**1. Introduction**

Public passenger transport (PPT) is an integral part of a modern city infrastructure and a means of its residents’ commuting. It provides access to performing economic functions and implementing social needs to all segments of the population, including those who cannot afford a private car (people with low incomes), lack physical ability to operate a car, or have no driver’s license (underage children, elderly people with health problems, and disabled persons). Thus, municipal public transit is one of the mechanisms to secure citizens’ constitutional rights to work, education, medical care, and recreation. Besides, the PPT industry itself is a source of jobs. Research findings show that investments in the PPT infrastructure create by 19 % more jobs than similar investments in the construction of roads and road facilities [1].

The current rapid increase in private car ownership is a worldwide trend, and Ukraine is not an exception. By early 2014, the existing fleet of private cars in Ukraine had reached 6,514,500 units, i.e. almost 1.5 million cars more than in 2000 [2]. During the same period of time, the corresponding rate of car ownership, i.e. the number of registered private cars per 1,000 residents of the country had increased from 104 to 143 units per 1,000 persons (Fig. 1) [3].

The planning and development of cities in the former USSR depended on the standard rate of motorization, which amounted to 60–70 cars per 1,000 residents with a maximum promising value of 180 cars per 1,000 residents [4]. The growing rate of private car ownership in Ukraine (given the fact that concentration of cars in cities is higher than the national average) shows that the maximum level of car ownership will be (if not yet) exceeded in the near future.

![Graph showing the dynamics of the rates of private car ownership and PPT commuting in Ukraine during 2000–2012](image-url)

**Fig. 1. The dynamics of the rates of private car ownership and PPT commuting in Ukraine during 2000–2012**

The increase in the rate of private car ownership leads to a larger fraction of city residents’ intercity commutes in personal vehicles and, consequently, reduces the volumes of PPT transits and passenger traffic, which is defined as a number of PPT commutes per capita per year (Fig. 1). According to experts on urban transport [4], the share of commutes in personal vehicles in intercity traffic comprises 54 % when the rate of motorization is 150 cars per 1,000 people, and it increases to almost 75 % when the rate of motorization is 300 cars per 1,000 people.

Therefore, attracting car owners to use PPT is a possible way to overcome the negative effects of motorization. This involvement on a voluntary basis is possible only if the ser-
vice quality rate and the PPT commute costs are at least not worse in comparison with commuting in a private car.

The quality of passenger transit services is determined by several factors, among which the most important one is the commuting system development rate. The latter is a geographically and temporally determined complex of all routes and particular PPT types that function within a given transport network [3]. The territorial linkage provides a consistent placement of individual routes, whose sum forms a route network of one or various PPT types, on the city maps. Respectively, parameters and characteristics of a commuting network directly affect the degree of the PPT attractiveness for city residents. Therefore, the urgent task is to assess the nature and extent of the impact of the commuting network development rate on the PPT routes of city residents.

2. Analysis of previous studies and statement of the problem

Ukrainian and foreign researchers have contributed much attention to the problems of optimal design and improvement of the PPT route networks. The development rate of a route network determines a potential accessibility of residents to PPT and affects the parameters that reflect the level of quality of its services, such as the passenger’s commuting time, transit combinations, and travel costs.

Since the emergence of the theory of urban passenger transport, there have been suggested parameters derived analytically from the physical nature of passenger transportation and from certain assumptions about passenger behaviour — the route network density and the route ratio [5]. The above parameters are useful since their values are quite manageable at the stage of designing a route network, and they directly affect PPT performance characteristics.

In the second half of the 20th century, characteristics of commuting networks such as, in particular, degree of circuitness, complexity index, and degree of connectivity as well as indices of coverage and directness, were commonly based on the classic theory of graphs [6]. Subsequently, these parameters have been analysed from the point of view of their relation to socioeconomic indices of development of areas that are serviced by the studied commuting networks [7].

It is natural that the first objects of study within PPT route networks were urban underground networks, which is due to their topological simplicity, relatively few lines as well as public availability of information on the networks’ structure and the passenger traffic. The latter reason has prevented extensive research of traditional route networks of land PPT (bus, trolleybus, and tram) that are much larger and much more complex in big cities. However, in recent years, due to the rapid development of information systems and technologies, the increased computing capacity and the availability of data on the structure of route networks in the Internet, such networks are increasingly becoming objects of research aimed at a comprehensive analysis and a comparison. An important impetus for this development was the relatively new field of knowledge – the theory of complex networks [8] – that laid the basis for a number of additional characteristics that are determined by the route network topology and allow a comprehensive comparative analysis of the structure of various PPT route networks.

Within the framework of the theory of complex networks, there are studies of the topology and development rate of a number of PPT route networks, including underground networks in 19 cities of the world [9], the route networks of city buses in China [10] and India [11], and land PPT in major cities of Ukraine [12]. However, the research has focused on the comparative analysis of route networks and their classification as well as common characteristics and differences between them but overlooked the task of searching for a connection between characteristics of a route network development and performance indices of passenger traffic.

Study [13] presents a statistical analysis of the dependence between development indices of underground networks in 19 cities of the world and passenger mobility on the subways of the respective cities, whereas another study [14] presents similar research on subways in 50 US cities, with an aim to reveal statistical dependence between the performance of these networks, their load, and specific indicators of a daily mileage of a rolling stock per a passenger transported. However, currently there are no similar studies of land PPT networks; thus, the nature and extent of dependence between network parameters and passenger traffic indices (which reflect attractiveness of PPT to passengers) have been unexplored.

3. The purpose and objectives of the study

The purpose of the research is to identify the nature and extent of the impact of developing urban land route networks of electric transport in large cities of Ukraine with population of 0.5–1.0 million residents on the population commuting rates in the studied cities as assessment of the transport attractiveness to their residents.

The purpose can be achieved by solving the following objectives:

1. use data on the configuration of route networks of urban land electric transport in formalizing their representation on the basis of the theory of graphs and the theory of complex networks and calculate their development indices,

2. use methods of correlation and regression analyses to reveal the nature and extent of the influence of the development of the studied networks on the passenger mobility and give a relevant interpretation of the results.

4. General characteristics of the studied cities and their commuting networks

Ukraine has four cities with a population of 0.5 to 1.0 million residents that according to DBN 360-92** “Town planning. Planning and development of urban and rural settlements” belong to a group of large settlements: Donetsk, Zaporizhzhia, Kryvyi Rih, and Lviv. PPT in these cities is multimodal and represented in its traditional forms – bus (shuttle bus included), trolleybus, and tram. There are no subway lines in these cities, but Kryvyi Rih has an operating speed tram line with underground sections. The city of Odesa (Ukraine) is also included in the list of the studied cities since its population fluctuates around 1 million residents, and its PPT has similar characteristics to those of the above-mentioned major cities. General characteristics of the studied cities and their route networks are presented in Table 1.
5. Formalising municipal route networks in graphs

It is convenient to present PPT route network as a graph. In mathematics, the graph theory defines the notion of graph G as a combination of two sets G = {V,E}: a nonempty V set, all elements of which are called the graph vertices, and a set of unordered pairs of vertices E of set V, each of which is an edge of the graph [16]. The graph vertices are identified by their serial numbers in set V. Two different vertices of the graph vᵢ, vⱼ ∈ V (i ≠ j) are called adjacent if they are connected by an edge (vᵢ, vⱼ) ∈ E.

The PPT route network graph can be presented in different ways that are distinguished by approaches to the formation of sets of the graph vertices and edges that are known as spaces [8]. A route network fragment (Fig. 2, a) consisting of seven stops (1–7) and three routes (A, B, and C) is presented as a graph in different spaces, as shown in Fig. 2, b–d.

The space of stops (L-space, Fig. 2, b) is a simple graph whose vertices represent municipal PPT stops. Two vertices are connected by edges if stops that correspond to the vertices are consistent at least on one of PPT routes. Vertices connected by an edge in this space may not be physically consistent on the road network (on which the routes are laid) if public transport of some routes does not use all stops (for example, in case with express traffic mode).

The space of connections (P-space, Fig. 2, c) is a simple graph whose vertices represent public transport stops. Two vertices are connected by an edge if stops that correspond to these vertices at the same time belong to at least one of the routes. In other words, the presence of an edge between vertices in this space means that a passenger can travel between these vertices at the same time.

The space of routes (C-space, Fig. 2, d) is a simple graph whose vertices represent routes of municipal public transport. Two vertices are connected by an edge if routes that correspond to the vertices have at least one common stop.

6. Parameters of the route network development and calculation of their values for the studied cities

The main topological parameters of the route networks that are studied in the theory of complex networks and influence the development of the latter include [17]: the average degree of the network vertex \( k \), the average length of the shortest path in the network \( l \), the clustering coefficient \( C \), and the assortativity coefficient \( r \).

The average degree of a network vertex \( k \) is defined as the arithmetic mean of the degrees of all vertices in the network, i.e.

\[
\langle k \rangle = \frac{1}{V} \sum_{i=1}^{V} k_i,
\]

where \( V \) is the number of vertices in a network and \( k_i \) is the degree of vertex \( i \), i.e. the number of edges which are incidental to the vertex.
The average length of the shortest path in a network (l) determines its linear characteristics and is calculated as the arithmetic mean of the shortest paths between all pairs of vertices in the network $|v_i|$ that are expressed in the number of edges on each path:

$$l = \frac{2}{V(V-1)} \sum_{i=1}^{V} l_{ij},$$  

where $l_{ij}$ is the length of the shortest path between vertices $i$ and $j$.

The clustering coefficient of some $i$ vertex in the network determines the probability that two vertices adjacent to it are adjacent to each other; the former is calculated by the following formula:

$$C_i = \frac{2E_i}{k_i(k_i-1)},$$

where $E_i$ is a sum total of the number of edges that interconnect all vertices adjacent to the given one.

The clustering coefficient of the whole network $C$ is calculated as the arithmetic mean of the clustering coefficients of all its vertices, i.e.

$$C = \frac{1}{V} \sum_{i=1}^{V} C_i.$$

The assortativity coefficient of the network $r$ is calculated as the coefficient of the linear Pearson correlation between pairs of degrees of all adjacent vertices in the network by the following formula:

$$r = \frac{\sum_{i=1}^{V} \sum_{j=1}^{V} k_i k_j - \left( \sum_{i=1}^{V} k_i \right)^2}{\sum_{i=1}^{V} \sum_{j=1}^{V} k_i^2 - \left( \sum_{i=1}^{V} k_i \right)^2},$$

where $k_i$ and $k_j$ are degrees of the network vertices that are incidental to the given edge.

Table 2 shows calculated topological indices of municipal electric transport route networks in the studied cities. In Table 2, trolleybus is designated as TR and tram – as T. Indices of the relevant parameters indicate the space for which these values are calculated, i.e. L, P or C (Fig. 2).

Analysis of the obtained values of the vertex average degree $\langle k \rangle$, length of the average shortest path $\langle l \rangle$ and the clustering coefficient $C$ shows that the studied route networks in all spaces occupy an intermediate position between the classic Erdős-Rényi (ER) random graphs and regular graphs (D), which can be represented by the following ratios [18]:

$$\langle k_{ER} \rangle = V \cdot \langle k \rangle,$$

$$\langle k_{D} \rangle = \text{const},$$

$$\langle l_{ER} \rangle = \frac{\ln(V)}{\ln(k_{ER})},$$

$$\langle l \rangle = V^{\frac{1}{\langle k \rangle}},$$

where $V$ is the number of vertices in a network.

The calculated values suggest an idea of the studied networks and allow drawing some conclusions about their structure and characteristics. For example, in terms of a route network scheme, the most extensive are the networks of electric transport in Lviv and a trolleybus network in Odesa with $\langle k \rangle = 2.53...2.60$, whereas the least ramified are route networks of electric transport in Zaporizhia and the tram network in Donetsk, with close to tree-shaped topologies and $\langle k \rangle = 2.06...2.07$. Meanwhile, given an equal probability of passenger correspondence between all stops in the network, the average length of a trolleybus travel in Kryvyi Rih ($\langle l \rangle = 24.6$) exceeds its counterpart in Odessa almost twice ($\langle l \rangle = 12.1$). Under the same assumptions, the tram network in Kryvyi Rih, with $\langle l \rangle = 1.31$, is a network with the fewest connections, whereas the tram network in Odessa, with $\langle l \rangle = 2.59$, has most of all connections in comparison with other studied networks.

### Table 2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Donetsk</th>
<th>Zaporizhia</th>
<th>Kryvyi Rih</th>
<th>Lviv</th>
<th>Odesa</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\langle k_v \rangle$</td>
<td>2.07</td>
<td>2.07</td>
<td>2.14</td>
<td>2.17</td>
<td>2.53</td>
</tr>
<tr>
<td>$\langle k_e \rangle$</td>
<td>26.7</td>
<td>32.6</td>
<td>36.7</td>
<td>34.4</td>
<td>47.3</td>
</tr>
<tr>
<td>$\langle l_v \rangle$</td>
<td>4.22</td>
<td>3.17</td>
<td>6.20</td>
<td>6.50</td>
<td>11.3</td>
</tr>
<tr>
<td>$\langle l_e \rangle$</td>
<td>22.2</td>
<td>19.2</td>
<td>15.4</td>
<td>15.1</td>
<td>14.9</td>
</tr>
<tr>
<td>$\langle l \rangle$</td>
<td>2.22</td>
<td>2.70</td>
<td>1.63</td>
<td>1.67</td>
<td>1.31</td>
</tr>
<tr>
<td>$\langle l_p \rangle$</td>
<td>1.56</td>
<td>2.80</td>
<td>1.31</td>
<td>1.07</td>
<td>1.31</td>
</tr>
<tr>
<td>$C_P$</td>
<td>0.965</td>
<td>0.903</td>
<td>0.855</td>
<td>0.871</td>
<td>0.872</td>
</tr>
<tr>
<td>$C_C$</td>
<td>0.644</td>
<td>0.603</td>
<td>0.864</td>
<td>0.941</td>
<td>0.874</td>
</tr>
<tr>
<td>$r_L$</td>
<td>0.220</td>
<td>0.004</td>
<td>0.045</td>
<td>0.141</td>
<td>0.467</td>
</tr>
<tr>
<td>$r_P$</td>
<td>0.224</td>
<td>0.165</td>
<td>0.020</td>
<td>-0.13</td>
<td>-0.19</td>
</tr>
<tr>
<td>$r_C$</td>
<td>-0.26</td>
<td>-0.20</td>
<td>-0.17</td>
<td>-0.32</td>
<td>-0.14</td>
</tr>
</tbody>
</table>
The researched networks are characterized by high values of the clustering coefficient in the spaces of routes and connections, the latter having signs of the “tight world”, i.e., there are small values of the average shortest path in comparison with the number of vertices of the network.

### 7. A correlation-regression analysis of how indices of the transportation network development affects passenger traffic

The nature and extent of the impact of electric transport networks’ development indices on passenger traffic \( BPC \) (commutes on public electric transport per capita per year) are analysed with the help of the linear Pearson correlation coefficient \( r_{xy} \). Since the latter requires normal distribution of factorial and efficiency features and is very sensitive to random emission as well as correlation between passenger traffic \( BPC \) (the result) and each individual parameter of the route network (the factor variable), the research is made in the following sequence:

1. excluding abnormal emissions from statistical sampling by the Shovene criterion [19],
2. testing emission-verified samples for normal distribution by the Shapiro-Wilk criterion [19],
3. calculating the linear Pearson correlation coefficient \( r_{xy} \) for each “factor – result” [20].

The main statistical characteristics of factors and results of calculation of the linear correlation coefficient between them and passenger traffic are shown in Table 3.

**Table 3**

<table>
<thead>
<tr>
<th>Parameter (factorial feature)</th>
<th>Mathematical expectation ( \langle x \rangle )</th>
<th>Standard deviation ( \sigma_x )</th>
<th>The coefficient of variation ( v = \frac{\sigma_x}{\langle x \rangle} )</th>
<th>The coefficient of correlation ( r_{xy} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \langle k_r \rangle )</td>
<td>2.255</td>
<td>0.216</td>
<td>0.096</td>
<td>-0.167</td>
</tr>
<tr>
<td>( \langle k_c \rangle )</td>
<td>32.99</td>
<td>6.733</td>
<td>0.204</td>
<td>0.289</td>
</tr>
<tr>
<td>( \langle l_c \rangle )</td>
<td>6.099</td>
<td>2.359</td>
<td>0.387</td>
<td>-0.573</td>
</tr>
<tr>
<td>( \langle l_r \rangle )</td>
<td>16.78</td>
<td>5.718</td>
<td>0.341</td>
<td>0.280</td>
</tr>
<tr>
<td>( \langle k_r \rangle )</td>
<td>2.017</td>
<td>0.470</td>
<td>0.233</td>
<td>0.551</td>
</tr>
<tr>
<td>( \langle a_r \rangle )</td>
<td>1.701</td>
<td>0.523</td>
<td>0.307</td>
<td>0.171</td>
</tr>
<tr>
<td>( C_r )</td>
<td>0.081</td>
<td>0.066</td>
<td>0.080</td>
<td>0.023</td>
</tr>
<tr>
<td>( C_p )</td>
<td>0.863</td>
<td>0.051</td>
<td>0.059</td>
<td>0.485</td>
</tr>
<tr>
<td>( C_c )</td>
<td>0.749</td>
<td>0.128</td>
<td>0.171</td>
<td>-0.557</td>
</tr>
<tr>
<td>( r_r )</td>
<td>0.154</td>
<td>0.154</td>
<td>1.002</td>
<td>-0.182</td>
</tr>
<tr>
<td>( r_p )</td>
<td>0.052</td>
<td>0.141</td>
<td>2.703</td>
<td>0.582</td>
</tr>
<tr>
<td>( C_r )</td>
<td>-0.042</td>
<td>0.279</td>
<td>6.681</td>
<td>-0.387</td>
</tr>
</tbody>
</table>

An analysis of the calculations shown in Table 3 indicates that parameters \( \langle l_r \rangle \), \( r_p \), \( \langle k_r \rangle \) and that represent the route network in the spaces of connections and routes have an average correlation dependence \( (r_{xy} = 0.5...0.7) \). Diagnostics of dispersion for these parameters with overlaying calculation lines of regression derived by the method of least squares are shown in Fig. 3, \( a–d \).

**Fig. 3.** Diagrams of dispersion and an empirical regression line of the dependence of the number of commutes per capita per year \( BPC \) on the topological parameters of electric transport route networks: \( a \) — the average shortest path in the space of connections \( \langle l_r \rangle \); \( b \) — the coefficient of assortativity in the space of connections \( \langle k_r \rangle \); \( c \) — the average degree of vertices in the space of routes \( \langle k_c \rangle \); \( d \) — the clustering coefficient of the network in the space of routes \( C_c \).

The results of the pair linear regression analysis of the parameters shown in Fig. 3 are shown in Table 4.

**Table 4**

<table>
<thead>
<tr>
<th>Factor</th>
<th>Regression equation</th>
<th>The coefficient of determination ( R^2 )</th>
<th>The standard error ( S )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \langle l_r \rangle )</td>
<td>( BPC = 1.08 + 26.13 \cdot \langle l_r \rangle )</td>
<td>0.30</td>
<td>17.51</td>
</tr>
<tr>
<td>( r_p )</td>
<td>( BPC = 43.54 + 81.88 \cdot r_p )</td>
<td>0.34</td>
<td>17.06</td>
</tr>
<tr>
<td>( \langle k_r \rangle )</td>
<td>( BPC = 77.11 - 4.81 \cdot \langle k_r \rangle )</td>
<td>0.33</td>
<td>17.19</td>
</tr>
<tr>
<td>( C_c )</td>
<td>( BPC = 112.1 - 85.89 \cdot C_c )</td>
<td>0.31</td>
<td>17.43</td>
</tr>
</tbody>
</table>

According to the data on the calculated coefficient of determination \( R^2 \), 30–35% of the changing passenger traffic on municipal electric transport in the studied cities is statistically predetermined by the varying selected factors.

**8. Discussing the research findings**

The researched route networks show that the degree of their development is not decisive in terms of attractiveness to passengers. Lower fares, in comparison with bus transport fares, and free of charge travel for a considerable proportion of the urban population of Ukraine have led to a situation...
where municipal electric transport is mostly used by persons with relatively low incomes. However, as the above calculations show, some parameters of route networks still have a significant correlation with passenger traffic in these networks, so they require substantive interpretation.

The average length of the route network shortest path in the space of connections \( L_P \) reduced by a unit reflects the average number of connections passengers make when travelling between two randomly selected stops. Thus, higher values \( L_P \) correspond to the route network that has a potentially higher shuttle connectivity assuming a constant value for passenger correspondence between all the stops. The possibility of travelling almost without connections attracts potential passengers, but on the other hand, a more extensive connectivity combination results in more route commutes. Respectively, the latter factor prevails, thus increasing the value by 1 % leads to almost the same increase in the proportion of annual route travels.

The factor of the network assortativity \( r_P \), \( 0 \leq r_P \leq 1 \) is represented by the property of its vertices to be adjacent. This is especially true for high-degree vertices (the so-called “hubs”). Networks with positive assortativity coefficient values are called assortative, while those with negative values are disassortative. In the networks under consideration, high-degree vertices are the stops from which passengers can get directly to a large number of other stops. Obviously, these stops are common to many routes and, therefore, represent major interchange nodes. Negative values \( r_P \) correspond to route networks whose interchange nodes are located at a considerable distance from each other; positive – on the contrary – reveal the concentrations of interchange nodes in the city. Thus, route networks which are assortative in the space of connections are characterized by relatively larger passenger traffic; when the assortativity coefficient is raised by 0.01 %, the BPC value increases by 1.8 %.

The value of the average degree of the network vertex represented in the space of routes \( k_P \) is an average number of routes with which this route has at least one common stop. If the parameter value increases, there is an increase in the route overlays, i.e. their full or partial duplication. Such networks are characterized by a high value of the route coefficient [5]. If the latter increases while the capacity of transport vehicles remains unvaried (which is typical of the studied networks), the network traffic interval and, respectively, the average waiting time at stops become longer. Thus, an increasing value \( k_P \) makes the route network less attractive to potential passengers, and a 1 % increase of this index leads to a lower passenger traffic on average by 0.61 %.

A similar characteristic of the route network is reflected by its clustering coefficient \( C_C \), \( 0 \leq C_C \leq 1 \) in the space of routes. It suggests a probability that any random pair of routes, each of which has at least one common stop with the given route, also have at least one common stop. Such situations usually occur when a stop is common for three or more routes. Respectively, higher values of clustering coefficients correspond to relatively larger traffic intervals on the network and reduce the transport traffic on average by 1.37 % with an increase in value \( C_C \) by 1 %.

Thus, the studied characteristics allow making a comparative analysis of different route networks in terms of passenger traffic and forecasting the volumes of transport traffic in networks with varied topological structures.

9. Conclusions

1. Graph theory methods were used to formalize representation of route networks of urban electric transport in large cities of Ukraine in the spaces of stops, connections and routes and calculate the indices of their development, such as the average degrees of vertices, the values of average shortest paths, clustering coefficients as well as the coefficients of assortativity and centrality of mediation vertices – on the basis of the theory of complex networks. It is found that the studied networks occupy an intermediate position between the Erdős-Rényi (ER) random graphs and regular graphs.

2. The method of correlation and regression analysis was used to research the nature and the extent of impact of the studied route network characteristics on the number of commuters per capita per year in the respective network. It is found that the average degree of correlation with passenger traffic characterizes the indices of the shortest path, the coefficient of assortativity of the route network represented in the space of connections, the average degree of the vertex and the clustering coefficient of the network represented in the space of routes. The suggested substantive interpretation presents a correlation observed between factors and passenger traffic on municipal electric transport in the studied cities.

References

Экосистема с ее структурными единицами (подсистемами) рассматривается как открытая термодинамическая система, в которой постоянно происходит обмен энергией и веществом с внешней средой. При подаче энергии в экосистему часть ее рассеивается, а другая часть превращается в тепло. Рассмотренная система соответствует требованиям, предъявляемым к системам способным к самоорганизации [1, 2]:

1. Вступ

Представлен результаты анализа моделей нелинейной кинетики экосистемных процессов при вспомоществовании и почернении организмов в окружающей среде. Обсуждены необходимость учета при анализе антропогенного влияния на биосферу процессов автокатализа и самоорганизации живых систем. Разработана модель синергетических закономерностей эволюции видов в контексте традиционного континуального представления при учете бифуркационных механизмов синергетической теории познания.

Ключевые слова: нелинейная кинетика, экосистемные процессы, модели, техногенные факторы, синергетические закономерности