The coordination of intersectoral interests in the development of Aktobe, the functional zoning of its territory, and the establishment of special urban planning regulations considering land distribution are key aspects of agglomeration planning. A comprehensive approach considers various types of urban areas, including residential zones, industrial districts, major transport infrastructure, recreational spaces, and green belts. Special attention is given to the balanced development of the city's central core, suburban areas, and transport-infrastructure hubs.

One of the key challenges in Aktobe's urban development is the spatial heterogeneity of settlement patterns, which complicates the effective formation of agglomeration processes. The central part of the city is characterized by high population density, whereas the occupancy levels of peripheral areas depend directly on the accessibility of transport corridors and the quality of infrastructure. According to international experience, uneven population distribution within the urban environment is one of the factors limiting sustainable urban development. This study presents the settlement system of Aktobe and its suburban zones (Fig. 3).

In the 1990s, there was significant migration of the population, particularly young people, from settlements in the Aktobe region that were experiencing economic decline, toward more developed urban areas. In recent years, migration patterns have shifted, with an increasing number of residents from the Kyzylorda, Mangystau, Atyrau, and West Kazakhstan regions relocating to Aktobe. Migrants are attracted not only to major cities, such as Aktobe and Khromtau, but also to nearby settlements.

Scientific and technological progress has had a profound impact on the territorial organization of economic activity, facilitating the formation and expansion of agglomeration processes. This progress has contributed to industrial diversification and the implementation of advanced organizational models, such as industrial clustering and production cooperation, which influence the location of industrial facilities and promote the development of strong linkages between production centers and settlements. In Aktobe, the creation of a full-cycle ferrous metallurgy industry has served as a foundation for the emergence of a large-scale industrial complex. In the modern economic landscape, industrial development requires close collaboration with educational and research institutions. The establishment and growth of higher and specialized secondary educational institutions in Aktobe and Khromtau have played a key role in supplying the industrial sector with skilled personnel and conducting scientific research aimed at improving production efficiency. Under the influence



Population of Aktobe city and its outskirts			
Name	2017	2020	2030 (forecast)
Aktobe agglomeration	634 043	696 022	1 000 107
Aktobe city administration	470 444	519 563	745 410
Alga district	36 471	39 419	57 015
Kargaly district	14 788	16 029	23 021
Kobda district	10 392	11 146	16 088
Myrtoke district	27 500	29 653	42 768
Mughalzhar district	39 982	42 920	62 052
Khromtau district	34 466	37 292	53 753

Figure 3. Population settlement system of the Aktobe and its suburbs.

of these factors, a distinct spatial structure has emerged, shaping a system of various interconnections between settlements. A defining characteristic of urban agglomerations is the territorial proximity of settlements clustered around a central city (or multiple centers) and their functional complementarity, which ensures the comprehensive development of the region.

The Aktobe agglomeration encompasses the territories of five districts—Alga, Kargaly, Martuk, Mughalzhar, and Khromtau, as well as the administrative boundaries of the city of Aktobe. These areas are situated within the same one-hour isochrone distance and include 70 settlements, among them two small towns, Alga and Kandyagash, the monotown of Khromtau, and Aktobe itself. The total area of the agglomeration is 4,800 km², with a population of 512,400 people, accounting for 72% of the total population of the region (as of 2024) (National Bureau of Statistics 2025). Under the Aktobe City Development Project and the Territorial Development Program for 2021–2025, comprehensive measures have been planned to ensure water supply, gasification, modernization of transport infrastructure, and reduction of unemployment in the settlements. Additionally, the program includes initiatives aimed at improving the environmental situation in the region and preventing potential emergencies.

In 2013, the central administrative boundaries of Aktobe included five rural districts comprising 22 settlements: Blagodarsky rural district—11 villages; Kargalinsky rural district—three villages; Kurgailinsky rural district—five villages; Zhanakonys rural district—two villages; Sazdy rural district—one village (Official Information Source of the Prime Minister of the Republic of Kazakhstan 2020). Additionally, the city consists of several residential districts, including Gorodishche, Vozdushny Gorodok, Yugo-Zapadny, Zarechny, Kargalinsky, Kirpichny Zavod, Akzhar, Bratya, and 41st Razyezd, among others. Since the early 2000s, more than 30 new residential districts have been established. In 2012, construction of the Nur-Aktobe micro district was completed, comprising five residential neighborhoods with a total population of approximately 260,000 people.

The General Plan for the Development of Aktobe envisions the formation of several planned districts, incorporating both residential and industrial zones: the Elek District (central part of the city), the Kargaly District (east of the Elek River), the Eastern District (east of Kargaly), the Western District (west of the Elek District), the Northwestern Industrial Zone, and the Southern Transport and Utilities Zone.

The boundaries of these districts are defined by major arterial roads with high traffic intensity, which are connected to external highways, as well as by natural landscape features such as ravines, reservoirs, and rivers. The suburban area of Aktobe encompasses a radius of 18–25 km from the city center. According to the urban planning project, the nearest boundary of the city core's influence zone is set at 18 km. Within the framework of agglomeration analysis, the inner urban area is defined by a radius equivalent to the size of Aktobe's central part. Settlements located beyond 60 km are classified as part of the outer agglomeration zone, with its boundaries determined by the administrative division of the region. A key factor in the development of urban settlements is transport accessibility and the level of transportation infrastructure.

To evaluate temporal accessibility using the isochrone method, three zones were identified: the first zone—a 30-minute (0.5-hour) isochrone relative to the boundary of the urban core; the second zone—a 1-hour isochrone; the third

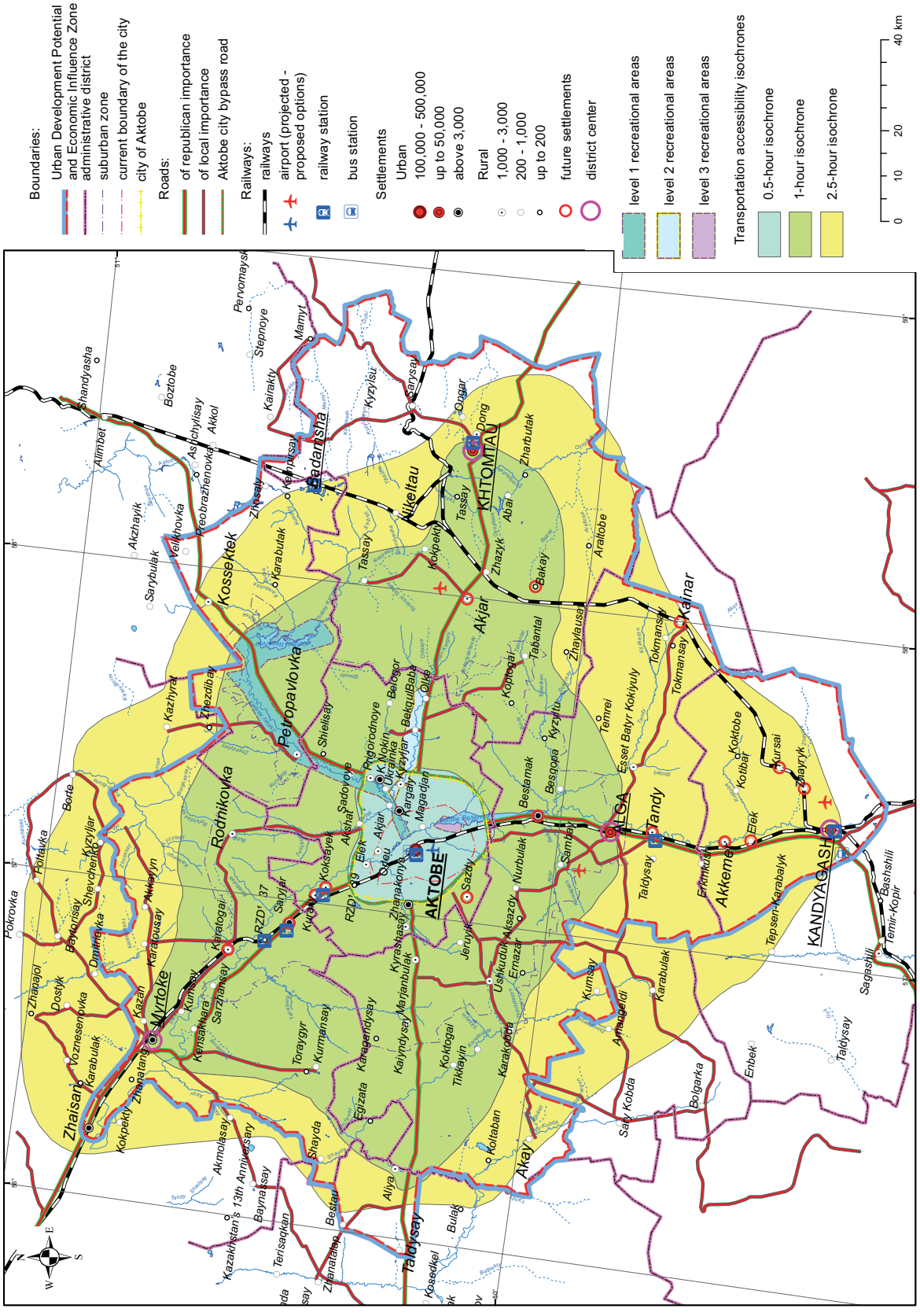


Figure 4. Isochrones of accessibility for the Aktobe city centre.

zone—a 2.5-hour isochrone, encompassing medium-sized and large cities located near Aktobe's boundaries. In the transport accessibility analysis, a 2-hour isochrone to the city center was used in combination with a 30-minute isochrone for medium-sized and large settlements. The standardized methodology for assessing transport accessibility assumes a 1-hour travel interval to a major urban center, along with the calculation of distances from the periphery to the center, considering a 30-minute accessibility threshold.

Three primary transport accessibility boundaries have been established for Aktobe: 0.5-hour accessibility—the optimal travel time for public transport within the urban agglomeration; 1-hour accessibility—reflects the influence of the urban center on nearby settlements; 2-hour accessibility—characterizes connections with remote settlements and medium-sized cities in the region. The intersection of 1-hour isochrones demonstrates the formation of agglomeration linkages between the following cities: Aktobe–Khromtau; Aktobe–Martuk; Aktobe–Alga. Meanwhile, the 2-hour isochrone reflects interactions with more distant settlements, except for Kandyagash. However, connections between districts within the region remain unevenly developed, and in some cases, absent. The transport accessibility isochrones for Aktobe's city center are presented in Fig. 4.

4. Discussion

The central core of Aktobe forms the foundation of the city's territorial organization. The city exhibits a heterogeneous spatial structure, which varies depending on building types, population density, road network density, and settlement distribution.

Fig. 5 shows the comparison of the travel time from the city center to the base (basic) and BPR model (considering road load) for settlements at different distances from the city of Aktobe. Based on this graph and text, the following analysis can be made.

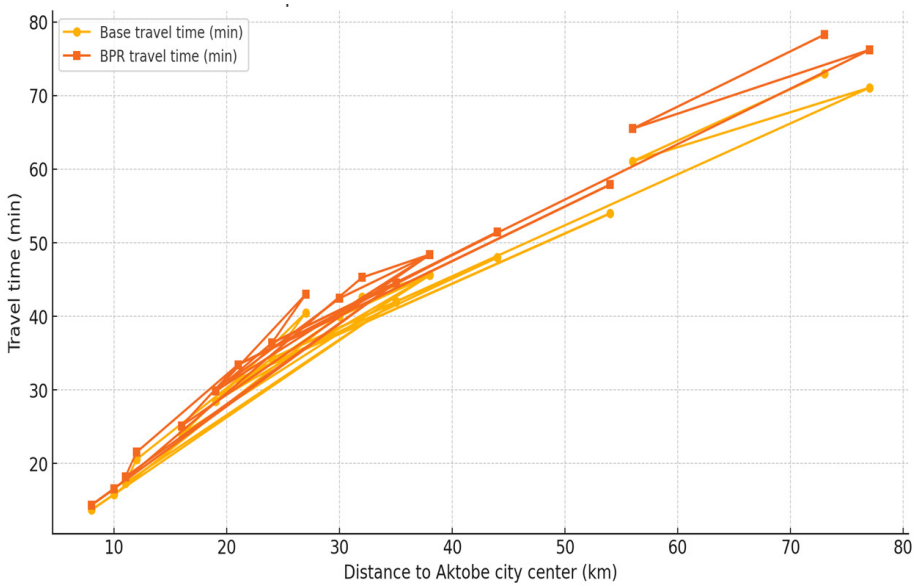


Figure 5. Comparison of base travel time and BPR model.

The vertical axis (y-axis) represents travel time in minutes, while the horizontal axis (x-axis) indicates the distance in kilometers from the center of Aktobe; the yellow line depicts the base travel time under normal free-flow traffic conditions, and the orange line shows the BPR model-estimated travel time, which accounts for traffic congestion—in all cases, the BPR-based travel time exceeds the base time, reflecting the impact of traffic density and infrastructure load.

Three transportation accessibility zones around Aktobe are determined based on the results of the analysis. The first zone (30–55 minutes, 15–45 km) encompasses settlements such as Sazdy, Akzhar, Kyzylzhar, Ukrainka, Kurashasay, and Zhanakonys. This zone is highly convenient for daily commuting to the city, with relatively stable travel time (though showing a slight increase according to the BPR model) and is highly integrated through close socio-economic ties with the city, forming part of the suburban belt. The second zone (~1 hour, 45–65 km) includes 17 settlements in Martuk District (26% of the agglomeration), the cities of Alga and Khromtau, and some settlements in Kargaly District. This zone has a very high proportion of the workforce commuting daily to Aktobe (50% of the working-age population), but travel times exceeding one hour make the impact of traffic congestion evident, and improving transport infrastructure could significantly enhance the efficiency of labor migration. The third zone (~2.5 hours, 70–80 km) covers the city of Kandyagash and remote settlements in Khromtau and Kargaly Districts. Here, commuting times are long, transport infrastructure is weak, and connections with the agglomeration are weak or possibly only seasonal, resulting in significantly slower urbanization processes. These zones demonstrate substantial differences in the intensity and density of connections with the center of the Aktobe agglomeration.

The agglomeration structure and cause-effect relationships are exemplified by the specific case of Martuk District, where high commuting levels to Aktobe (with 50% of the working-age population traveling daily) are driven by its rural population of 10,149, its distance of 81 km to Aktobe, making commuting to the central city more economically viable than to other urban centers, and Aktobe's role as the agglomeration core concentrating employment and economic opportunities. This dynamic occurs within a broader peri-urban structure comprising 48 settlements near Aktobe, distributed with 16 in the Khromtau area, 17 in the Martuk district, nine near Alga, and eight in the Kobda district; this spatial pattern corresponds to a "radial-integrative model" of agglomeration, characterized by transport corridors radiating from the city center that exhibit higher economic activity due to enhanced accessibility.

In conclusion, transport accessibility and travel time are key indicators of socio-economic integration within the agglomeration. The increase in travel time (as per the BPR model) highlights either inadequate road infrastructure or high traffic loads. Although areas like Martuk show a high level of integration with Aktobe, infrastructural barriers persist. Modernizing transport infrastructure is a crucial condition for ensuring sustainable agglomeration development and enhancing population mobility.

A key characteristic of Aktobe's development is the rapid expansion of suburban areas. To identify the factors influencing the formation of the suburban settlement network, it is necessary to consider the following key criteria, which shape the directions of development both within the city and beyond:

natural-geographical factors—topography, water bodies, forests, soil types, vegetation, land resources, and mineral deposits; industrial-economic factors—location of industrial facilities and economic linkages between settlements; socio-demographic factors—population growth rates and demographic composition (age and gender distribution); social and cultural infrastructure—availability of social, cultural, and public services; environmental factors—level of environmental pollution and impact of industrial zones; transport infrastructure—development of road and railway networks, as well as access to public transportation.

Among the key factors influencing the formation of suburban settlement networks, natural-geographical factors such as topography, water bodies, forests, soil types, vegetation, land resources, and mineral deposits are considered the main criteria that shape the direction of development both within the city and in its surrounding areas. Therefore, to provide clarity for the reader, it is important to briefly describe the positive or negative impacts of these factors on the development of suburban settlements.

Table 1. The settlements in the suburban zone of Aktobe.

Name of the settlement	Population (number of people)	Distance from the city center (km)	Distance in time from the city center (minutes)
Kenes Nokin	5,568	21	29
Akshat	640	16	23
Belagorka	304	38	68
Bekkul-Baba	1,131	30	41
Kyzylzhar	2,268	19	28
Prigorodnoe	2,169	24	31
Sadovoe	753	27	33
Ukrainka	560	19	28
Olke	269	38	50
Shielisai	122	32	37
Kargaly	20,805	10	19
Magadzhan	643	8	16
Kurajly	8,272	35	44
Orleu	2,367	11	19
Zhanakonys	10,385	12	25
Kurashasai	2,094	21	33
Alga	23,459	54	70
Sazdy	4,447	21	30
Eset Batyr	1,576	44	62
Bestamak	3,453	35	46
Marzhanbulak	1,559	24	30
Saryzhar	4,604	35	46
Karatogai	1,700	77	89
Sarzhansai	800	56	57

Topography: The city's location on the Pre-Ural Ridge (elevations 250–400 m) likely concentrated early development on gentler slopes (e.g., old district on Aktobe hill), while newer expansions (e.g., northwestern districts) targeted more manageable terrain.

Water bodies: The Ilek River historically anchored the city's founding. Suburbs likely emerged along its banks for water access but avoided low-lying flood-prone zones.

Forests: Green belts/recreational zones in Aktobe city (mentioned in planning) suggest that forests were preserved in the suburbs, pushing development toward open areas.

Soil types and vegetation: Agro-industrial potential of Aktobe city (SWOT analysis) implies that fertile soils in some suburbs may have been protected from sprawl, directing growth to less fertile lands.

Land resources: Chaotic suburban growth of the city (noted in the study) partly resulted from the uncoordinated use of available land, leading to inefficient sprawl.

Mineral deposits: Resource-rich areas attract industrial clusters and worker settlements but may limit residential appeal due to pollution/noise. Mining zones often become monotowns (e.g., Khromtau near Aktobe). The metallurgical plant drove industrial satellite towns (e.g., Khromtau), while mineral-rich zones likely dictated industrial zoning in the suburbs.

In conclusion, physical geography acts as a foundational framework for suburban growth, it dictates where development is feasible, cost-effective, and sustainable. In Aktobe, leveraging favorable terrain while respecting ecological constraints could have mitigated chaotic expansion. Planners must prioritize these factors to balance growth with resilience.

The high rate of demographic growth and migration influx toward Aktobe has shaped the following territorial settlement systems: Western system—centered around Kobda village, including eight settlements; Southern system—centered around Kandyagash city, including eight settlements; Eastern system—centered around Khromtau city, including 16 settlements; Northern system—centered around Martuk village, including 17 settlements.

Aktobe serves as the primary agglomeration center, driving the development of surrounding areas through a multi-level system of socio-economic interactions. Suburban towns and settlements play a crucial role in providing affordable housing for migrants from rural areas. These settlements are characterized by rapid physical expansion and significant urbanization rates. The residential location choices of migrants in suburban villages are largely determined by their economic capabilities.

Despite rapid and uneven changes in the socio-demographic composition of suburban areas, these zones often become concentration points for low-income populations, including urban professionals living in informal settlements. The rural districts and settlements adjacent to Aktobe possess unique spatial characteristics, influenced by their territorial proximity to the city. This distinguishes them not only from other rural areas but also from settlements on the urban periphery. Key spatial characteristics influencing the development of rural and suburban settlements include population size and growth rate; distance from the city center of Aktobe; proximity to major highways; share of urban population within the overall settlement structure; extent of land use for

non-agricultural purposes; origin of migrants and their socio-economic status. Table 1 presents the population size of suburban settlements located near Aktobe, as well as their distance from the city center.

Suburban towns and settlements provide residents with a wide range of socio-economic opportunities, fostering a favorable environment for the migrant influx and contributing to positive population growth dynamics. The interaction between urban and suburban populations influences housing conditions, service consumption levels, and the development of urban infrastructure.

As a major industrial center in Kazakhstan, Aktobe exerts a significant influence on adjacent urban and rural settlements. One of the key factors driving the attractiveness of suburban areas is their proximity to major transport corridors, which connect the city with its surrounding districts and ensure transport connectivity between cities and settlements.

One of the key directions in Aktobe's territorial development is the expansion of the suburban real estate sector. A real estate market is emerging around the city, necessitating an analysis of demographic pressure on suburban areas and their transport infrastructure. The geographical distribution of suburban settlements is shaped by both natural and economic factors, including the development of transport infrastructure, proximity to rural or urban settlements, and natural and landscape attractiveness of the area.

There are approximately 11 cottage settlements in the vicinity of Aktobe, located at varying distances from the city. Spatial analysis of suburban settlements indicates that the majority are concentrated along railway and highway corridors. In most cases, cottage settlements are situated near existing populated areas, which can be attributed to the availability of engineering and social infrastructure.

Table 2. SWOT analysis of the development of Aktobe's suburban areas.

Strengths	**Weaknesses**
Favorable economic-geographical and transport-logistics location	Shortage of drinking water
Agro-industrial potential	Poor road conditions
Recreational potential	Lack of specific programs for waste processing, disposal, and landfill management
Production of construction materials	Limited opportunities for the development of alternative energy sources
	Underdeveloped engineering infrastructure
Opportunities	**Threats**
Development of residential construction	Deterioration of the environmental situation
Growth of small, medium, and large businesses	Barriers to entrepreneurial development
Favorable conditions for the establishment of new industries	Poor development of the public transportation system
Opportunities for the construction of technology parks	Failure to formalize agglomeration mechanisms and utilize their potential
Conditions for the development of training centers for specialists	Lack of a unified policy for the socio-economic development of the agglomeration

The suburban zone of Aktobe is developing in a chaotic manner, largely due to the absence of a unified urban planning regulation system. Incoherence in land resource management results in inefficient use of vacant areas and spontaneous residential development.

Population growth in suburban areas will inevitably lead to increased pressure on transport infrastructure, necessitating further expansion of road networks and public transportation systems to ensure the sustainable development of the agglomeration.

A SWOT analysis of Aktobe's suburban areas has identified their strengths, weaknesses, opportunities, and threats (Table 2).

5. Conclusion

An analysis of contemporary scientific research indicates that issues related to the spatial organization of cities, their role in regional production and settlement systems, and the comprehensive development of regions remain insufficiently explored. Migration processes between urban and suburban areas form the foundation for urban structure development and the creation of a unified, compact space. The study of these processes is crucial both for the optimal allocation of labor resources and for assessing the impact on transport and environmental systems. Moreover, these processes contribute to the formation of new spatial settlement models.

Aktobe occupies a strategically important geo-economic position, serving as a multi-communication hub that connects the central, southern, and northern growth centers of Kazakhstan. This creates favorable conditions for the development of satellite cities, the formation of a linear settlement pattern, and the expansion of the urbanization zone. At present, Aktobe continues to develop a core spatial structure, reflecting the spatial organization of population distribution and economic activities. The transformation of nodal and network elements of the urban system facilitates the gradual development of all territorial positioning levels, from the regional to the national scale. Under conditions of high road congestion, actual travel time can differ significantly from the estimated calculations. This factor must be considered when planning urban transportation routes. The highest traffic load is observed on roads within 20–40 km of the center of Aktobe. These sections require additional measures to alleviate congestion, such as road expansion, the creation of additional traffic interchanges, and the development of public transportation.

Suburban settlements with high commuting activity (Alga, Khromtau, Sazdy) experience a significant increase in travel time. This may harm their economic activity and the quality of life for residents. A key direction for development at this stage is the construction of new transport corridors and the formation of a second-tier agglomeration in Aktobe. This process contributes to the region's integration into national and international markets through the development of prospective industrial and innovation-driven economic zones, thereby accelerating cluster formation and economic diversification.

Future research could focus on a detailed analysis of transport flows, the impact of urbanization on the environmental situation, and the efficiency of urban resource management. The development of Aktobe and its suburban areas requires a comprehensive and strategic approach, considering social, econom-

ic, environmental, and infrastructural factors. The formation of a sustainable urban system will not only enhance the quality of life for residents but also strengthen the city's position in both regional and international contexts.

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Data availability

All of the data that support the findings of this study are available in the main text or Supplementary Information.