CHANGES IN THE POPULATION DISTRIBUTION AND TRANSPORT NETWORK OF SAINT PETERSBURG

L. Xiaoling[*]
A. A. Anokhin[**]
A. V. Shendrik[**]
X. Chunliang[***]

The authors explore the interdependence between demographic changes and transport network centrality, using Saint Petersburg as an example. The article describes the demographic data for the period 2002—2015 and the transportation network data of 2006. The authors employ several methods of demographic research; they identified the centre of gravity of the population, produce the standard deviational ellipsis and use the kernel density estimation. The street network centrality of Saint Petersburg was analyzed using the Multiple Centrality Assessment Model (MCA) and the Urban Network Analysis Tool for ArcGIS. The analysis of the population distribution in Saint Petersburg shows that each area of the city has seen their population grow over the last thirteen years. However, the population of suburban areas increased the most. The core area of the city has the tendency of outward diffusion, and the population gravity centre has been moving northwards. Spatial characteristics of the population growth, changes in the population gravity centre, the standard deviational ellipse and characteristics of the street network centrality show that Saint Petersburg is at the final stage of urbanization and its development pattern is similar to that of other major cities.

Key words: population distribution, population density, street network centrality, Saint Petersburg

Introduction

Changes in urban population distribution reflect the state of the economy and the expansion and restructuring of space. Urban transport is the backbone of a city's internal space and it plays an important role in developing the urban spatial structure [12, 14].

The US researcher Ray M. Northam, a specialist in urban geography,

[*] Northeast Normal University,
5268 Renmin St., Changchun,
130024, China
[**] Saint-Petersburg State University
7—9, Universitetskaya nab.,
St. Petersburg, 199034, Russia
[***] Northeastern University,
3—11 Wenhua Road, Shenyang,
110819, China.

Submitted on August 17, 2016.

doi: 10.5922/2079-8555-2016-4-4

introduced the notion of S curve and distinguished between three stages of urbanisation — urbanisation, suburbanisation, and re-urbanisation. Today, Russia has a high level of urbanisation and a developed urban space. The urban population is continuously increasing within a certain threshold range. Historically, Saint Petersburg developed within a land/sea system. Today, it is one of the key metropolisation [1] areas in Russia and a major European port. Saint Petersburg is a typical multifunctional city developing in a globalising world [2].

To understand changes in the urbanisation process, it is important to analyse transport network distribution and population distribution in developed urbanised spaces. This holds true for the studies into the regulation of space expansion and port city enhancement in developing countries. Firstly, the objective of this work is to analyse the spatial changes in the city from 2002 to 2015, using a population gravity model and the standard deviation ellipse. Secondly, it is to study the features of the city's transport network, using the network analysis tool. Thirdly, it is to trace changes in the city's population density distribution employing the method of kernel density, and to estimate its correlation with the parameters of transport network centrality.

1. Research methods and data processing

1.1. Research methods

As dynamic spatial systems, cities are constantly changing. The initial concentration process transforms into diffusion; later, diffusion can be replaced by concentration. The population centre of gravity is an important parameter for identifying the direction and features of urban or regional population distribution [10]. The trajectory and rate of shifts in the population centre of gravity have become an important benchmark for devising settlement policies in western countries. Changes in the population distribution in Saint Petersburg were analysed with the centre of gravity model and the standard deviation ellipse.

The formula for calculating the population centre of gravity is

$$X = \sum P_i \cdot X_i / \sum P_i,\ Y = \sum P_i \cdot Y_i / \sum P_i,$$

where X, Y stand for the coordinates of the population centre of gravity; X_i, Y_i, stand for the coordinates of the centre of gravity of population group i; P_i stands for the size of population group i.

The diffusion of population distribution is measured using the standard deviation ellipse [9]. The standard deviation ellipse consists of a major and a minor axis, a deviation angle, and the centre of gravity of the ellipse. The major axis is the proportion of population distribution in the principal direction from the population centre of gravity. The minor axis is the proportion of population distribution in the secondary direction. The deviation angle represents the principal direction of population distribution. The ellipse can account for over 68 % of the population of an area under consideration. The standard deviation ellipse fully reflects the deviation of population distribution in different directions and can be indicative of population distribution trends.

Betweenness centrality and straightness centrality introduced within the multiple centrality assessment model (MCA) are two important indices used to identify the centrality of a city's transport network [16]. Transport routes serve as the edges of a city's network and intersections and terminals as nodes connecting the edges. Distances between nodes along an actual transport network are calculated to measure the centrality of a transport network [11]. Betweenness centrality is measured using the number of shortest paths between each pair of the network's nodes, containing a selected node.

The formula for calculating betweenness centrality is

$$C_i^B = \frac{1}{(N-1)(N-2)} \sum_{j=1;k=1;j\neq k\neq 1}^{N} \frac{n_{jk}(i)}{n_{jk}},$$

where C_i^B stands for the betweenness centrality of node i, N for the number of nodes in the transport network, n_{jk} for the number of shortest paths between network nodes, and $n_{jk}(i)$ for the number of shortest paths containing i. Betweenness centrality is of immense significance for studying a city network. Betweenness centrality is an important parameter for measuring the transport traffic between network nodes.

Straightness centrality measures the shortest paths between two nodes, containing node i, and the extent of their deviation from a virtual straight route. The smaller the extent of deviation, the higher the straightness centrality of node i and the transport efficiency. If a node can be reached from a selected node via the shortest path, the best straightness centrality and highest transport efficiency are attained.

The formula to calculate the straightness centrality is

$$C_i^S = \frac{1}{N-1} \sum_{j=1;\, j\neq i}^{N} \frac{d_{ij}^{Eucl}}{d_{ij}},$$

where C_i^S stands for the straightness centrality of node i, N for the number of nodes in a transport network, d_{ij} for the shortest path between nodes i and j, and d_{ij}^{Eucl} for the Euclidian distance between nodes i and j.

Straightness centrality is an important parameter for measuring transport efficiency. It is also of enormous significance for studying the spatial structure of complex networks.

In this study, centrality is measured using the urban network analysis tool (UNA), which was developed on the basis of ArcGIS software at the Singapore University of Technology and Design in collaboration with the Massachusetts Institute of Technology [17].

The UNA offers special opportunities for network space analysis: 1) it can be used to analyse networks from the perspective of geometry or typology; 2) it includes a third network element alongside nodes and edges; 3) intersections can be weighted within a network.

When studying the correlation between a city's transport network and spatial distribution of population density, it is necessary to use spatial interpolation of a transport network's centrality and population density using kernel density estimation (KDE).

Discrete points shown on the map do not always make it possible to identify spatial distribution trends. KDE enables obtaining a layer of changes in the density of the studied phenomenon and observing continuous spatial changes. The method calculates densities of discrete points within a certain area (window).

The ArcGIS Kernel Density tool calculates the density of features in a neighbourhood around those features. It can be calculated for both point and line features. A smoothly curved surface is fitted over a point. The surface value is highest at the location of the point and it diminishes as distance from the point increases to reach zero at the search radius distance from the point. The volume under the surface equals the population field value for the point, or 1 if NONE is specified. The density at each output raster cell is calculated by adding the values of all the kernel surfaces where they overlay the raster cell centre [18].

The geometric value of a KDE equation is as follows. Density distribution is highest in the centre of each point Xi, and it diminishes when the distance from the centre reaches a certain threshold range (fig. 1) [13]. The KDE formula is

$$f(x)=\frac{1}{nh^d}\sum_{i=1}^{n}k\left(\frac{x-x_i}{h}\right),$$

where h stands for the threshold, n for the number of points within a range, and d for data dimensionality.

For instance, for a d = 2, the equation will be

$$f(x)=\frac{1}{nh^2\pi}\sum_{i=1}^{n}\left[1-\frac{(x-x_i)^2+(y-y_i)^2}{h^2}\right]^2,,$$

where $(x-x_i)^2+(y-y_i)^2$ is the deviation between points (x_i, y_i) and (x, y).

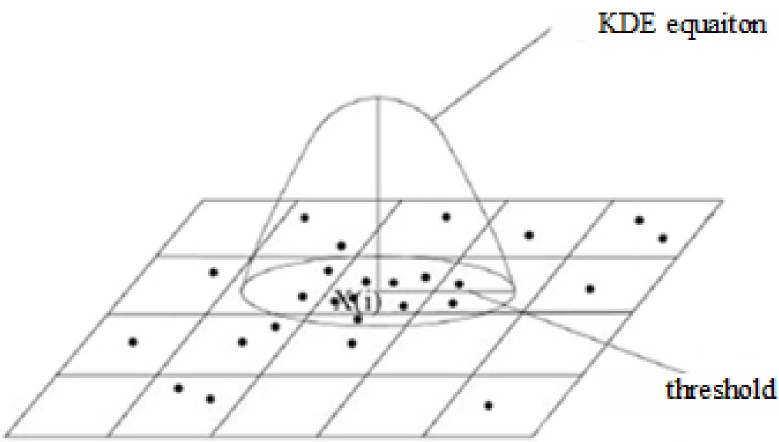

Fig. 1. Kernel density estimation method

The calculations were carried out using the ArcGIS software. Distribution of population density and transport network centrality was estimated for different periods.

1.2. Characteristics of the region

In 2015, the city's population reached 5,191,700 people [3]. Saint Petersburg is the northernmost city in the world with a population above one million people. It is the most populated non-capital city completely located in the European part of Eurasia [5]. With an area of 1439 km^2, it ranks second after Moscow in Russia [3]. Saint Petersburg comprises 18 districts [3], which are further divided into 111 municipalities — 81 city municipalities, nine towns (Zelenogorsk, Kolpino, Krasnoye Selo, Kronshtadt, Lomonosov, Pavlovsk, Petergof, Pushkin, Sestroretsk), and 21 villages [3].

1.3. Sources and data processing

This article uses the population size data from Saint Petersburg statistical yearbooks of 2002, 2010, and 2015 [3]. The 2016 data on the city's transport network are taken from the Open Street Map project [4]. Spatial adjustment was carried out using Google Maps. District and municipal level data were obtained from the official website of Saint Petersburg [5].

2. Conclusions

2.1. Spatial changes in population by zones

In 2002—2015, the total population of Saint Petersburg was increasing. However, population growth rates differed at the zone level. In 2002, the population of the city reached 4,661,200 and in 2015 it rose to 5,191,700. The annual growth rate was 0.77 %. This article divides Saint Petersburg into three zones — central, suburban, and outer suburban ones. The division is based on materials from the report 'The potential for the socioeconomic development of Saint Petersburg until 2020: Possible strategies' [6]. In 2002—2015, the spatial distribution of the city's population density was changing from high to low as distance from the centre increased, from the central through the suburban to the outer suburban zone. The city's population continues to concentrate around the centre.

The population density differentiation trend is manifested in the fact that the most rapid increase in population is observed in the suburban zone, to be followed by the outer suburban zone and the central one (fig. 2—4).

Fig. 2. Population density in Saint Petersburg in 2002

Compiled by the authors based on [3].

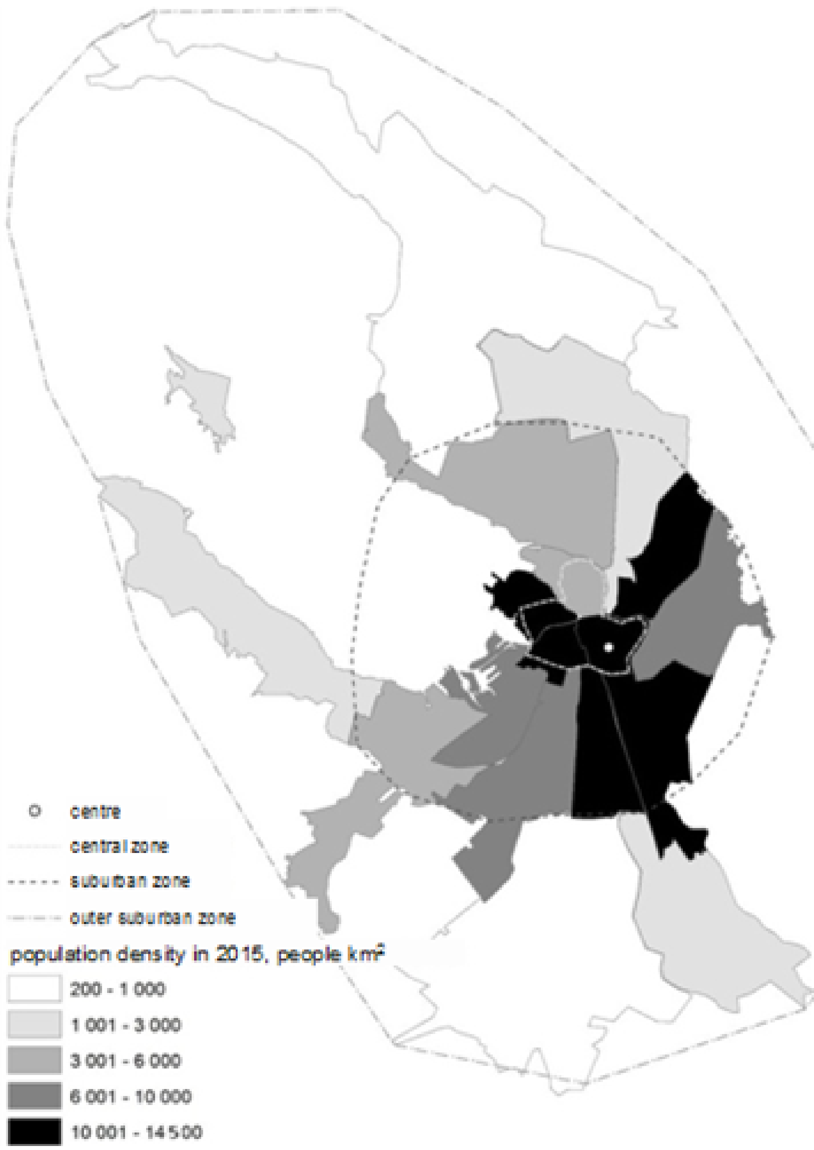

Fig. 3. Population density in Saint Petersburg districts in 2015

Compiled by the authors based on [3].

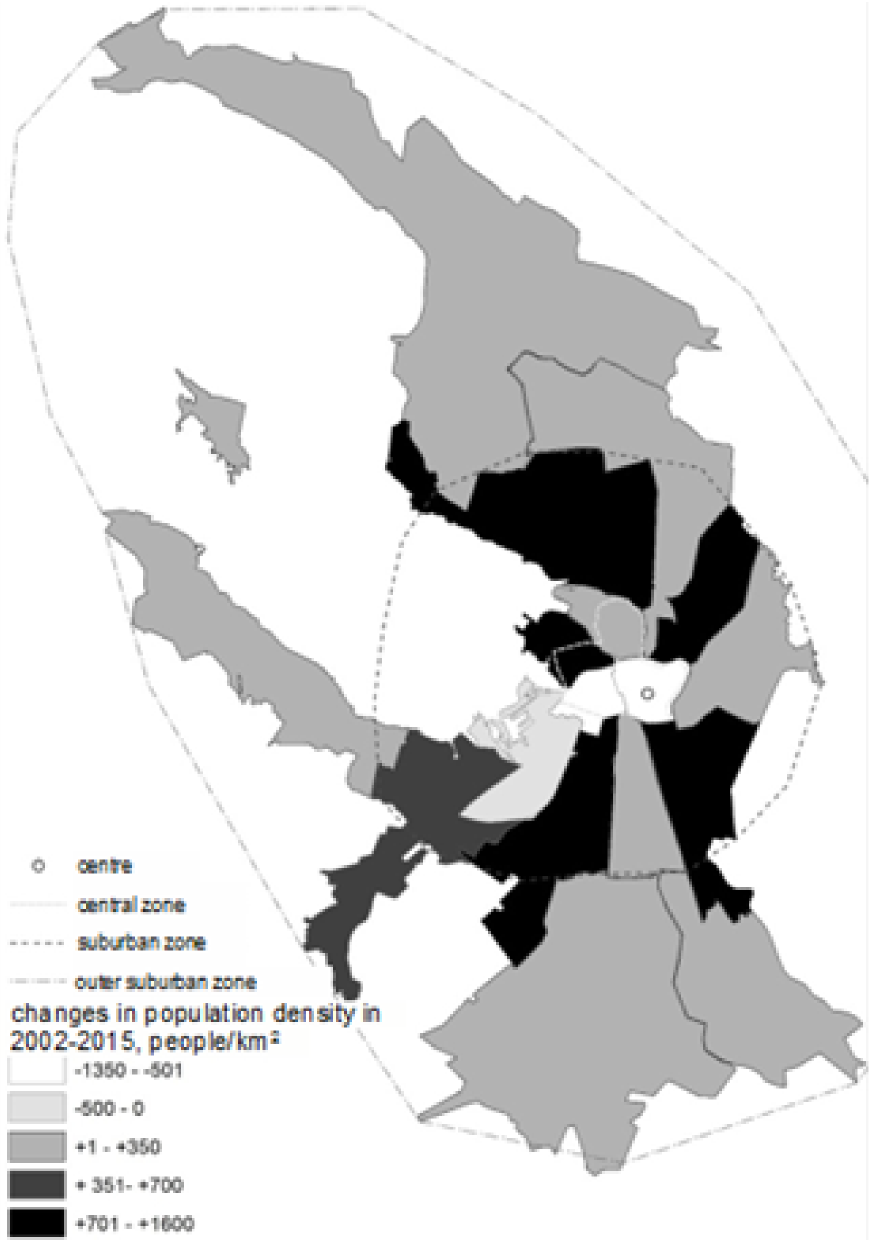

Fig. 4. Changes in population density
in Saint Petersburg districts in 2002—2015

Compiled by the authors based on [3].

2.2 Spatial changes in population density by district

In 2002—2015, a population gain was observed in 16 out of 18 districts of Saint Petersburg. The highest population growth rates were registered in the Primorksy, Nevsky, Kalininsky, Moskovsky, Pushkinsky, and Krasnoye Selo districts. Population figures saw a drop only in the Central and Admiralteysky districts, (fig. 2—4).

The most densely populated area is the Central district with 13658 people/km^2. A significant proportion of Saint Petersburg residents (approximately 40 %) live in high-density districts (above 10,000 people/km^2). This proportion was increasing in 2002—2015. Districts with a population density of 6000—10,000 people/km^2 accounted for 19.6 % of residents and the proportion of such districts was diminishing. Districts with a population density of 3000—6000 people/km^2 were home to 20 % of the city's population and their proportion was decreasing more rapidly than that of districts with a density of 6000—10,000 people/km^2 did. Districts with a population density of 1000—3000 people/km^2 accounted for 16.3 % of the city's total population and their proportion was stable in 2002—2015. Those with a population density below 1000 people/km^2 accounted for 4.7 % of the total population size, and their proportion was increasing over the studied period (table 1).

Table 1

Changes in population distribution in Saint Petersburg, 2002—2015 (%)

Population density (people /km^2)	District (2002, 2010)	District (2015)	% 2002	% 2010	% 2015
>10000	Central Kalininsky Vasileostrovsky Admiralteysky Frunzensky	Central Kalininsky Vasileostrovsky Admiralteysky Frunzensky Nevsky	32.2	30.4	39.3
6000—10000	Nevsky Kirovsky Moskovsky	Kirovsky Moskovsky Krasnogvardeysky	22.6	22.3	19.6
3000—6000	Krasnogvardeysky Petrogradsky Primorsky Krasnoye Selo	Petrogradsky Primorsky Krasnoye Selo	25.1	26.8	20.0
1000—3000	Vyborgsky Kronshtadt Kolpinsky Petrodvortsovy	Vyborgsky Kronshtadt Kolpinsky Petrodvortsovy	16.2	16.3	16.3
<1000	Pushkin Kurortny	Pushkin Kurortny	4.0	4.2	4.7

*Compiled by the authors based on [3].

General trends in population change were as follows:

1) Population density decreased gradually from the centre to the periphery.

2) Population distribution underwent slight changes — it increased only in two districts of neighbouring types. In the Nevsky district, it grew from 6000—10,000 people/km^2 to 10,000 people/km^2 and, in the Krasnogvardeysky district, from 3000—6000 people/km^2 to 6000—10,000 people/km^2.

2.3. Trends in population distribution

The population gravity centre and standard deviation ellipse for Saint Petersburg in 2002—2015 were calculated based on population data for the two periods (fig. 5). The results show that, for both periods, the population gravity centres were found in the central district and no significant changes were observed in this respect. However, in 2015, the gravity centre shifted northward from the city centre. This is indicative of a higher population increase rate in the northern districts. The obtained results correlate to the above data on changes in population density.

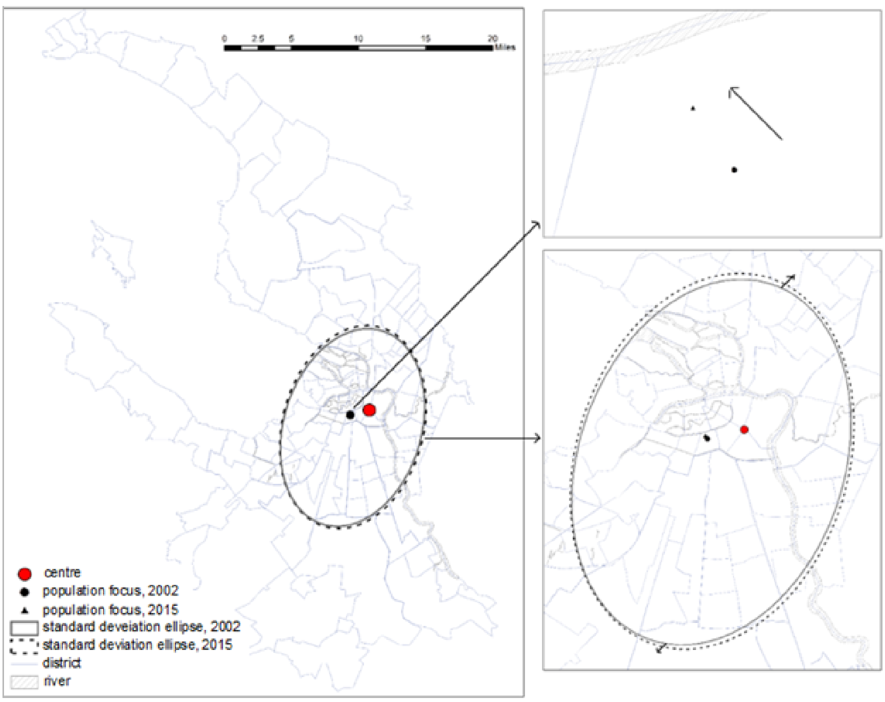

Fig. 5. Spatial changes in the centre of gravity
and standard deviation ellipse in 2002—2015

Compiled by the authors based on [3; 4].

The standard deviation ellipse shows a small deviation, which suggests that:

1) In 2002—2015, the principal population distribution area did not change dramatically in Saint Petersburg. The standard deviation ellipses includes the city's core (the Central and Admiralteysky districts, most of the Vasileostrovsky district, and the Petrogradsky district), as well as the Moskovsky, Frunzensky, Nevsky, Krasnogvardeysky, Kalininsky, Vyborgsky, and Kirovsky districts). These districts constitute the territorial core of economic and cultural development, being home to 68 % of the city's population;

2) The deviation angle of the standard deviation ellipse is a slight — approximately 10° — deviation from north to east. The spatial distribution of population in Saint Petersburg is dominated by the north-east — south-west vector;

3) The major axis of the ellipses elongated over the period under consideration. The distance increased towards northeast more significantly than towards southwest. The major population distribution area was expanding towards the periphery, primarily towards northeast and southwest. The diffusion rate towards northeast is higher than towards southwest.

2.4. Analysis of transport network centrality

Figures 6—9 show that the transport network centrality changes from high to low from the central through the suburban to the outer suburban zone, i. e. it decreases from the centre towards the periphery. The highest centrality is observed in the Central and Admiralteysky districts, followed by the Kirovsky, Petrogradsky, and Primorsky ones, which are characterised by shortest paths and busiest traffic. In other districts (Vasileostrovsky, Vyborgsky, Moskovsky, Krasnogvardeysky, Nevsky) and the outer suburban zone (Krasnoye Selo, Kronshtadt, Kolpinsky, Petrodvortsovy, Pushkin, Kurortny district), the transport network centrality is low.

The results of straightness centrality assessment are similar to those of centrality. However, the spatial distribution centrality is broader than that of betweenness centrality — the former spread to the entire suburban zone and parts of the suburban zone (Krasnoye Selo, Kronshtadt, Pushkin districts). This means that the spatial location of zones with high transport efficiency is scattered and that of zones with heavy traffic is more concentrated.

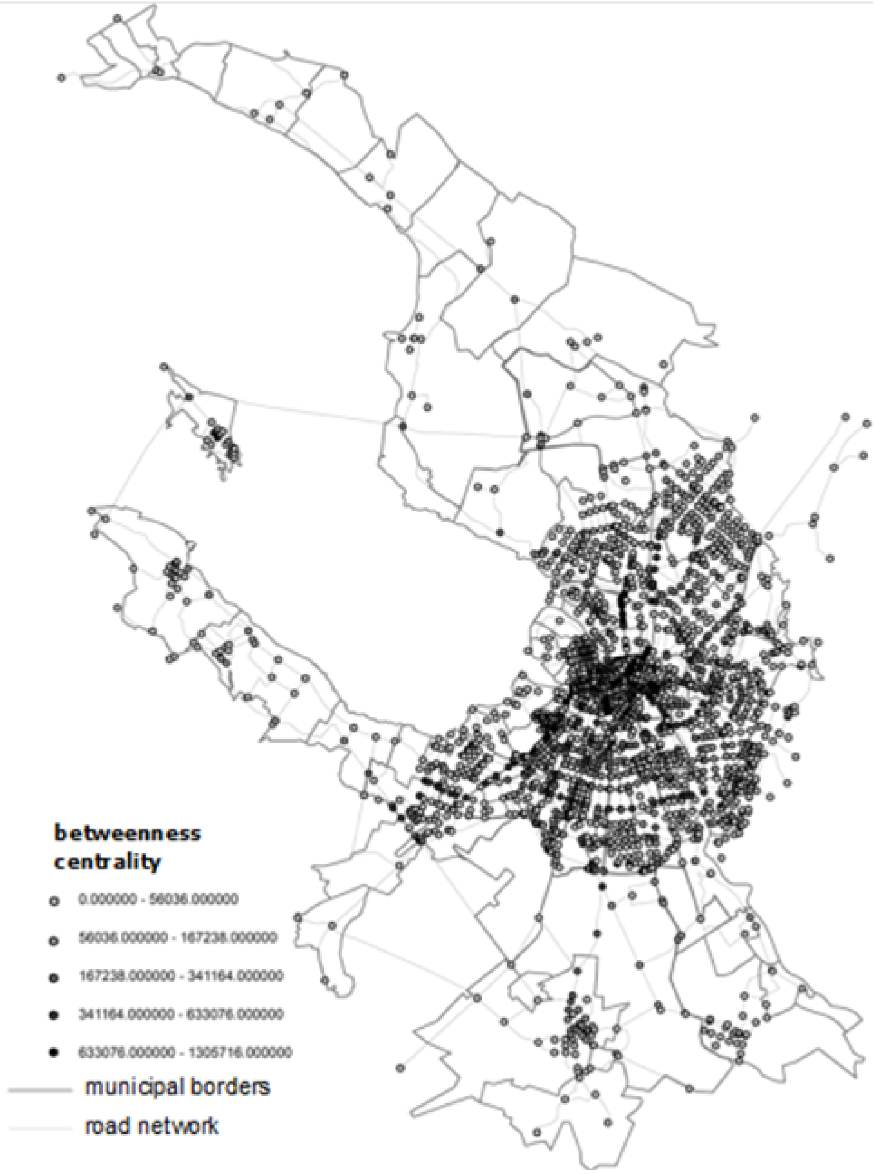

Fig. 6. Betweenness centrality of Saint Petersburg transport network zones

Compiled by the authors based on [3; 4].

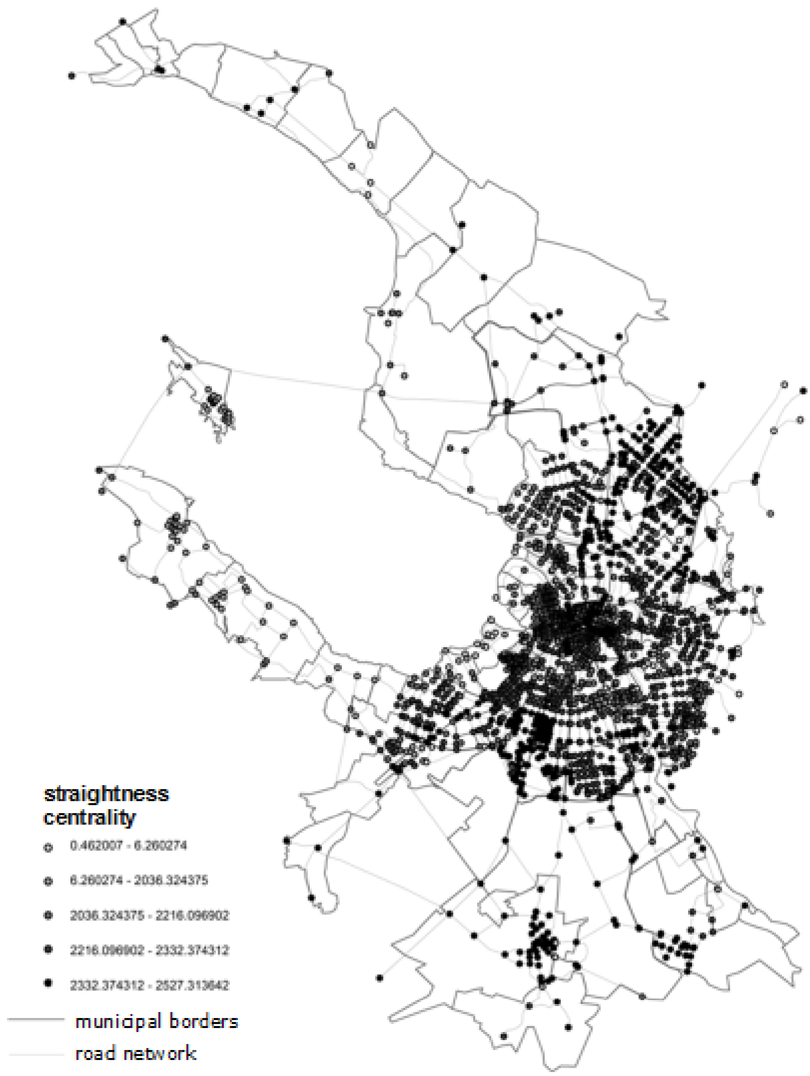

Fig. 7. Straightness centrality of Saint-Petersburg transport network nodes

Compiled by the authors based on [3; 4].

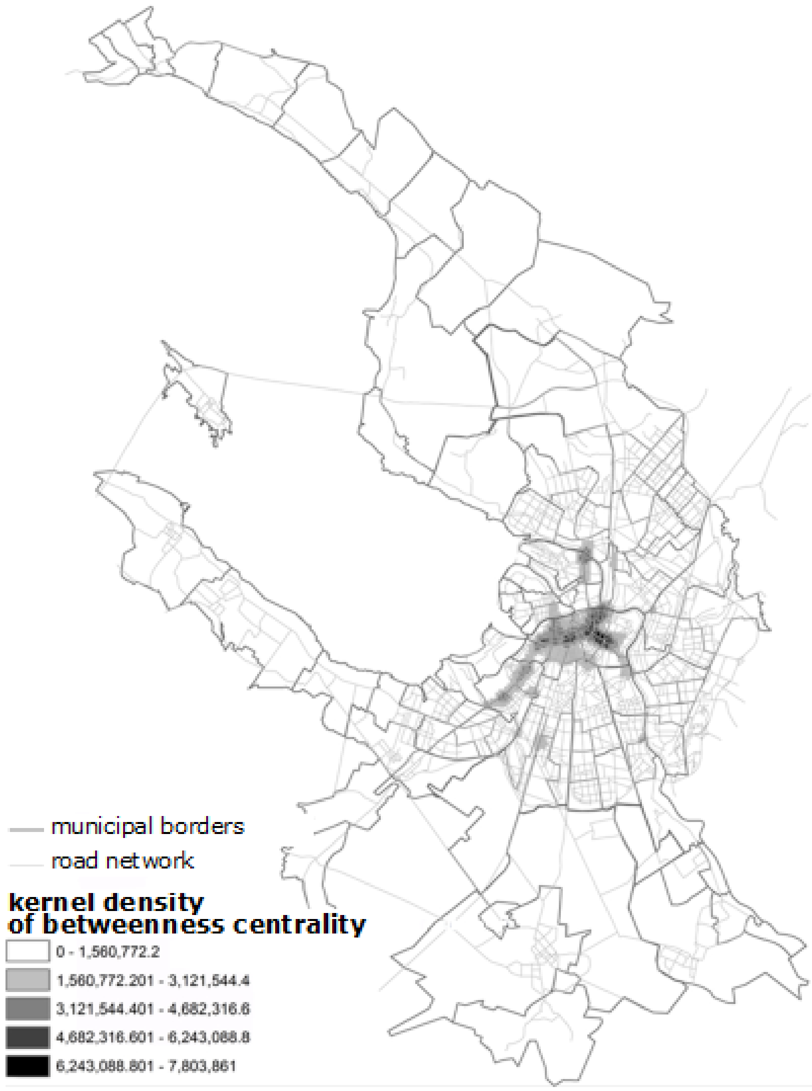

Fig. 8. Kernel density of betweenness centrality
of Saint Petersburg transport network (KDE method)

Composed by authors based on [3; 4].

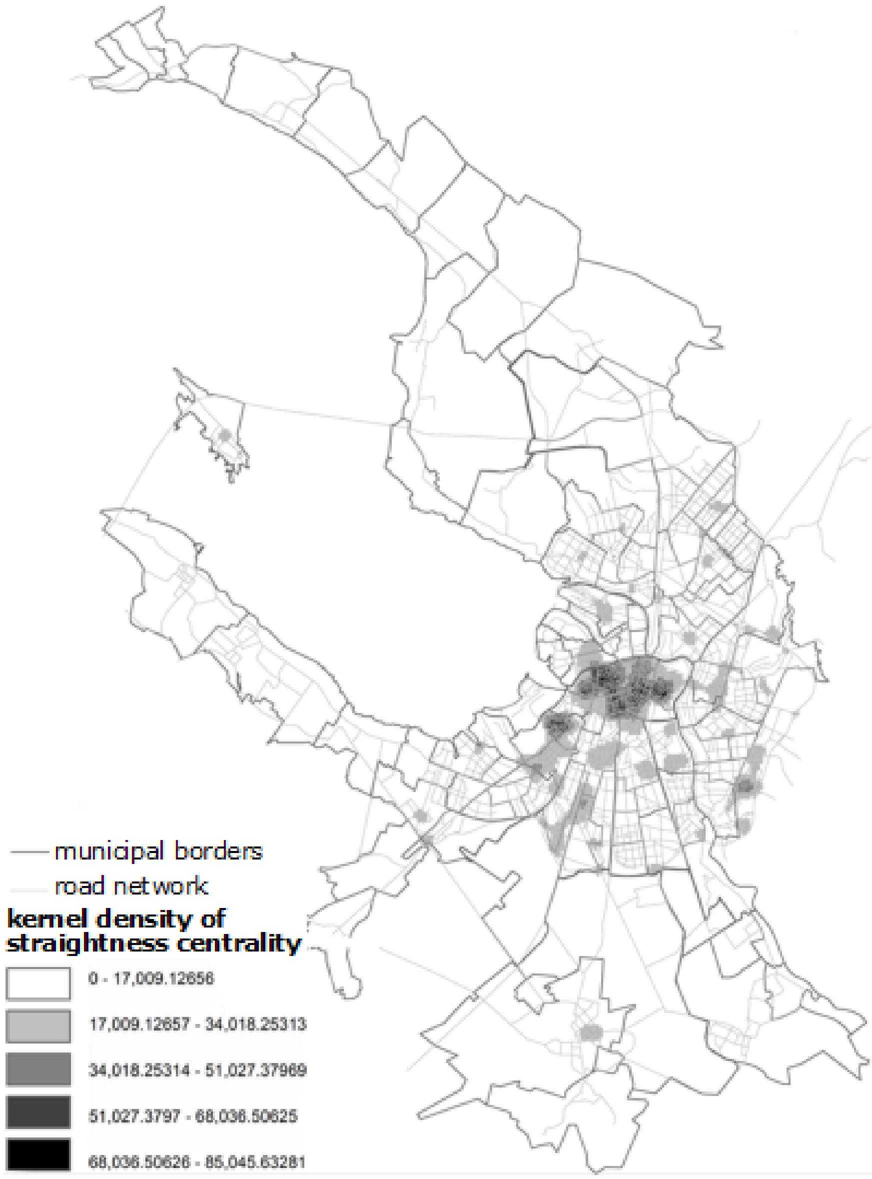

Fig. 9. Kernel density of straightness centrality
of Saint Petersburg transport network (KDE)

Compiled by the authors based on [3; 4].

2.5. Correlation between changes in population distribution and transport network centrality

The analysis of the spatial distribution of population kernel density in different years (2002, 2010, 2015) suggests that:

1) Areas with a high kernel density were associated with a high transport network centrality. They were concentrated in the suburban zone. The outer suburban zone did not demonstrate a tendency towards concentrated distribution.

2) The spatial distribution of kernel density is a polycentric structure. Population distribution in the Central and Admiralteysky districts is the densest. Moreover, the Kirovsky, Moskovsky, Frunzensky, Nevsky, and Vyborg districts also show a tendency towards concentrated population distribution.

3) In 2002—2015, the area of kernel density expanded. In 2015, the outer suburban zone showed a tendency towards concentrated distribution.

4) The direction of spatial diffusion of kernel density in 2002—2015 corroborates the results of the analysis for the standard deviation ellipse: the ellipse is stretched from northeast to southwest, which corresponds to the direction of the city's transport network development.

The analysis shows that there is a correlation between population kernel density and transport network centrality. The results obtained suggest that:

1) Population density and transport network centrality show an average correlation, and this dependence was increasing in 2002—2015.

2) The correlation between kernel density and straightness centrality is higher than that between kernel density and betweenness centrality. This suggests that, when choosing the place of residents, special attention is paid to transport efficiency (fig. 10—12, table 2).

Table 2

Coefficient of correlation between kernel density and transport network centrality

Population density	Betweenness centrality	Straightness centrality	Average centrality value
2002	0.40723	0.43997	162.0777
2010	0.49744	0.56788	162.7490
2015	0.50930	0.58589	172.9097

* Compiled by the authors based on [3; 4].

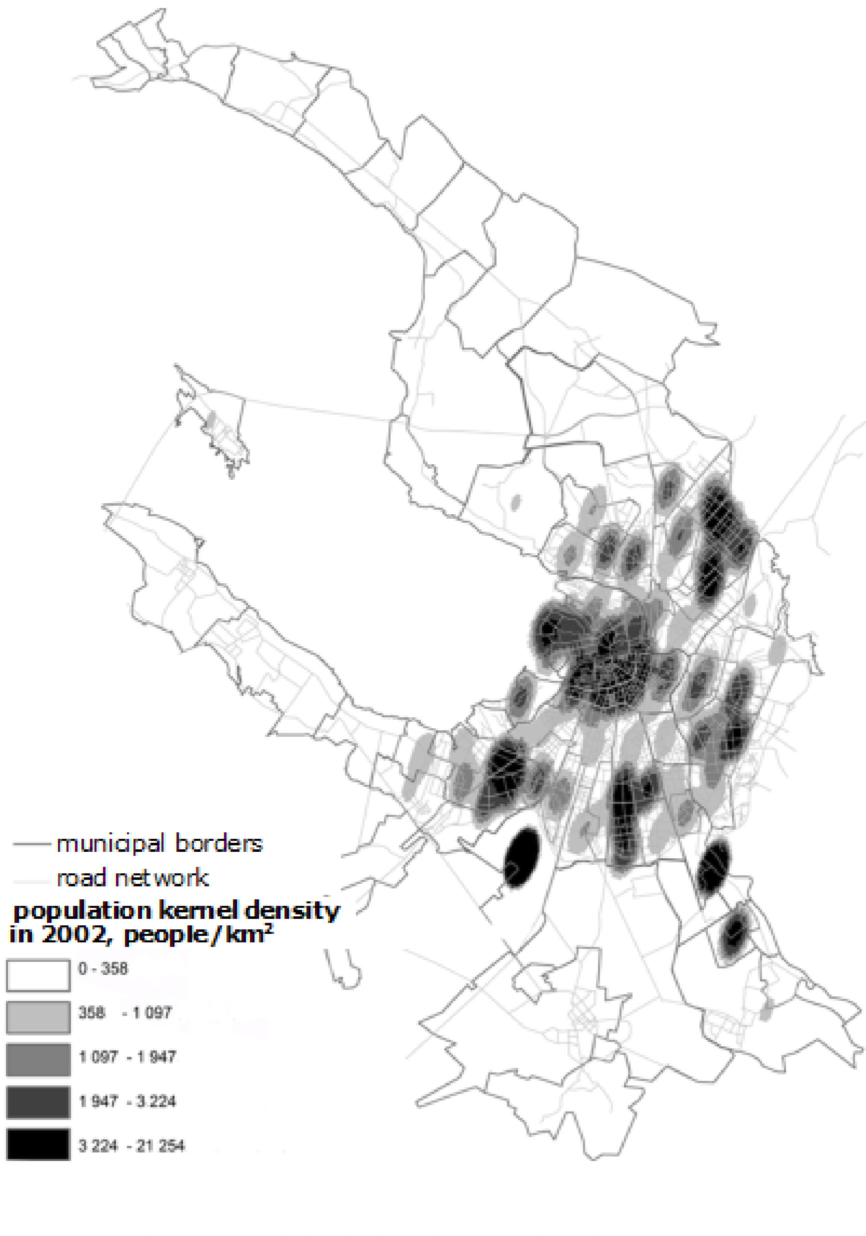

Fig. 10. Kernel density in Saint Petersburg in 2002 (KDE)

Compiled by the authors based on [3; 4].

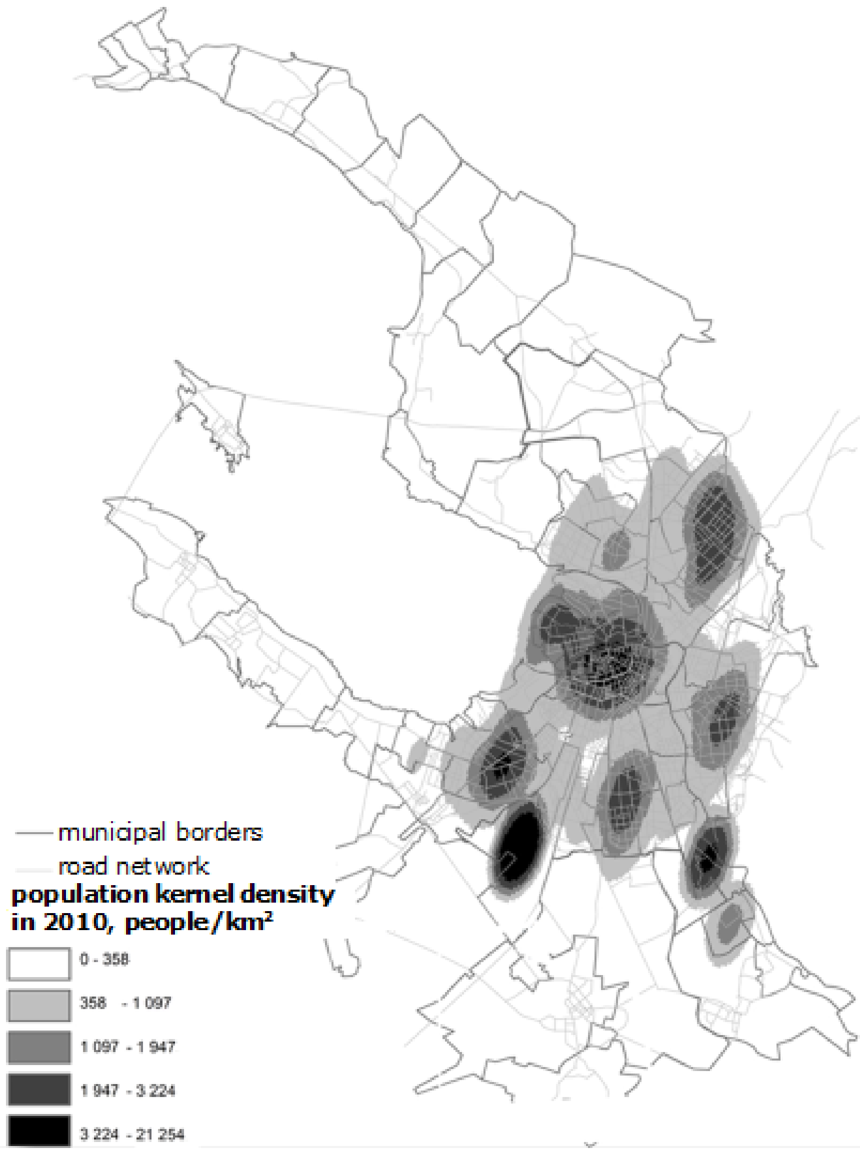

Fig. 11. Kernel density in Saint Petersburg in 2010 (KDE)

Compiled by the authors based on [3; 4].

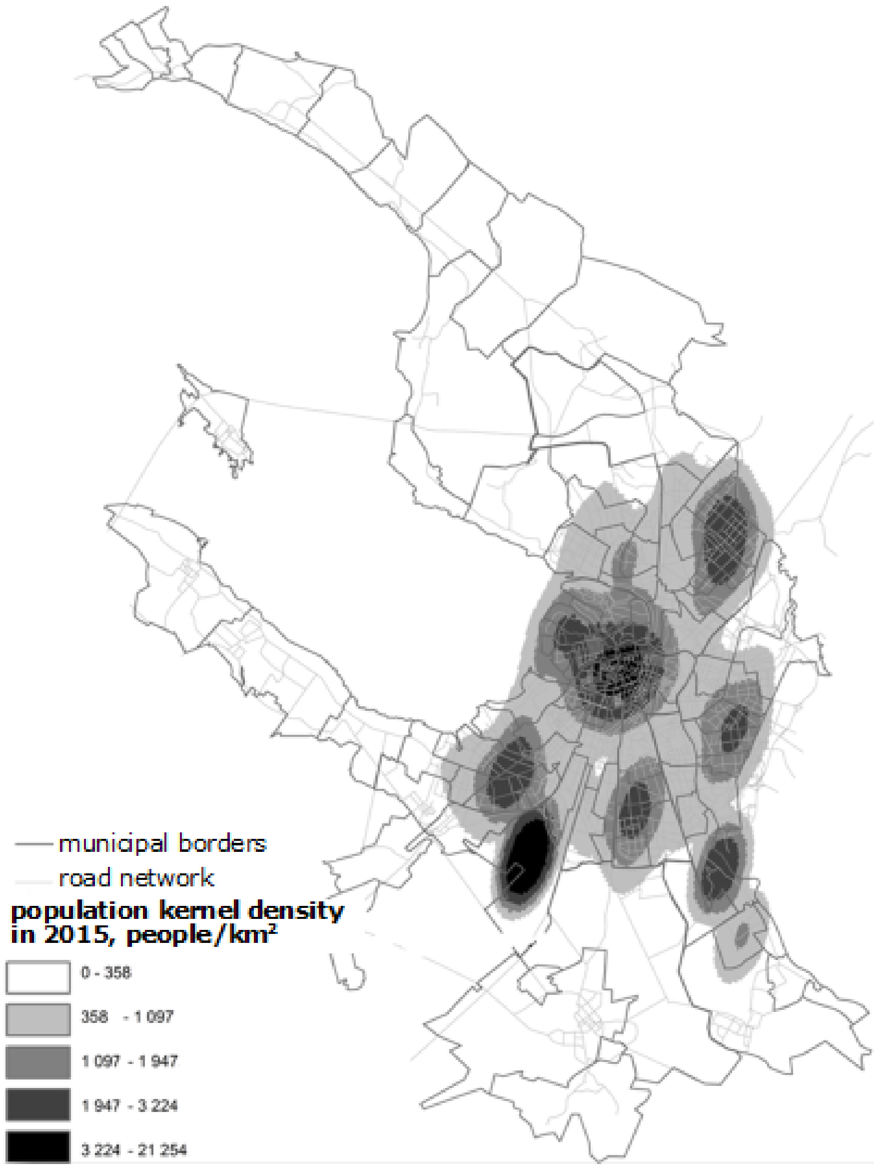

Fig. 12. Kernel density in Saint Petersburg, 2015 (KDE)

Compiled by the authors based on [3; 4].

3. Conclusions

Overall, it can be concluded that

1) In 2002—2015, the population of Saint Petersburg increased. As in many other large cities, this process was accompanied by changes in population distribution in the centre and the suburbs. Despite a continuing decrease in population density gradient from the centre to the suburbs, changes in this parameter over the period under consideration suggest an opposite trend: the density increased the most in the suburban zone and decreased in the centre.

2) A specific feature of spatial distribution of population in Saint Petersburg is its northeast — southwest axis. The population gravity centre shifted northward from the city's centre over the studied period and the principal population distribution area was expanding towards northeast and southwest. The diffusion rate in the north-eastern direction was higher than in the south-western one. Spatial features of the population growth in Saint Petersburg, steady changes in the population gravity centre, and alterations in the standard deviation ellipse are indicative of the post-urbanisation process. They constitute a principal pattern of spatial development of large cities. Similar processes are observed in large Chinese cities, such as Beijing [8] and Nanjing [15].

3) The centrality of Saint Petersburg transport network expectedly decreases from the centre to the outer suburban zone. However, the spatial distribution of the straightness centrality parameters is broader than that of the betweenness centrality. A similar distribution pattern is observed in large Chinese cities, for instance, Changchun [7].

4) There is an average positive correlation between the population density and the transport network centrality, and this correlation is growing. The correlation between the population density and the straightness centrality is higher than that between the population density and the betweenness centrality. This can be indicative of the propensity to base residential decision on transport efficiency parameters.

Changes in population distribution suggest a complex combination of various factors — the transport network, urban land use policy, environmental changes, and residential preferences. Studying the correlation between spatial changes in population and numerous factors is of crucial significance for understanding the laws of urban space development. The authors of this article believe that the trends considered above will increase, which has to be taken into account in urban planning in suburban districts, especially, in the northeast and southwest of Saint Petersburg.

This research was supported by the National Natural Science Foundation of China (41471141).

References

1. Druzhinin, A.G. 2014, Mother countries and metropolisation in contemporary Russia: conceptual approaches in political and geographical contexts, *Izv. RAN. Ser. geogr*, no. 1, p.19—27. (In Russ.)

2. Lachininskij, S.S., Semenova, I.V. 2015, *Sankt-Peterburgskij primorskij region: geoehkonomicheskaya transformaciya territorii* [St. Petersburg coastal region: geo-economic transformation of the territory], St. Petersburg. (In Russ.)

3. Database of indicators of municipalities of St. Petersburg, available at: http://petrostat.gks.ru (accessed 03.04.2015). (In Russ.)

4. Open Street Map Project data, available at: http://beryllium. gis-lab. info (accessed 03 April 2016).

5. Official web site of Administration of St. Petersburg, available at: http://gov.spb.ru (accessed 03 April 2016).

6. Development of capacity of the city of St. Petersburg, available at: http://csr-nw.ru (accessed 03 April 2016) (In Russ.)

7. Chen, Chen, Wang, Fa Hui, Xiu, Chun Liang, 2013, The Relationship Between the Spatial Distribution of Commercial Networks and Street Centrality, *Changchun. Economic Geography*, Vol. 33, no. 10, p. 40—47.

8. Meng, Yan Chun, Tang, Cang Song, 2015, Study on the Trend of Population Spatial Distribution in Being since the Reform and Opening-up:Based on Analyzing the Data of Four Population Census from 1982 to 2010, *China Population, Resources and Environment,* Vol. 25, no. 3, p. 135—142

9. O'Sullivan, D, Unwin, D. 2003, *Geographic Information Analysis*, New York, JohnWiley&Sons.

10. Plane, D. A., Rogerson, P. A. 2003, *The Geographical Analysis of Population:With Applications to Planning and Business [M], New* York, JohnWiley &Sons.

11. Porta, S., Latora, V., Wang, F. H. 2009, Street centrality and densities of retail and services in Bologna, Italy[J], *Environ. Plan. B : Plan*, no. 12(36), p. 450—465.

12. Qianqian, T., Kaiyu, L., Meiyue, L. 2015, Research on Optimization Strategy of the Urban Spatial Form under the Perspective of Low Carbon—A Case Study of Xi'an city [J], *Journal of Low Carbon Economy*, no. 4(3), p. 21—27.

13. Timothée, P, Nicolas, L B, Emanuele, S. et al. 2010, A Network Based Kernel Density Estimator Applied to Barcelona Economic Ac-tivities [J], *Computational Science and Its Applications*, Vol. 6, no. 16, p. 32—45.

14. XU, Xueqiang, Zhu, Jianru, 1988, *Contemporary urban geography*, China Architecture & Building Press, Beijing.

15. Zeng, Wen, Zhang, Xiao lin, Xiang, Lili et al. 2016, The Features of Population Redistribution of Nanjing Metropolitan Area in 2000—2010, *Scientia Geographica Sinica,* no. 01, p. 81—89.

16. University of Strathclyde. Urban Design Studies Unit / Multiple Centrality Assessment Model (MCA), available at: http://www.udsu-strath.com/msc-urban-design/2012-2013/analysis-2012-2013/mca-multiple-centrality-assessment/ (accessed 03 April 2016).

17. City Form Lab. Urban Network Analysis Tool for ArcGIS, available at: http://cityform.mit.edu/projects/urban-network-analysis (accessed 03 April 2016).

18. Arc GIS Pro. How Kernel Density Works, available at: https://pro.arcgis.com/en/pro-app/tool-reference/spatial-analyst/how-kernel-density-works.htm (accessed 03 April 2016).

The authors

Li Xiaoling, College of Geography Science, Northeast Normal University, Changchun, China

E-mail: lixl027@nenu.edu.cn

Prof. Anatolii A. Anokhin, Department of Economic and Social Geography, Saint-Petersburg State University

E-mail: a.anohin@spbu.ru

Alexander V. Shendrik, Research Assistant, Department of Economic and Social Geography, Saint-Petersburg State University

E-mail: shen@mail.ru

Dr Xiu Chunliang, College of Jang Ho Architecture, Northeastern University, Shenyang, China

E-mail: xiuchunliang@mail.neu.edu.cn

To cite this article:

Xiaoling, L., Anokhin, A. A., Shendrik, A. V., Chunliang, X. 2016, Changes in the Population Distribution and Transport Network of Saint Petersburg, *Balt. reg.,* Vol. 8, no. 4, p. 39—60. doi: 10.5922/ 2079-8555-2016-4-4.