The network patterns characteristics research as one of the factors of traffic congestion

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Abstract. The article presents the planning structures analysis method of urbanized areas base on the geometric indicators of graph theory. For research, we developed a software package written in the Python programming language. The methodology of the analysis consists of identifying areas with a planning structure of a certain type in urban area and evaluating the selected area according to several calculated indicators. According to the results of the study, hypotheses were made about the impact of the type of planning structure on the level of traffic load of the city’s road network.

1. Introduction
Modern urban science identifies several basic types of planning structures - regular, scenic, radial-circular, combined. The indicated types of planning structure schemes appeared in ancient times and continue to be used in modern city-planning projects in explicit or modified form. At present, in the theory of urban planning, the question of the optimal choice of the type of planning structure when designing territories, based on their prospects for the development of the transport network, remains relevant.

This paper presents some criteria for comparing the types of planning structures, calculates the values of the criteria for each type and compares the characteristics of the planning structures in the context of the modern city fabric. The study examines the basic types of planning structures implemented in twelve cities of the world. The twelve examples considered are obviously insufficient number to form valid conclusions, therefore the objective of this study is limited to hypothesizing. However, the above method of analyzing the planning structures may be applicable for a full-scale study in order to prove the hypotheses put forward.

To conduct the research we developed a software package written in the Python programming language. Additionally, we used third-party libraries OSMnx, GeoPandas, NetworkX. We used maps of cities downloaded from OpenStreetMap. The following cities were studied: Adelaide (Australia), Bologna (Italy), Vancouver (Canada), Vienna (Austria), Yekaterinburg (Russia), Yokohama (Japan), Lyon (France), Manchester (United Kingdom), Samara (Russia), Barcelona (Spain), St. Louis (USA), Frankfurt (Germany). The choice of cities is due to the following criteria: the city is a large industrial
center, it is not a capital city (except for the city of Vienna), it has an extensive transport network and continues active urban development.

2. Selection of study areas in cities
The methodology of the analysis consists of identifying areas with a planning structure of a certain type in urban tissue and evaluating the selected area according to several calculated indicators. In order to solve the problem in each of the twelve cities, two sites were allocated with a regular and scenic planning structure. Since the radial-circular structure is extremely rare as a layout of individual sections of the city, examples with this structure were found only for two cities. To illustrate the characteristics of the planning scheme of the combined type, large-scale areas are considered, covering almost the entire territory of the city.

The size of the selected areas was limited to an area of no more than 10,000 square meters. Plots are selected in the vicinity of the central district of the city. For each site, the software selected a planning scheme, for which the basic and design characteristics of road networks are analyzed. The calculation of the characteristics was carried out in terms of the unit area of the urbanized territory.

An example of the selected area and the corresponding selected planning scheme for the city of Vancouver is presented in Figure 1.

![Figure 1. Vancouver city planning schemes (a) regular structure; (b) scenic structure; (c) combined structure.](image)

3. Congestion level of the cities
The congestion level is the main factor determining the delayed movement of vehicles. Increasing the congestion level leads to a decrease in the speed of the traffic flow. The load limit is usually reached on city highways during peak hours. Table 5 shows the average values of the congestion level for the studied cities, according to the Tomtom Traffic Index [1].
According to the given data, the most congested transport networks are owned by the cities of Vancouver, Yekaterinburg, Lyon, Manchester (the congestion level is more than 30%). The less busy cities are St. Louis, Yokohama, Vienna.

We should also note cities with high levels of transport service and comfort of living. Among the cities under consideration, according to the rating of the international consulting company Mercer, for 2017 there are Vienna (2nd place), Vancouver (3rd place), Adelaide (6th place), and Frankfurt (7th place in Europe) [2]. The Mercer index is based on the results of an annual comparative study of 450 cities in the world. Data evaluation is carried out according to 39 factors grouped into 10 categories, including the level of transport service quality (in the category "Public services and transportation / electricity, water, public transportation, traffic congestion, etc.").

Let’s consider the characteristics of the planning structures and transport networks of these cities and try to identify the differences inherent in cities with high quality transport service.

### 4. Main geometric characteristics of the transport network

As the main characteristics of the transport network, we considered the following indicators: the length of the transport network (km), the average length of the streets (km), the number of sections of the road network, the number of intersections. The obtained indicators show a general picture of the development of the transport network for each section, and also are the basis for calculating the more complex integral characteristics of transport networks.

The length of the transport network is the total length of all sections of the road network. It is measured along the street axis in one direction, regardless of the number of lanes [3]. Graphs of the obtained indicators of the transport network for various types of planning structures are presented in Figure 2.

| City         | Congestion Level, % |
|--------------|---------------------|
| St. Louis    | 13                  |
| Yokohama     | 21                  |
| Vienna       | 23                  |
| Bologna      | 24                  |
| Barcelona    | 25                  |
| Adelaide     | 27                  |
| Frankfurt    | 28                  |
| Samara       | 28                  |
| Manchester   | 30                  |
| Lyon         | 33                  |
| Yekaterinburg| 34                  |
| Vancouver    | 39                  |
Figure 2. Main indicators of the transport network for various types of planning structures (a) regular structure; (b) scenic structure; (c) combined structure.

Analyzing the graphs of indicators of transport networks on a regular layout, we can see that for the cities of Yokohama, Manchester and Lyon there is a large number of sections of the road network and intersections with low values of the average street length and the total length of roads, which indicates an increased density of the transport network on considered sites. Regular and combined planning of the cities of Yekaterinburg, Vancouver and Samara is characterized by a high value of the average length of the street, which can adversely affect the traffic load of these cities. Considering the regular planning structures of the cities of St. Louis, Barcelona and Lyon, we can see that the geometry of the quarter is close to the square, but this fact does not affect the values of the main indicators of transport networks.

Areas of the territory with a scenic layout of the cities of Yokohama and Samara are distinguished by an increased value of the indicator of the total length of roads. It is worth noting that in both cities the scenic planning structure on the considered sites was formed in relatively recent times with unregulated development of the territory; in the other cities the scenic parts were formed in the Middle Ages. The scenic layouts of Vancouver and Adelaide are characterized by a high degree of curvature of the roads, but this fact does not affect the picture of the main characteristics.

Studying the combined planning structures of the cities of Vienna, Bologna, Frankfurt and Adelaide we obtained a similar picture of the main indicators, determined by the correlated values of the average length of the street and the number of road network sites, we note that in these cities the combined planning is closest in its configuration to the radial-circular one.

5. Calculated transport network characteristics
To calculate the characteristics of the transport network, we represent the transport network as a connected planar graph $G$, having a certain number of vertices $n$ and edges $m$. As the estimated
characteristics of the transport network we consider the density of the road network, network connectivity, and Engel coefficient.

The density of road network is one of the main indicators of the development of the city’s road network and is determined by the ratio of the total length of streets and roads (L) to the built-up area of the territory (S) according to the following formula [4]:

\[ D = \frac{L}{S} \] (1)

The density of the network reflects the transport security of the territory and is measured by the number of kilometers of the network per 1000 km² of urbanized territory.

Increasing the density of the transport network increases the value of the indicator of service of the population of the city, but worsens the comfort of living. According to the current town planning standards (TSN 300-301-2002), the recommended density of transport networks in cities is accepted in the range of 4–5.5 km / km² [5].

The rank of network connectivity is the number of network links that can be removed (or blocked) without breaking the network into isolated fragments. Thus, the rank of network connectivity determines the number of possible alternative routes on the transport network [6].

A network is called connected if for any two of its vertices \( n_1 \) and \( n_2 \) there is a path from the vertex \( n_1 \) to the vertex \( n_2 \).

A connected network component is a certain subset of points such that for any two points of this set there is a path from one to another, and there is no way from the point of this set to a point that does not belong to this set.

Let a graph of a network \( G \) with \( n \) vertices and \( m \) edges contain \( k \) connected components. Then the rank of the connectivity of the network \( R \) is determined by the Euler formula:

\[ R(S) = m - n + k \] (2)

When presenting a road network as a graph, similar terms from graph theory can be used. In this case, the network connectivity rank is the cyclomatic number of the graph.

The zero value of the rank of connectivity between two points means the absence of a path between them. If the rank of the connection is equal to one, then the route has no alternative, i.e. there is only one path between two points.

Low network connectivity increases the likelihood of congestion and eliminates the use of smart transport systems, so one of the significant tasks of network design is to increase the connectivity rank [7]. The rank of connectivity should also be taken into account in the management of transport infrastructure [8]. Modern studies of the dependence of the connectivity on the accident rate on the road network determine that higher connectivity is associated with lower accident rates with the participation of pedestrians and cyclists [9, 10].

The meshedness coefficient (Gamma index) is an important property that evaluates the complexity and structure of the transport network with cycles of arbitrary lengths [11-13].

The entire network is represented through a set of elementary loops. The following elementary cycles are distinguished: triangular (length is equal to three), regular (length 4), hexagonal (length 6). The meshedness coefficient is determined by the formula:

\[ M = \frac{F}{F_{max}} \] (3)

where \( F \) – number of faces (without outer face) of a planar graph,
\( N \) – number of vertices,
\( K \) – number of edges by Euler formula \( (F = K - N + 1) \).
\( F_{max} \) – maximum possible number of faces in a connected planar graph having the same number of vertices \( N \) and edges \( K_{max} = 3N - 6 \). Thus, \( F_{max} = 2N - 5 \).

The value of the meshedness coefficient can take a value in the range \([0,1]\). In this case, the value zero corresponds to tree structure, and the value one is a connected graph.
Thus, the meshedness coefficient and the complexity of the structure are directly proportional. The Engel coefficient is interpreted as an indicator of public service and is used to assess the provision of a territory with a transport network. Calculated by the following formula:

\[ k_E = \frac{L}{\sqrt{S \cdot H}} \]  

(4)

where \( L \) – length of transport network in the region, km; \( S \) – territory space, km\(^2\); \( H \) – population, thousands people.

The calculation of the Engel coefficient was made only for the urban area as a whole, which is due to the lack of accurate population data for sites with regular and scenic planning structures. The values of the estimated indicators of transport networks obtained in the framework of the study are presented in Figure 3.

We can see on the presented graphs that there is no correlation between the density of road network, the meshedness coefficient and the type of planning structure. However, for the planning structure of the combined type, the rank of connectivity is an order of magnitude higher than for the planning structures of other types, which indicates an increased reliability of the transport network on the combined structure.

The cities of St. Louis, Manchester, Adelaide, Vancouver are leading in terms of the high Engel coefficient, which means a decent level of accessibility to the transport infrastructure in these cities. In the planning structures of these cities, an increased number of diagonal links are formed, forming the shortest paths of the peripheral points with the central regions of the city. It can also be concluded that the Engel coefficient or transport accessibility does not affect the level of traffic in the transport networks.

![Figure 3. Calculated indicators of transport networks.](image-url)
6. Conclusion
This paper presents a method for analyzing the planning structures of urbanized areas based on geometric indicators of graph theory. The proposed method is based on graph-analytical technique, which is one of the key tools for assessing and analyzing the urban development situation of an urbanized space.

The proposed method allows to:
- explore the existing or emerging planning structure in a specific area of urbanized territory;
- calculate objective indicators of transport networks on the presented planning structures;
- based on the calculated indicators, form an understanding of the quality of transport infrastructure and the level of transport accessibility at the studied site;
- make correct and reasoned design decisions when choosing a planning structure based on knowledge of the patterns of their operation.

The limited number of considered cities makes it impossible to draw an objective conclusion about the dependence of geometric indicators on the type of planning structure. Nevertheless, the proposed hypotheses indicate the necessary direction of research.

According to the results of the study, the following hypotheses were proposed:
- the main geometric indicators of the planning structure do not depend on its type;
- there is no correlation between the road network density, the meshedness coefficient and the type of planning structure;
- for a planning structure of the combined type, the rank of connectivity is an order of magnitude higher than for planning structures of other types;
- an increase in the number of diagonal links leads to an increase in transport accessibility;
- transport accessibility does not affect the level of congestion of transport networks;
- trunk networks of cities that have a radial-circular configuration, have similar values of average street length and number of sections of road network.

The direction of further research should be related to the justification of the proposed hypotheses. For these purposes, it is necessary to study planning structures for a larger number of urbanized sites in various cities of the world with the involvement of Big Data technologies.

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