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Analyzing regional connectivity through population mobility data from cellular operators

ABSTRACT
Relevance. In the current economic climate, maintaining the integrity of regional economic space is crucial. This involves ensuring uniform socio-economic development across regions and promoting a high rate of technology transfer from the center to the periphery. Therefore, it is essential to identify sustainable points of spatial development that represent centers of power concentration and guide spatial transformation.
Research objective. The study aims to assess the connectivity of the region's economic space by measuring population mobility. This approach will help identify the centers of social and labor communications that represent sustainable points of spatial development. The focus of the study is on the municipal districts of Sverdlovsk region, which are key elements of its economic space.
Data and methods. The study employed geoinformation analysis of origin-destination matrix of population flows in Sverdlovsk region (Russian Federation), provided by Russian mobile operators.
Results. The paper presents the analysis of intracity and intercity population flows based on the average daily data of mobile operators for 2022. The intensity and diversification of population flows in the region's municipal districts, reflecting the connectivity of its economic space, were estimated using geographic information systems and the Python programming language. The study revealed that Sverdlovsk region has a bicentric system of spatial interconnections, with two distinct centers of attraction: Ekaterinburg and Nizhny Tagil, with Ekaterinburg being the dominant center.
Conclusions. The proposed classification of municipal districts by the level of their inclusion into the economic space of Sverdlovsk region illustrates that only 5% are characterized by intensive and diversified inter-territorial interaction, while 34% are characterized by low indicators of intensity and diversification of mobile population flows. The spatial structure of the municipalities in Sverdlovsk region, which are located in the zone of attraction to the agglomeration centers, will be maintained and reinforced.

KEYWORDS
population mobility, economic relations of territories, intermunicipal communications, localisation of cellular network users, zones of attraction, geoinformation analysis

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Оценка связанности экономического пространства региона на основе измерения мобильности населения по данным сотовых операторов

АННОТАЦИЯ
Актуальность. В современных условиях хозяйствования важно сохранить целостность экономического пространства регионов, обеспечивающую территориальную равномерность их социально-экономического развития, а также высокую скорость трансфера технологий в направле-

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мобильность населения, экономические связи территорий,

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нии «центр-периферия». В связи с этим необходимо определить устойчивые точки пространственного развития, представляющие собой центры концентрации силы и направлений пространственных преобразований.
Целью исследования является оценка связанности экономического пространства региона на основе измерения мобильности населения, позволяющая выявить центры социально-трудовых коммуникаций, представляющие собой устойчивые точки пространственного развития. Объектом исследования являются муниципальные образования Свердловской области, являющиеся элементами ее экономического пространства.
Данные и методы. Исследование выполнено на основе геоинформационного анализа матриц корреспонденций перемещений населения Свердловской области, предоставленных российскими сотовыми операторами.
Результаты. В работе проведен анализ внутригородских и междугородних перемещений населения на основе среднесуточных данных сотовых операторов за 2022 год. С использованием геоинформационных систем и языка программирования Python оценены интенсивность и диверсифицированность мобильных потоков для муниципальных образований Свердловской области, отражающие связанность ее экономического пространства. Было выявлено, что Свердловская область обладает бицентрической системой пространственных взаимосвязей с двумя явно выраженными центрами притяжения – городскими округами Екатеринбург и Нижний Тагил при существенном доминировании Екатеринбурга.
Выводы. Предложенная классификация муниципальных образований по уровню их включенности в экономическое пространство Свердловской области, иллюстрирует, что только 5% из них характеризуются интенсивным и диверсифицированным межтерриториальным взаимодействием, 34% характеризуются низкими показателями интенсивности и диверсифицированности мобильных потоков населения. Существующая структура пространственных связей для муниципальных образований Свердловской области, находящихся в зоне притяжения к центрам агломераций, будет далее сохраняться и укрепляться.

межмуниципальные коммуникации, локализация пользователей сотовой сети, зоны притяжения, геоинформационный анализ

БЛАГОДАРНОСТИ
Работа выполнена в соответствии с планом НИР Института экономики УрО РАН

ДЛЯ ЦИТИРОВАНИЯ
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根据移动电话运营商数据衡量人口流动性，并评估地区经济空间连通性

摘要
现实性：在现代经济条件下，保持各地区经济空间的完整性，使社会经济发展具有地域统一性，并在“中心-外围”方向上实现高技术转让率非常重要。为此，有必要确定空间发展的可持续点，即权力中心和空间转型方向。
研究目标：在衡量人口流动性的基础上，评估地区经济空间的连通性，从而确定可持续空间发展点的社会劳动交流中心。研究对象是斯维尔德洛夫州（下称斯州）的城市，它们是斯州经济空间的组成部分。
数据与方法：数据来源为俄罗斯移动运营商提供的斯州的人口流动信息。本研究是在此对应矩阵的地理信息基础上进行的。
研究结果：本文根据移动运营商 2022 年的日均数据分析了城内和城际的人口流动情况。通过使用地理信息系统和Python编程语言，评估了斯州各城市人口流动的强度和多样性，这反映了斯州经济空间的连通性。结果显示，斯州具有双中心空间互联系统，有两个明显吸引力中心--叶卡捷琳堡和下塔吉尔市，其中叶卡捷琳堡占主导地位。
结论：根据斯州经济空间纳入水平对城市的分类表明，只有5%的城市存在密集和多样化的区域间互动，34%的城市具有低强度和流动人口多样化的特征。位于吸引力集聚中心的斯州各市现有的空间联系将得到进一步维持和加强。

关键词
人口流动、地区经济关系、城际通信、移动电话用户定位、吸引力区域、地理信息分析

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Introduction

The communication between municipal districts, which determines the economic connectivity of a region, plays a crucial role in shaping sustainable spatial development. However, assessing economic connectivity is a complicated task. Researchers typically use generalized indicators of connectivity within a spatial framework to obtain regional estimates (Myslyakova et al., 2021). While the analysis may encompass parameters such as availability, capacity, and spatial location of transport infrastructure, the real level of interaction through this infrastructure remains underexplored.

Additionally, analysis of spatial communications is challenging due to the lack of official statistical data on inter-territorial connections, their strength, and directions. Some studies address specific issues of freight and passenger flow assessment through transport network analysis and traffic surveys. These studies are time-consuming, resource-intensive, and not systematic, often resulting in significant errors.

To address this, data from mobile phone operators, which enable regular monitoring of population flows within and outside municipal districts, can serve as a reliable source of information. Since nearly every resident has a mobile phone, these data can accurately estimate economic connectivity. This study hypothesizes that mobility data reflect both the availability of transport infrastructure and the intensity of economic interaction, making them suitable indicators of regional economic connectivity.

The objective of this study is to assess the connectivity of the region's economic space by measuring population mobility, enabling the identification of centers of social and labor communications that represent sustainable points of spatial development. First, the study will substantiate population mobility as an indicator of the connectivity of the region's economic space. Second, it will develop methodological recommendations based on the population mobility metric to assess the connectivity of the region's economic space. Third, these methodological recommendations will be tested using Sverdlovsk region as a case study to identify sustainable points of development within its economic space.

The proposed methodological recommendations constitute an assessment toolkit for a deeper analysis of the connectivity of Russian regions' economic spaces. This toolkit synthesizes principles that consider population mobility, reflecting the intensity of intra-regional social and labor communications, along with the infrastructural features of municipal districts. It can be used to identify the regional potential for uniform socio-economic development across municipalities.

Theoretical Framework

There is no clear interpretation of the concept of territorial connectivity in the Russian legislative framework. Consequently, the majority of authors define this concept through the characteristics of economic space, which reflects the conditions of effective movement of resources, capital, people and information.

As outlined by Cherkashin (2018), there are several distinct types of connectivity in economic space such as natural-resource connectivity, social connectivity (population movements), economic connectivity (meeting the needs of economic entities), and institutional connectivity (strategic planning of socio-economic development and ensuring national security). Another type of connectivity, as proposed by Häckner (1990), is innovative one. It reflects the impact of new technologies and modernization processes on sustainable spatial development and ensures the double circulation of migration flows, attracting talented young people and skilled professionals (Lee, 2024) as well as economically active population with higher education to major cities of regions (Shi et al., 2024). In parallel, new mobility paradigms are emerging and actively developing in social sciences (Sheller & Urry, 2006), reflecting the multifactorial connectivity of territories in the context of gender and age-specific movements (Cañibano et al., 2016). Szell (2014) also notes the significance of the spatial influence of environmental parameters on the transformation of regional socio-economic systems, which is reflected in the territorial specificity of sites at different levels.

The determinants of the connectivity of a particular territory's economic space depend on the level of societal development. More "developed" societies are able to purposefully shape their own space, including through investment and the launch of holistic formations of joint business activity – agglomeration projects and innovative forms of cooperation. In less developed societies, the capacity to adapt to spontaneous and forced changes in their own economic space is limited. The so-

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cio-cultural environment of a particular region is of equal importance, which justifies the rejection of spatial development programs that are focused on a single cultural pattern (Shcherbyna, 2023).

Concurrently, the accomplishment of territories of each type of connectivity in the economic space is contingent upon the degree of advancement of infrastructural links between its individual territories. These links represent a fundamental necessity for the sustenance of the population, the expansion of business activity, and the operational resolution of state tasks (Kuznetsova, 2010).

Mol and Law (1994) propose an intriguing perspective on the definition of economic space. They posit that economic space is constituted by two key elements: areas in which objects are grouped together, and networks in which distance is a function of relations between elements, while direction expresses the presence of a variety of connections between them. We concur with this perspective and propose to consider the connectivity of regional economic space in two ways. Firstly, in terms of the intensity of inter-municipal movements facilitated by the development and use of transport and communication networks (Granberg, 2003), which determine the scale of inter-territorial interaction based on commodity exchange (Polozhentseva, 2018). Secondly, in terms of the geography of population flows, reflecting inter-municipal interaction, which determines the integration of each municipality into the system of economic relations of a region.

In favor of our position, we can cite the opinion of Makar and Stroev (2023), who reveal connectivity through the degree of intensity of interactions between some centers and peripheral territories. Polyakova & Simarova (2014a, 2014b) define connectivity in terms of the intensity of socio-economic cooperation at the intraregional and interregional levels. Bondareva (2022) argues that the connectivity of economic space is contingent upon the synthesis of geographical and technological proximity of economic entities.

The intensity of economic relations is contingent upon the resource potential, the target attitudes and values of the population, which determine the behavioral motives of individuals and society as a whole, and the economic activity of economic entities.

The connectivity of economic space is expressed through various characteristics of socio-economic interactions between territories, ensuring the inclusion of their economic entities into the regional economic space. Key principles for ensuring this connectivity are accessibility, intensity, balance, and complementarity (Ufimceva et al., 2016; Volchkova et al., 2017). Kirillova and Kantor (2010) also assess the connectivity of a territory by examining its incorporation into regional and national economic systems.

In recent years, the development of local self-governance has led to the establishment of economic ties between inter-municipal entities. As a result, it has become essential to distinguish inter-municipal cooperation as a distinct and autonomous category of economic relations. This distinction ensures the sustainability of territories and protects the interests of municipalities at all levels of government (Rostanets & Topilin, 2014).

In the context of inter-municipal cooperation, the primary concern revolves around satisfying the basic needs of the population in municipal territories, particularly in creating employment opportunities. Danilova et al. (2022) highlight the importance of enhancing links between municipalities, ensuring adequate infrastructure, fostering entrepreneurial activity, and more.

To improve economic space connectivity, indicators such as population mobility, investment in fixed assets, and natural resource advantages crucial for domestic tourism can be usedd. However, several factors currently hinder economic cohesion in the region:

– the concentration of development in regional centers, which need to shift from being dominant growth poles to effective engines of broader development;

– significant socio-economic disparities among municipalities, necessitating tailored development strategies that account for each area's economic context;

– infrastructure gaps stemming from mismatches between demand for transportation and accessibility; and

– challenges related to the accessibility and adequacy of regional infrastructure (Sekushina, 2020).

Traditionally, assessing the connectivity of economic space focuses on intensity, supported by methodologies that gauge the efficiency of transport network use and infrastructure effectiveness for freight and goods flows (Adzhikova & Shkol'nikova, 2016; Houston et al., 2016). Indicators like transport network density, Engel's coeffi-

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cient, and Uspensky coefficient are used to assess the provision level of railway and motorway infrastructure in a region.

However, we align more with Bondareva (2022), who argues that assessing economic space connectivity solely based on transport communications is narrow. Bondareva suggests exploring various aspects, such as population mobility, which reflects the social efficiency of transport infrastructure use and the economic dynamics between regions influenced by population movements.

Furthermore, the question of whether mobile movements can reliably indicate regional connectivity remains unanswered in Russian academic literature and will be addressed in our study.

Method and Data

To answer the above question, it is necessary to identify the travel patterns of the region's population using origin-destination matrix. The practice of constructing these matrices involves the application of spatial interaction theory (Roy & Thill, 2004; Yan & Zhou, 2019), gravity modelling (Odlyzko, 2015), the Weber-Fechner law (Slovic et al., 1977), or game theory (Su et al., 2007), which allow the estimation of mobility preferences between two territories.

The construction of population mobility trajectories is inherently challenging due to the limited accessibility and commercialization of information reflecting them. The "Origin-Destination Matrix" data package (ODM) of the "Geodata Analysis" module of the regional geoinformation system of Sverdlovsk region (data for 2022) was employed as a source of primary materials for the study. Sverdlovsk region was selected for analysis because of its significant role as one of the largest industrial centers in the national economy, and its leading positions in scientific and technological development.

The cartogram in Fig. 1 provides the illustration of population distribution and inter-municipal transport connectivity in Sverdlovsk Oblast. It is evident that the transport network exhibits a pronounced radial structure, with a minimal number of ring elements. The center of the highway and railway network is Ekaterinburg, which is home to approximately 1.6 million people, representing 37% of Sverdlovsk Oblast's population. Concurrently, the so-called "Big Ekaterinburg" (comprising urban districts Ekaterinburg, Aramilsky, Beryozovsky, Sredneuralsk and Verkhnyaya Pyshma) is home to more than 1.7 million people. The population of the greater Ekaterinburg area, which includes 18 municipalities, is estimated at approximately 2.4 million, representing over 50% of the region's total population. The population of Ekaterinburg agglomeration exhibits a notable prevalence of shuttle migration, with a substantial proportion of daily labor migration directed from the periphery of the agglomeration to its center (Martynenko & Vakalyuk, 2023).

Ekaterinburg is currently the administrative, economic, cultural and financial center of Sverdlovsk Oblast (and by many indicators of the whole Urals), but in terms of industrial output it is inferior to Nizhny Tagil, which is the second largest city in the region with population of more than 300,000 people (more than 600,000 people in the agglomeration, which includes 10 other municipalities). In addition to its smaller population, Nizhny Tagil also lags behind Ekaterinburg in terms of its position within the transport network (Martynenko & Petrov, 2016).

Serov agglomeration, located in the north of the region, is the third most populous area in the region, with an estimated population of approximately 300,000 (100,000 in Serov city). Kamensk-Uralsky city, located in the south of the region, is the fourth most populous area, with estimated population of more than 150,000. From the perspective of transport, the aforementioned centers collectively form a meridional axis along which the majority of intra-regional passenger and freight traffic is carried out by rail and motorways.

With regard to all other municipal districts, the configuration of road and railway networks results in each of them being transport-oriented towards one of the four aforementioned centers (in the majority of cases, towards Ekaterinburg). This leads to a two-level structure of transport connectivity in the region.

The content of the Geodata Analysis module is based on mobile operators' data on the movements of their subscribers. In particular, the ODM contains pairwise values of population travels between all municipalities of Sverdlovsk region, as well as volumes of travels within each municipal district.

The ODM contains data for different types of travels (total number of travels, work-home travels, travels to tourist sites, etc.) at different time intervals (half-hour intervals are used separately

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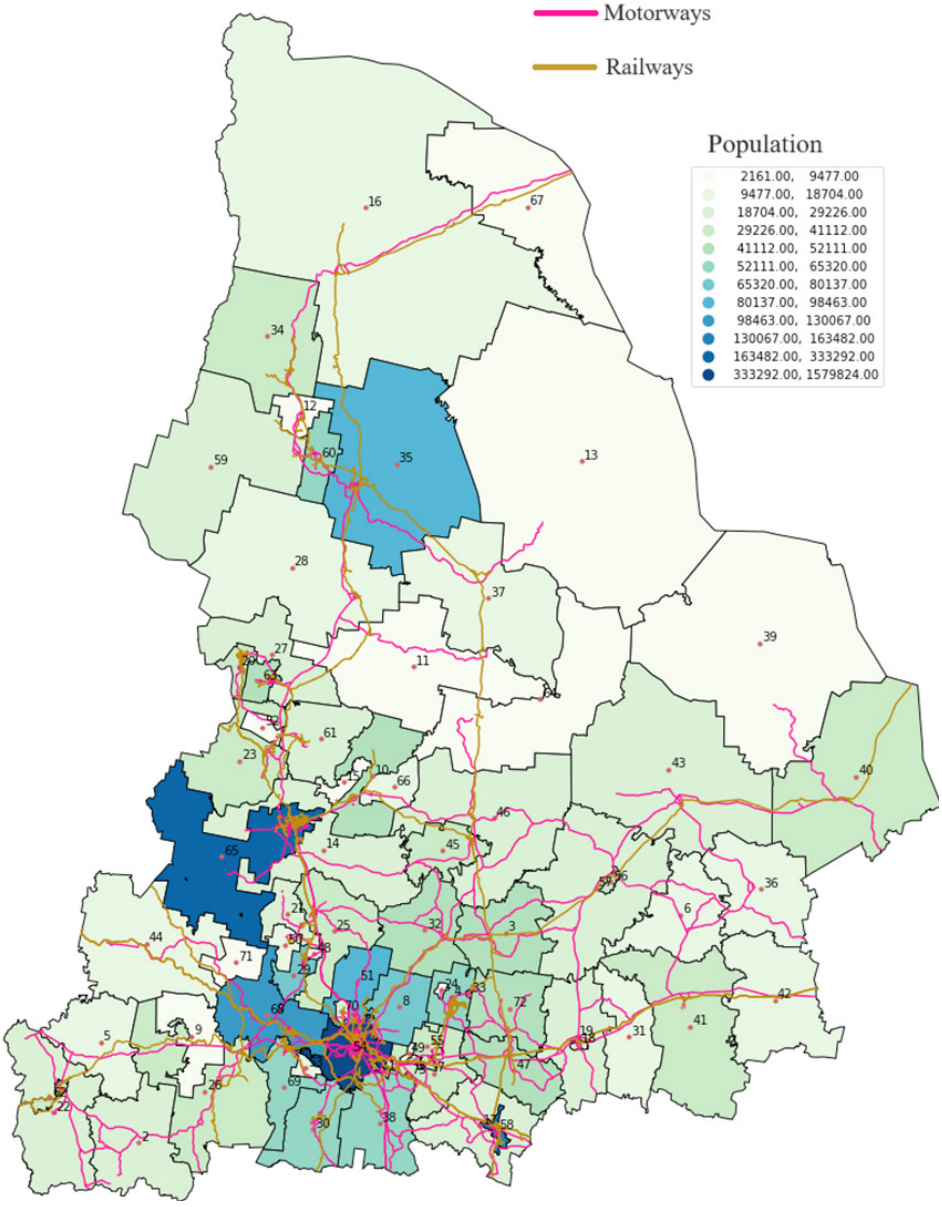

(UD-urban district; MD – municipal district; CATU- Closed Administrative Territorial Unit)

1 – Aramilsky UD, 2 – Arti UD, 3 – Artemovsky UD, 4 – Asbestovsky UD, 5 – Achit UD, 6 – Baikalovsky MD, 7 – Beloyarsky UD, 8 – Beryozovsky UD, 9 – Bisertsky UD, 10 – Verkhnesaldinsky UD, 11 – Verkhotursky UD, 12 – Volchansky UD, 13 – Gari UD, 14 – Gornouralsky UD, 15 – CATU Svobodny, 16 – Ivdelsky UD, 17 – Kamensky UD, 18 – Kamyshlovsky UD, 19 – Kamyshlovsky MD, 20 – Kachkanarsky UD, 21 – Kirovgradsky UD, 22 – Krasnoufimsky UD, 23 – Kushvinsky UD, 24 – Malyshevsky UD, 25 – Nevyansky UD, 26 – Nizhneserginsky MD, 27 – Nizhneturinsky UD, 28 – Novolyalinsky UD, 29 – Novouralsky UD, 30 – Polevskoy UD, 31 – Pyshminsky UD, 32 – Rezhevsky UD, 33 – Reftinsky UD, 34 – Severouralsky UD, 35 – Serovsky UD, 36 – Slobodo-Turinsky MD, 37 – Sosvinsky UD, 38 – Sysertsky UD, 39 – Taborinsky MD, 40 – Tavda UD, 41 – Talitsky UD, 42 – Tugulymsky UD, 43 – Turinsky UD, 44 – Shalya UD, 45 – UD Alapaevsk, 46 – UD Alapaevskoye, 47 – Bogdanovich UD, 48 – Verkh-Neyvinsky UD, 49 – Verkhneye Dubrovo UD, 50 – Verkhny Tagil UD, 51 – Verkhnyaya Pyshma UD, 52 – Verkhnyaya Tura UD, 53 – Degtyarsk UD, 54 – Ekaterinburg UD, 55 – UD Zarechny, 56 – UD Irbit, 57 – UD Irbitskoye, 58 – UD Kamensk-Uralsky, 59 – UD Karpinsk, 60 – UD Krasnoturyinsk, 61 – UD Krasnouralsk, 62 – UD Krasnoufimsk, 63 – UD Lesnoy, 64 – UD Makhnevskoye, 65 – UD Nizhny Tagil, 66 – UD Nizhnyaya Salda, 67 – UD Pelym, 68 – UD Pervouralsk, 69 – UD Revda, 70 – UD Sredneuralsk, 71 – UD Staroutkinsk, 72 – UD Sukhoi Log, 73 – Uralsky UD

Figure 1. *Population of municipal districts and transport infrastructure of Sverdlovsk region.*

Source: compiled by the authors based on population data from https://66.rosstat.gov.ru/ and map data from https://www.openstreetmap.org using tools of the Plotly library of the Python programming language.

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for weekdays and weekends). Thus, the data contained in the ODM provide a fairly complete picture of the spatial distribution of inter-municipal social and economic interactions.

To test the hypothesis, we need to make a few preliminary methodological clarifications and assumptions:

1) The condition of fixing the intensity of inter-municipal interactions – travels of the population of a municipality outside its boundaries are greater than within its territory.

2) The condition of fixing the intensity of inter-municipal interactions is defined as the extent to which the population of a municipality is engaged in travels beyond its boundaries. This can be measured by the number of individuals who reside in one municipality but work or study in another one.

3) The condition of fixing the diversification of inter-municipal interactions is represented by different directions characterizing the geography of travel, which characterize the mobility of the population outside the municipality.

4) The assessment of the inclusion of a municipality in the economic space of the region is based on two indicators: the intensity and diversification of its inter-municipal interaction.

5) The economic space of the region is considered to be connected if the majority of its municipalities simultaneously possess high intensity and diversification of mobile flows. Such points of attraction serve as sustainable centers of spatial development for the region.

This research uses average daily volumes of shuttle migration on working days as a metric to assess the economic connectivity of the region, primarily driven by economic factors such as population labor migration and business trips.

The study will proceed through the following methodological steps:

1. Assessing the closeness of relationships between all municipal districts (MDs) of Sverdlovsk region;

2. Calculating the intensity of inter-municipal interactions among MDs;

3. Identifying the diversification of interactions between MDs in Sverdlovsk region;

4. Proposing a classification of MDs based on their degree of inclusion into the region's economic space;

5. Presenting conclusions on the connectivity of the region's economic space and identifying sustainable development focal points.

The methodology employed is outlined in the initial three stages of the study.

1. To quantitatively characterize the closeness of the relationship between MDi and MDj, we will further use the value of

$$u_{ij} = \frac{K_{ij}}{K_{ii}}, \quad (1)$$

where K_{ij} is the number of trips from MDi to MDj at $i \neq j$, and K_{ii} is the number of trips within MDi. The values u_{ij} quantify the ratio of external to internal linkages of MDi. The larger u_{ij} is, the more important for MDi the links with MDj are.

Based on the value of u_{ij}, we introduce indicators of intensity and diversification of inter-municipal interactions for each MD.

2. The intensity of interaction between MDi and all other MDs in the region is defined as

$$U_i = \sum_{j=1}^{n} u_{ij} = \sum_{j=1}^{n} \frac{K_{ij}}{K_{ii}} = \frac{1}{K_{ii}} \sum_{j=1}^{n} K_{ij}, \quad (2)$$

where n is the total number of MDs.

3. Diversification of interaction of MDi with all other MDs of the region is defined as

$$D_i = \frac{\bar{u}_i}{\sqrt{\frac{1}{n-1}\sum_{j=1}^{n}\left(u_{ij} - \bar{u}_i\right)^2}}, \quad (3)$$

where

$$\bar{u}_i = \frac{1}{n}\sum_{j=1}^{n} u_{ij}. \quad (4)$$

Both introduced indicators have a rather transparent meaning and together allow us to assess the "embeddedness" of each MD in the system of spatial interconnections of the region. The value of U_i shows how important the links with other MDs are for MDi: if the value of U_i is not high, it means that internal links are much more important than external ones, i.e. the dominance of spatial endogenous factors over exogenous ones is observed for the given MD. Accordingly, large U_i values indicate the opposite ratio of external and internal linkages.

In turn, the indicator D_i, which is the inverse of the coefficient of variation, characterizes the structure of external links of MDs: the larger D_i is, the more homogeneous is the structure of links. In particular, if u_{ij} are the same for all MDj, then $D_i = \infty$. Conversely, the stronger u_{ij} will dif-

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fer from each other, the smaller the value of D_i will be. Consequently, a low value of D_i signifies that for MDi, there are a limited number of other MDs whose interactions are considerably larger than those of all others.

Results

A general overview of the structure of the origin-destination matrix under consideration is provided by Figure 2, which illustrates the travels between the 38 largest MDs (in the diagram, the points of departure and arrival are ordered in descending order of the total number of departures). In particular, the sparsity of the matrix is clearly visible, with the majority of MDs exhibiting minimal travels. Furthermore, the vast majority of travels within MDs far exceed those between MDs.

The results of calculations of indicators U_i and D_i for Sverdlovsk region are presented in Fig. 3.

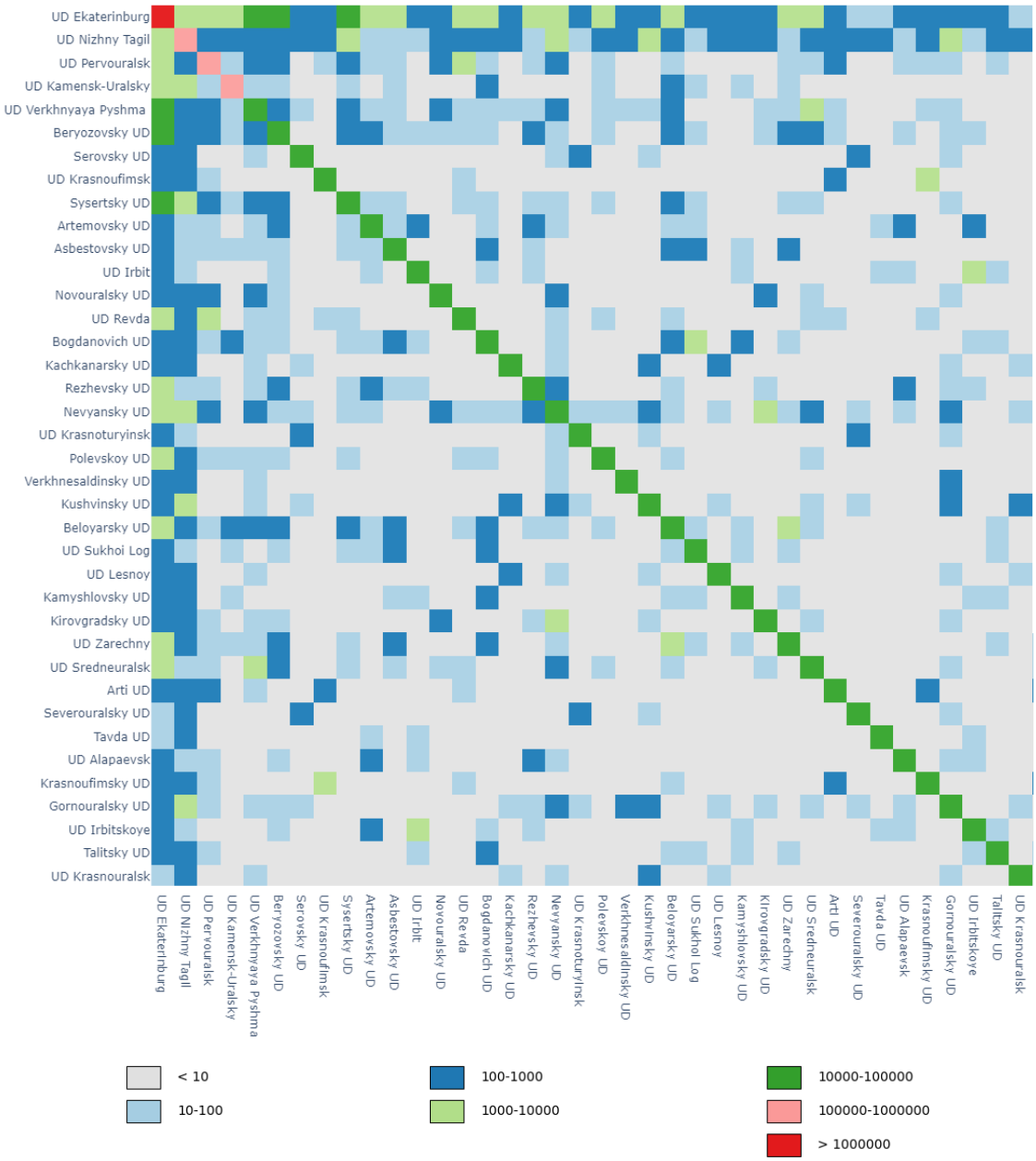

Figure 2. *Average number of inter-municipal travels per working day in 2022 (rows – departure points, columns – arrival points)*

Source: compiled by the authors based on data from the "Geodata Analysis" module of the regional geoinformation system of Sverdlovsk region.

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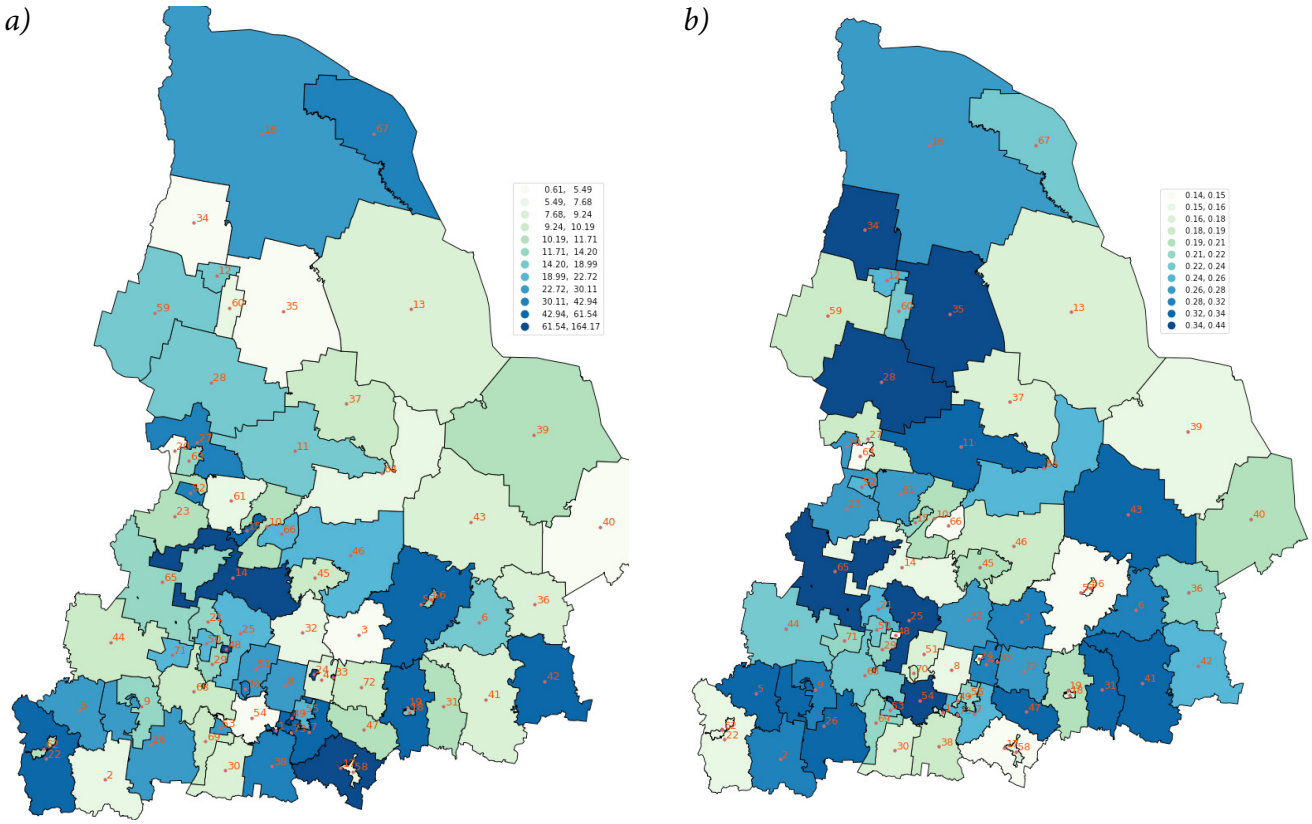

Figure 3. *Indicators of inter-municipal connectivity in Sverdlovsk region: a) intensity of interaction; b) diversification of interaction (numbering of municipal districts corresponds to the numbering in Fig. 1)*

Source: compiled by the authors based on data from the "Geodata Analysis" module of the regional geoinformation system of Sverdlovsk region and map data from https://www.openstreetmap.org using tools of the Plotly library of the Python programming language.

(U_i values in figure a) are given in per cent). The U_i indicator varies within a fairly wide range. Small values of U_i are characteristic of the MDs with high population (i.e., large cities).

For example, Ekaterinburg UD has a value of 5.5 %, UD Kamensk-Uralsky – 7.6 %, Serovsky UD – 3.4 %. Among large municipal districts, only Nizhny Tagil has U_i value greater than 10 % (U_i = 14.2 %).

Large values of indicator U_i are largely a consequence of the peculiarities of the region's administrative-territorial division. There are MDs that geographically and economically constitute a single territory and therefore the intensity of interaction between them is comparable or even exceeds the internal activity in one of them. A typical example is the situation when the center and periphery of the territory form different MDs. In these cases, the periphery has a large value of U_i. For example, UD Irbitskoye, representing the peripheral part of the territory with the center in UD Irbit, has U_i = 57 %. Similarly, for Krasnoufimsky UD (the periphery of the territory with the center in UD Krasnoufimsk) U_i = 55 %. Other examples are the MDs, which are two closely located cities, when one of the cities is practically a district of the second city. For example, Aramilsky UD is actually a district of Ekaterinburg and this is the reason for its very high level of interaction intensity U_i = 71 %. An example of even higher intensity is Verkh-Neyvinsky UD with U_i = 144 %, which actually merges into a single settlement with Novouralsky UD.

The diversification indicator D_i is quite low for all MDs. The maximum value is in UD Ekaterinburg with D_i = 0,44. Such a value indicates a strong heterogeneity and dispersion of u_{ij} values, which actually means that there are several MDj, which make the main contribution to D_i, while u_{ij} values for other MDs are near-zero. Figure 4 representing the histogram of the distribution of u_{ij} values for UD Ekaterinburg provide insight into the reasons for small values of D_i.

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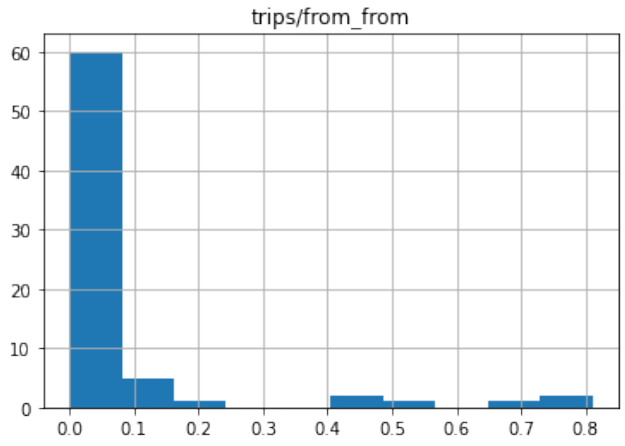

Figure 4. *Distribution of u_{ij} values for UD Ekaterinburg*

Source: compiled by the authors based on data from the "Geodata Analysis" module of the regional geoinformation system of Sverdlovsk region.

Comparison of D_i for different municipal districts shows that large municipal districts with high population have the highest values of the indicator. Thus, the second place after Ekaterinburg is occupied by Nizhny Tagil with D_i = 0,39 , followed by Serovsky and Severouralsky UDs with D_i = 0,37 . Small D_i values are characteristic of the above-mentioned MDs, which are connected with another MD either as "periphery – center" or as "big city district". In this case, the latter MD clearly dominates in terms of interaction over all other MDs.

Table 1

Classification of MDs according to their level of inclusion into the economic space

Class No.	Title	Criteria
I	Intensive diversified interaction	$U_i > \overline{U}, D_i > \overline{D}$
II	Intensive non-diversified interaction	$U_i > \overline{U}, D_i < \overline{D}$
III	Non-intensive diversified interaction	$U_i < \overline{U}, D_i > \overline{D}$
IV	Non-intensive non-diversified interaction	$U_i < \overline{U}, D_i < \overline{D}$

Source: compiled by the authors based on data from the "Geodata Analysis" module of the regional geoinformation system of Sverdlovsk region.

As noted above, based on the indicators U_i and D_i, we can assess the embeddedness of each MD into the system of spatial interconnections of the region. For this purpose, we classify all MDs on the basis of U_i and D_i indicators. We have used the average values of $\overline{U}$ = 26,15 and $\overline{D}$ = 0,235 as cut-off thresholds for class determination. As a result, all MDs have been divided into four classes according to the level of inclusion into the economic space (Table 1).

The classification results presented in Figure 5 and Table 2 show that U_i and D_i indicators exhib-

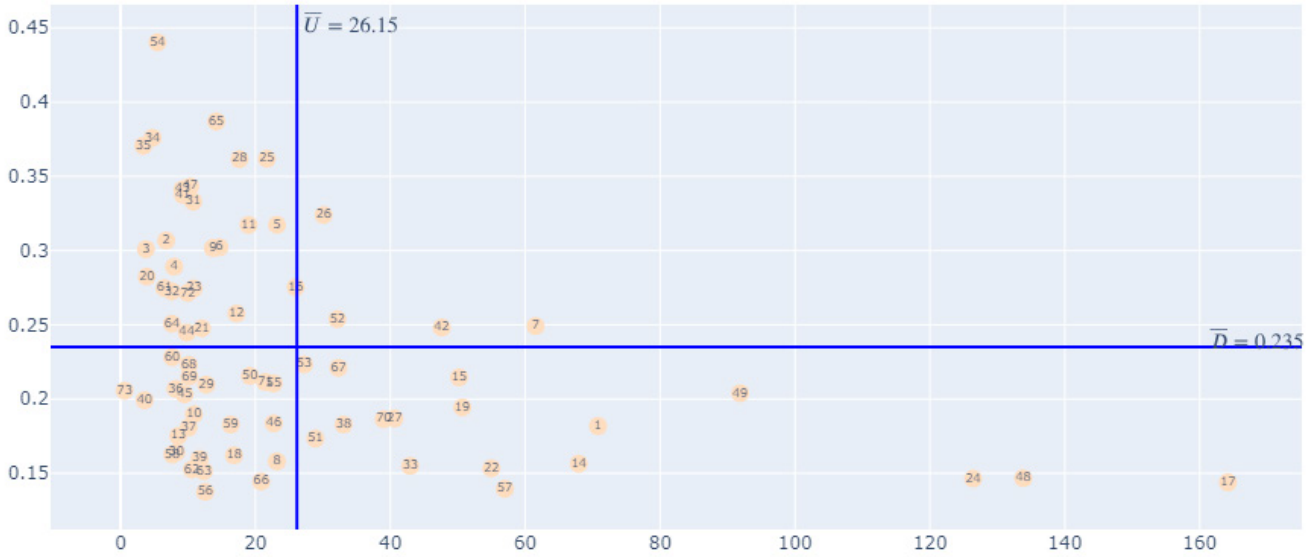

Figure 5. *Classification of MDs according to the values of intensity and diversifiability of interactions (the numbering of MDs corresponds to the numbering in Fig. 1).*

Source: compiled by the authors based on data from the "Geodata Analysis" module of the regional geoinformation system of Sverdlovsk region.

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Table 2

Distribution of MDs by level of involvement into the economic space

Class	I	II	III	IV
Number of districts	4	17	27	25
Share in the total number of MDs, %	5	23	38	34

Source: compiled by the authors based on data from the "Geodata Analysis" module of the regional geoinformation system of Sverdlovsk region.

it a mutually inverse relationship. For the majority of MDs, high interaction intensity is indicative of low diversification, and vice versa. MDs with low intensity have relatively well-diversified interactions.

Class I, which includes MDs with high intensity and diversified interactions, includes only four districts (5% of all MDs), while class IV (MDs with low intensity and diversified interactions) accounts for 34 % of all MDs.

The results demonstrate the spatial structure of inter-municipal interactions in Sverdlovsk region. Two regional centres (Ekaterinburg and Nizhny Tagil) have the highest diversification, with the majority of municipal districts in the region exhibiting a high intensity of interaction with them. Moreover, for these MDs, interaction with one or both of these centres is significantly higher than interaction with all other MDs (see Fig. 6).

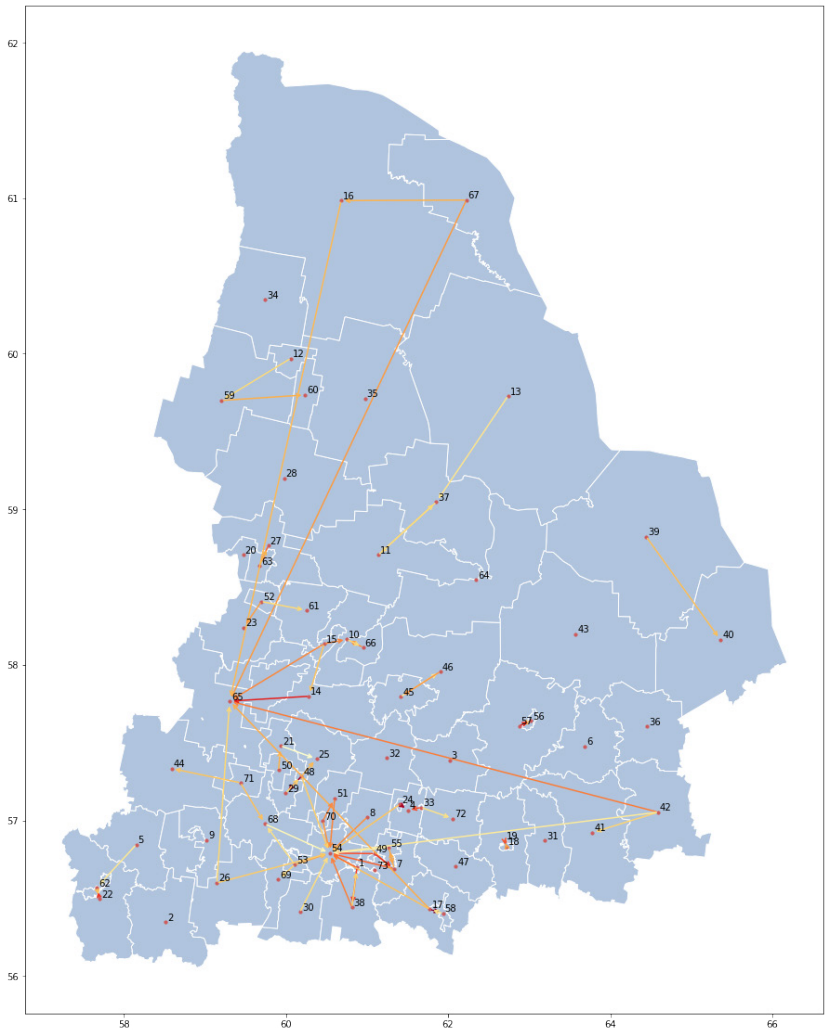

Figure 6. *Main inter-municipal interactions for u_{ij} > 5% (MD numbering corresponds to the numbering in Fig. 1).*

Source: compiled by the authors based on data from the "Geodata Analysis" module of the regional geoinformation system of Sverdlovsk region and map data from https://www.openstreetmap.org using tools of the Plotly library of the Python programming language.

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Discussion

The results of the study have revealed a number of distinctive characteristics in the structure of the economic space connectivity of Sverdlovsk region.

1. The spatial interrelations of the region are characterized by a bicentric system, with two distinct centers of attraction: the urban districts of Ekaterinburg and Nizhny Tagil. Ekaterinburg is the dominant center, exerting a significant influence over the region's spatial organization. Conversely, for the majority of peripheral municipal districts in Sverdlovsk region, inter-municipal communications are practically absent.

2. The data on population mobility demonstrate that Nizhny Tagil exhibits considerably stronger and more extensive interconnections with other MDs than would be expected based on its position in the transport network. Nizhny Tagil has a strong correspondence with several MDs in the southern part of the region, which is greater than their correspondence with Ekaterinburg, although the network configuration would suggest otherwise. It would be highly informative to ascertain the underlying causes of this phenomenon. However, this is beyond the scope of the present study, as a comprehensive analysis of the economic and social interconnections between these MDs and Nizhny Tagil is required.

3. The values of intensity and diversification of interactions differ significantly for the region's municipal districts. Based on the calculated estimates of these indicators, we proposed a classification of municipalities by the level of their inclusion into the economic space. The group with intensive diversified interaction includes only 5% of the considered municipal districts, 23% belong to the group with intensive non-diversified interaction, 38% of municipal entities are characterized by non-intensive diversified interaction and 34% fall on municipal entities with low intensity and diversification of interactions.

4. In terms of interaction intensity, we can emphasize a number of municipal districts with the lowest values of the indicator: Uralsky UD, Serovsky UD, Tavda UD, Artemovsky UD, the Kachkanarsky UD, Severouralsky UD, Ekaterinburg UD, and UD Krasnouralsk (U_i values ranging from 0.61 to 6.51), i.e. for these municipal districts, the intensity of internal links dominates over external ones for various reasons. Among the MDs where the intensity of external links dominates over internal ones, the highest indicators are observed in Malyshevsky UD, Verkh-Neyvinsky UD, Kamensky UD (U_i value, from 126.41 to 164.17). The obtained calculations show that the level of interaction intensity differs hundreds of times between the MDs with the minimum and maximum values, which indicates significant disparities in the level of communication between the municipal districts of Sverdlovsk region.

Conclusions

The analysis of population mobility data reveals that passenger flows align closely with the transport network and population distribution in Sverdlovsk region. The majority of population and economic activity is concentrated along the Kamensk-Uralsky – Ekaterinburg – Nizhny Tagil axis, particularly highlighting the industrial zone of Nizhny Tagil and the larger Ekaterinburg agglomeration. Additionally, a significant agglomeration is observed in the northern part of the region. In contrast, municipal districts outside these zones face poor transport connectivity, influenced by factors such as inadequate infrastructure, limited public transport options, and socio-economic conditions. Consequently, most passenger traffic from these districts is directed towards Ekaterinburg and Nizhny Tagil.

Therefore, estimates of population mobility derived from mobile operator data effectively capture both transport infrastructure availability and the intensity of resource exchange between municipal districts, enabling an assessment of the region's economic space connectivity.

The theoretical significance of these findings lies in advancing a socially-oriented approach to assessing regional economic space connectivity. This approach evaluates the efficiency of existing infrastructure through population mobility, a critical labor resource that shapes the socio-economic potential of any territory in both the short and long term.

These conclusions are valuable for policy-makers in formulating strategies to enhance regional spatial development policies by fostering cohesive and equitable infrastructure utilization across municipal districts.

Future research will explore significant factors influencing inter-territorial population mobility and sustainable trends in inter-municipal relations.

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