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RESEARCH ARTICLE

Scientific basis for improving the efficiency of urban street and road network operation

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Abstract
The study is an experimental and theoretical analysis of the patterns of traffic flows and the possibilities of their distribution on urban street and road networks. It considers and analyses modern approaches that make it possible to improve traffic flow control mechanisms and traffic conditions on a street and road network. Based on the established internal relationships, the paper develops a model of the influence of factors on the level of their priority, which makes it possible to divide them by hierarchy levels and, accordingly, to observe the level of their impact on independent components. The scientific novelty of the research lies in the newly developed method of vehicle traffic control, which involves the distribution of traffic flows along the urban street and road network. The conclusions presented in the study represent scientific and methodological developments and applied recommendations that can be used in urban planning to improve the conditions of transport services in populated areas.

1. Introduction

The number of vehicles on roads has dramatically increased worldwide, especially in cities, which causes numerous traffic problems. Vehicles are designed to improve the living conditions of people, but vehicle use, in many cases, has negative consequences, leading to the deterioration of these conditions. The reasons behind traffic problems in urban areas are inconsistency between the capacity of the street network and the present traffic volumes and the imperfection of approaches to the management and organisation of traffic and pedestrian flows. The street and road network is a complex element of the urban transport system; its development and operation are essential for the functioning of the entire city. Each city is an individual, unified, and integral dynamic system, with the street and road network as one of its components.

Traffic problems have become one of the main issues in large cities in Ukraine. The urban street and road network of Ukraine cannot withstand the traffic load that is growing daily. The increase in the number of vehicles, particularly individual transport, has led to overloading of the urban street and road network, lower speeds, traffic jams, and traffic delays. The failure to predict the behaviour of all road users aggravates the situation on urban streets. Drivers choose their traffic route at their discretion and thus overload individual runs and transport nodes on this street and road network. Furthermore, the increase in the number of vehicles causes a deterioration in traffic safety conditions, an increase in road traffic accidents (RTA), and a significant negative impact of harmful factors of vehicles on the environment.

Since the technical condition of the street and road network is imperfect, and urban planning does not comply with the actual traffic volume, many settlements have faced the following negative consequences: noise; gas pollution; an increase in the time spent on travel; excessive fuel consumption; frequent RTA; decreased efficiency of public transport; negative impact of vehicles on the environment; complicated organisation of street parking lots; and difficult maintenance work for the urban street and road network. The primary task of the street and road network operation is to ensure a convenient, comfortable, and safe process of moving vehicles and pedestrians (Kyrylenko et al., 2022).

The patterns of formation of traffic flows and the features of their movement over the urban street and road network indicate their uneven loading. Alternative routes can be used up to their maximum load instead of already congested streets. Therefore, Ukrainian cities urgently require the development and implementation of effective methods for the management of traffic and pedestrian flows that would provide an optimal distribution of traffic along the elements of the street and road network with minimal use of financial, energy, and material resources. Hence, the improved operation of the street and road network and vehicles involves creating and ensuring convenient and safe conditions for pedestrians, as well as conveying passengers and cargo, and with minimal time and energy resources.

Problems such as traffic jams and delays are due to heavy traffic on urban roads and highways that is not yet sufficiently controlled and organised. Therefore, it is necessary to develop a methodology that would prevent the causes of these problems and thus ensure effective operation of street and road networks in large cities in Ukraine under the intensive annual increase in vehicles.

In this paper, we aim to develop a methodology that can increase the efficiency of the street and road network operation in large cities in Ukraine. The achievement of the defined aim involves solving the following tasks:

- to analyse the current condition of the street and road network and identify the features and patterns of its development as the main component of the urban transport system;
- to identify the primary external and internal factors that affect the operation of the urban street and road network;
- to provide scientific substantiation of the criteria for assessing the efficiency of operation of the street and road network;
- to analyse and generalise scientific provisions on the formation and distribution of traffic flows on the main streets of urban areas;
- to develop and conduct a set of experimental studies to determine the time inevitably spent by vehicles moving over the urban street and road network;
- to theoretically substantiate the methods for solving problems of optimal traffic management on the street and road network based on the adopted methodology;
- to develop theoretical foundations and methodological approaches to the implementation of the traffic flow management and distribution system on the urban street and road network.

2. Materials and methods

The aim, objectives, and problems of efficient use of the urban street and road network were determined with the help of methods of systems theory and system analysis. The theoretical part of this research relies on methods of mathematical modelling, reliability theory, probability theory, mathematical statistics, and traffic flow theory. The experimental (empirical) part is based on field observations using generally accepted methods and special equipment. Thus, we experimentally assess the distribution of vehicles and the volume of traffic flows, calculate vehicle delays, and determine the mobility of the population.

The urban street and road network is a complex engineering structure primarily designed to provide vehicle and pedestrian traffic and service for road users, such as drivers, passengers, and pedestrians.

The main task when improving the operating characteristics of the urban street and road network is to create and ensure the efficiency of its operation. The study of the operating conditions of the street and road networks in the largest urban areas of Ukraine makes it possible to find the reserves of the maximum load of the corresponding sections of the network and the potential distribution of traffic flows along the given network (Kryshtanovych et al., 2021).

However, the experience of developed countries shows such measures cannot provide a sustainable and lasting effect under the conditions of increasing motorisation and limited financial opportunities. It is necessary to apply a set of measures that already have confirmed results in other countries that have experienced a critical period of motorisation similar to that which Ukraine is now experiencing. In this paper, we analyse the experience of developed countries to consider the possible measures for solving traffic problems in urban areas. The only possible way to solve traffic problems in urban areas is the integrated application and implementation of measures, such as legislative and regulatory, urban planning, technical, administrative, and traffic control measures (Stepanchuk, 2012).

The basis for all measures to improve the operating conditions of the street and road network is the regulatory legal framework, which includes the main legislative acts and regulatory documents relating to the design and development of settlements, streets, and urban roads, as well as issues of operation and maintenance of elements of urban transport systems.

When implementing urban planning measures, the primary task is to design a compact and convenient settlement that will partially or entirely eliminate the need to use personal transport vehicles. The need for cars and public transport to move people should be minimal. In the context of a growing number of cars and increased population mobility, urban planning measures make it possible to streamline the interchange system and ensure less car traffic.

Urban planning includes the following: specific land use; planning and development of urban areas; determination of the main directions and scale of development of the urban transport infrastructure and its zone of influence; design of street and road networks; and placement of garages and parking zones in the context of prospective development of the urban transport infrastructure. The efficient placement of places of attraction plays an essential role in urban planning since it helps to reduce the traffic volume and the total traffic load on the urban street and road network (Kryvoruchko, 2009; Stepanchuk and Bashinsky, 2016; Bieliatynskyi et al., 2022a).

Urban planning aimed at improving the efficiency of the street and road network is based on the division of the city into transport planning areas with an approximate regional balance between the number of the working population and the number of jobs. Such a balance does not determine that all the working population should work in the area of their residence. The transfer of the working population between city districts will occur, but will also comply with the requirement of a relative decrease in the number of trips. The regional balance makes it possible to reduce the mass transfer of the working population from one district to another. Such an approach reduces population mobility and, consequently, the traffic load on the urban street and road network.

According to data from the State Statistics Service of Ukraine (2016), it is possible to reduce the use of transport by 10–15% by streamlining the movement of people for cultural and domestic purposes. Technical measures involve the following: road construction; street and road network reconstruction; the construction of traffic interchanges, pedestrian bridges, and crosswalks; the arrangement of parking and storage facilities; the construction of ring roads to divert transit flows; and the use of underground space. These measures should also ensure that elements of the transport infrastructure comply with the requirements of industry construction standards (Derzhbud of Ukraine, 2007; Ministry of Regional Construction of Ukraine, 2016).

Both the organisation and the management of traffic over the urban street and road network are designed to maximise transport speed, increase the traffic capacity of the entire urban system, and improve traffic safety. Here, traffic organisation refers to the distribution of traffic flows in coplanar and non-coplanar space, and traffic management involves methods and techniques for distributing traffic flows in time (Vatamanyuk, 2019).

The introduction of administrative measures provides for toll roads, improved operating conditions of public transport, priority development of off-street transport, and temporary regulation of work shifts (transfer of the working population). Artificial methods for limiting the number of personal transport vehicles can involve a significant increase in car prices, imposition of high motor vehicle taxes, and introduction of a fine and toll system on particular sections of the highway. At the same time, it helps to create favourable conditions for using public transport.

The analysis of various measures to improve the street and road network in urban areas shows there is no single approach since each settlement has its planning, territorial, economic, and natural features. Therefore, the solution to traffic problems should be based on a specific integrated approach to the implementation of interrelated urban planning, organisational, technical, and administrative measures (Bieliatynskyi et al., 2022b). The integrated application of the above methods and techniques will improve transport interchange systems in urban areas and their zones of influence, bring it into line with the urban requirements, and solve the problem of designing transport systems within more realistic resource constraints.

3. Results

We analysed the main external and internal factors influencing the operation of the street and road network and divided them into the following groups: road factors; urban planning factors; operational factors; natural and climatic factors; human factors; and socio-economic factors.

Road factors comprise the following:

(a) The category of the street or road, which makes it possible to determine their designation; the nature of the development, which implies the size of the roadway, sidewalks, green zones, and other planning elements of the street and road network; and the permitted speed and traffic capacity of the section;
(b) The length of the urban street and road network;
(c) The number of intersections and junctions. Each intersection should have sufficient traffic capacity since traffic flows connect or intersect here. It follows that the traffic capacity of a particular section of a street depends on the traffic capacity of its intersections;
(d) Means and methods of traffic management. Technical means of traffic management and methods for introducing one-way or contraflow traffic should improve the conditions for organising, regulating, and controlling the traffic and pedestrian flows and reduce the number of RTA;
(e) Type and condition of road pavement. The public street façade and the quality of transportation services or pedestrian traffic largely depend on the quality and condition of the road pavement. In turn, the type and condition of road pavement significantly affects traffic capacity, speed, and the number of RTA;
(f) Elements of landscaping and maintenance of the street and road network. Street maintenance includes traffic service system (external street lighting, public transport stops, bus stations, parking, etc.) and landscaping (green zones, monuments, road infrastructure).

According to Lutsyk and Stepanchuk (2013), Bezlyubchenko et al. (2021), and Yang et al. (2022), the urban planning factors that affect the street and road network operation are as follows:

(a) Area of the city. The area of the city is the size of the territory occupied by the city. It significantly affects such indicators as road density and the average distance travelled on foot or by vehicles;
(b) Population. This is the main criterion for city classification. It influences the size of the territory, the planning structure, the choice of transport modes, the number of vehicles, the traffic volume, etc.
(c) Form of the city plan. Depending on the city plan, its form can be compact (the entire territory of a city represents a single array), dissected (the city territory is divided into several parts by a river or railway), or dispersed (approximately equal-sized residential areas are remote from each other). Dissected and dispersed forms complicate transport links within the city and its planning and increase trip distance;

(d) Planning scheme of the street and road network. The general design of the city plan is inseparably connected with zoning. The city plan involves developing the system of main streets and roads along the main routes of public transport and pedestrians;
(e) Functional and administrative subordination of the city. This factor is essential for specific land use and is functional in nature (industrial, port, resort, scientific, etc.). It affects urban planning and the location of industrial enterprises, cultural and community services, railway stations, ports, airports, bus stations, freight stations, access roads, etc. The administrative subordination of a city affects the size of its external relations, which entails greater or lower numbers of visitors;
(f) Access to places of attraction. The characteristics of this factor are the time expenditures and distances to the main places of attraction (workplaces, public centres, railway stations, etc.);
(g) The number of 'bottlenecks'. A bottleneck denotes the discrepancy between the maximum traffic needs and the traffic capacity of an element of a street and road network, e.g., a bridge, overpass, intersection, or section of a street. A 'bottleneck' appears when several vehicles use the corresponding element of the street and road network and exceed its traffic capacity in their number. The reason for the formation of 'bottlenecks' is the lack of alternative routes to a given location. Therefore, the number of bottlenecks on the street and road network indicates the possibility of laying a certain number of routes between the places of attraction.

According to Lipyanin and Milash (2022) and Lobashov (2011), operating factors are as follows:

(a) Traffic flow characteristics: traffic volume, traffic composition, traffic speed, traffic density, congestion level;
(b) Vehicle performance specifications, which are determined by the performance characteristics of each type of vehicle, such as the length, width, and height of the vehicle; its maximum speed, carrying capacity, maximum number of passengers, external and internal turning radius, and braking distance.

Pindus and Goncharenko (2013) and Bieliatynskyi et al. (2022c) distinguish the following natural and climatic factors:

(a) Terrain, which affects the location of streets, roads, intersections, junctions, the longitudinal slopes of the roadways and sidewalks, and surface drainage;
(b) Water obstacles, characterised by the presence of water bodies in the city, such as rivers, canals, lakes, and seas. These natural bodies generate the need to build bridges, dams, embankments, etc.;
(c) Climatic and meteorological conditions, such as atmospheric temperature, atmospheric pressure, wind, rain, fog, snow, and icy roads, that affect the well-being of drivers, passengers, and pedestrians, and vehicle operating conditions.

We analysed the works by Boykiv (2016) and Khitrov (2021) and determined the following human factors:

(a) Physical and psychological condition of road users. A driver has to perceive large amounts of information about road users, traffic control devices, the condition of the road and the environment, and the operation of systems and units of a vehicle. Furthermore, a driver has to analyse this information continuously and make appropriate decisions, often under severe time constraints;
(b) Driver qualification. The driver qualification is the level of general and special training of drivers, which has a significant impact on traffic safety, based on each driver's choice of the optimal speed, their choice of distances, their choice of the minimum time for decision-making, and their ability to choose the appropriate actions and make the right decisions;
(c) Age category and driving experience. This factor affects the road user's choice of a more appropriate option for decision-making and their state of health, and, consequently, the physical and psychological condition of road users;
(d) A person's social status influences their choice of modes of transportation and type of vehicle;

(e) The habits of a person. A habit is a special form of human behaviour that manifests itself in the tendency to perform particular actions that have become entrenched due to multiple repetitions. In this context, a habit manifests itself in choosing a route, vehicle type, violation or observance of traffic rules, etc.;
(f) Existential needs. These are manifested in the choice of a safe speed, observance of a safe passing distance, the use of personal protective equipment, behaviour on the road, etc.

Stepanchuk (2017) and Bieliatynskyi et al. (2022d) distinguish the following socio-economic factors:

(a) Living conditions and standards. These influence population mobility, trip distance, increase in traffic volume (especially on weekends), the level of motorisation, the choice of the type of transport (personal or public), etc.;
(b) Environmental conditions. This factor involves implementing measures to reduce the negative impact of vehicles and road infrastructure facilities on human health and the environment. These measures include bans on the movement of vehicles, the construction and reconstruction of elements of the street and road network, the expansion of transport nodes, places for parking and storage of vehicles, etc.;
(c) Economic development of a city. This factor determines the pace of life of a city and its financial capacities that provide for improving the conditions for the development of its transport system and infrastructure.

Each of the factors discussed has an impact on the operation of the street and road network to a certain extent. However, the problem arises because several different factors can have a simultaneous retaliatory effect. Interacting with each other, they have significant internal connections that do not allow the impact to be divided into independent components. These internal connections do not change the factors when determining the characteristics of the street and road network.

The study by Polishchuk et al. (2014) has shown that traffic jams on the street and road network of the city of Kyiv typically occur at signal-controlled intersections (69%), bridges (13%), multilevel intersections (9%), roundabouts (3%), and pot-holed roads (6%). Since traffic jams resulting from non-compliance with road traffic regulations or RTA are irregular, we do not consider them further in this study. Places with regular traffic jams are referred to in this paper as 'bottlenecks'. Bottlenecks include bridges, overpasses, signal-controlled intersections, and entry and exit roads. Such an approach makes it possible to consider bottlenecks as places of origination and absorption of traffic flows. They are places where traffic problems arise, such as traffic delays and traffic jams.

Features of the operation of the street and road network, such as traffic load, have their regularities. The operation of the street and road network largely depends on the zone of the city, the time of day, the day of the week, the functional designation of the street, etc. Therefore, it is possible to observe sections of streets and roads with gridlocks although they have a traffic load that is only 10–15% of their designed traffic capacity. If the problem with the traffic congestion on these sections is resolved first, they can serve as alternative routes (relief roads) for vehicles to be redirected along and unload complex sections of the street and road network. Hence, the indicator of the availability of alternative routes (relief roads) for overloaded main roads can be determined by the following formula:

$$K_R = \frac{1 + B_R}{B_{\mathrm{MR}}} \tag{1}$$

where

K_R is an indicator of the availability of relief roads for overloaded main roads;
B_R refers to the number of alternative routes (relief roads) for overloaded main roads;
B_{MR} means the total number of main roads of city and district designations with heavy traffic (their traffic capacity is close to the maximum traffic volume during peak hours).

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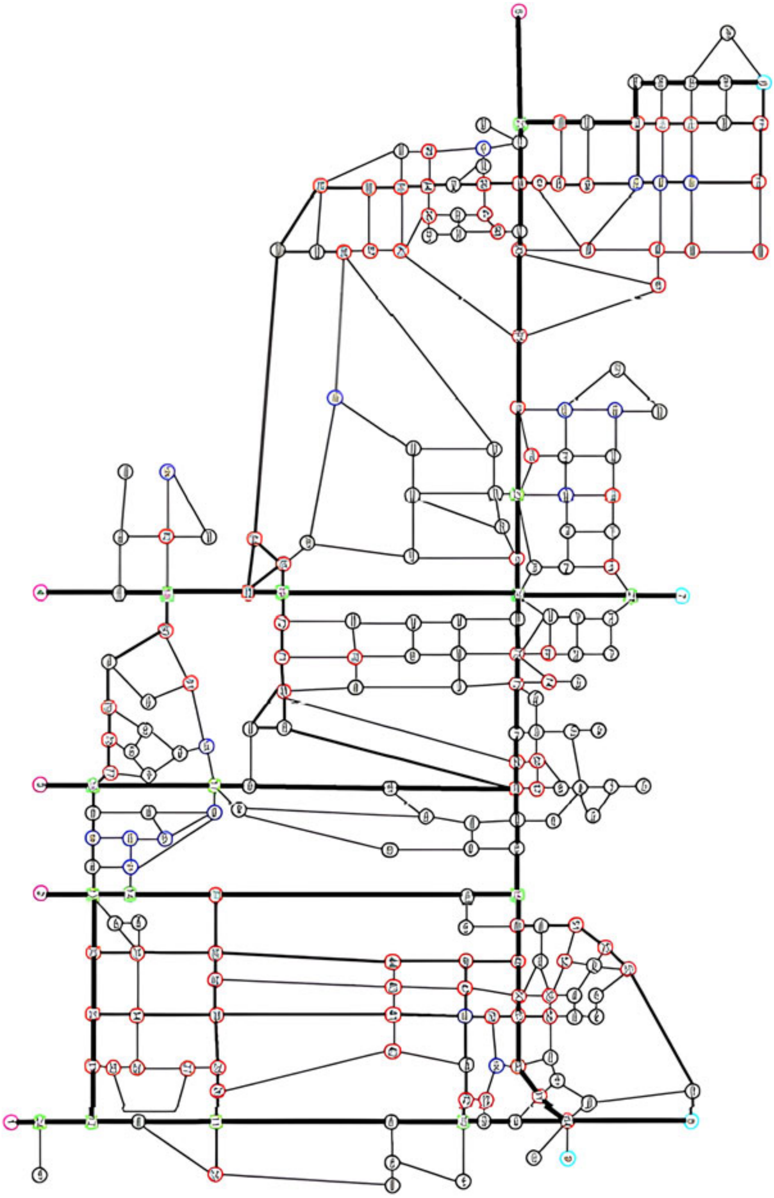

Figure 1. *Graphical model of the street and road network of the left-bank part of Kyiv.*

The graphical model of the street and road network of the left-bank part of Kyiv is shown in Figure 1. According to the results of our research, the vertices shown in Figure 1 can be divided into three groups, depending on their load (Gavrilov et al., 2007):

(1) flow-generating: a significant number of vehicles are concentrated here, and their movement is directed in a particular direction;
(2) flow-absorbing: vehicles are distributed in several directions here, or it is the endpoint for a vehicle;
(3) with uniform flow: a feature of such a transport node is its ability to ensure the movement of the same number of vehicles in one direction.

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An analysis of the graphical model of Kyiv shows that drivers do not always use all routes to bypass traffic jams; therefore, these unused routes do not play a significant role in the distribution of the main flow and can be removed from this model. In order to reduce the size of the graphical model, transit vertices (intersections and junctions) that are not flow-generating or flow-absorbing were also removed since they are not related to the origin-destination movement. As a result of the removal of transit streets (arcs) and intersections (vertices), a simplified network is adopted for the study that provides traffic for the maximum number of possible traffic routes on the urban street and road network.

Between the various districts of the city, therefore, there are bottlenecks in addition to the places that provide transport links. Bottlenecks influence the generation of traffic flows within and outside a district. Our approach makes it possible to exclude a certain number of streets and intersections from the management system since they do not significantly affect the generation of traffic flows. In order to study street and road network operation, it is necessary to consider only the nodes, where the traffic direction changes depending on the increased number of vehicles, and the elements of the street and road network to which main traffic flows are directed. Therefore, we suggest considering the given situation for Kyiv, highlighting only bottlenecks and elements of the street and road network that ensure the connection between districts. Thus, we distinguished 99 places on the street and road network of Kyiv that are bottlenecks, and their corresponding elements are as follows:

– 5 pedestrian bridges;
– 36 overpasses across a railway, metro line, or high-speed tram line;
– 24 multilevel interchanges;
– 23 signal-controlled intersections (located on the border of administrative districts or close to them);
– 11 entry and exit roads.

Based on the scheme of the Kyiv street and road network thus obtained, it is possible to design a geometrical graph. This graph is the source material for creating an algebraic image of the bottlenecks of the given street and road network, which can be used directly in mathematical models (Figure 2). A compressed graph represents the Kyiv street and road network, where each vertex is characterised as a bottleneck, including all adjacent nodes through which vehicles are directed to the given vertex. This model indicates a particular number of alternative routes and possible relief roads that help to redistribute traffic flows in the event of a difficult situation in one of the directions of traffic.

This model of bottlenecks on the urban street and road network is based on the selection of optimal sections for the passage of transit traffic flows to the relevant area with minimal time and financial expenditures. Each edge of the graph of this model can be characterised by a weight (t_{ij}) corresponding to the total time spent on movement over a given section of the street and road network. Stepanchuk (2012) recommends using the value of the reduced length of the edge, which depends on the trip time along it, and also suggests considering the delays associated with the street and road network overload and the passage of intersections. Given the research results, the indicator of edge weight can be determined by the following formula:

$$t_{ij} = L_{ij}\frac{(l_{ij} \times k_1)}{V_{ij}} + b_c \tag{2}$$

where

l_{ij} is the length of the edge, m;
V_{ij} is the permitted speed on the edge, m/s;
k_1 is the coefficient of the edge load;
b_c is the time spent on passing intersections located on the given edge, s.

Hence, k_1 is the coefficient that considers the time loss caused by overloading the street and road network with vehicles. It is the primary indicator of the interrelation between the traffic volume on a section of the street and that section's capacity. Zablotsky invented this coefficient to characterise the

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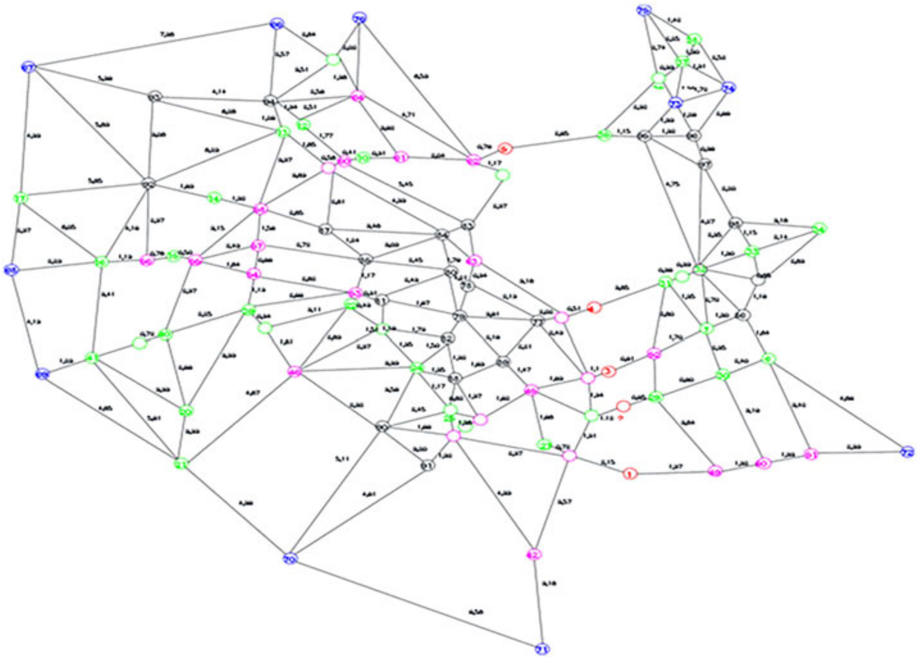

Figure 2. *Model of interconnected bottlenecks on the Kyiv street and road network.*

'traffic conditions' of transport flows along the street and road network. For each edge of the graph, this coefficient is determined by the following formula:

$$k_1 = e^{((N_{ij}/P_{ij})-1)} \tag{3}$$

where

e is a natural logarithm (Euler's number);
N_{ij} is the actual traffic volume on the edge, car/s;
P_{ij} is the traffic capacity on the edge, car/s.

It is possible to study the operation of the urban street and road network based on the assumption that the bottleneck is a node, and the main traffic flows are directed to or from it, according to the theory of networks (Ilchuk, 2010). Such an approach makes it possible to exclude a particular number of streets and intersections from the management system since they hardly influence the movement of vehicles. In order to study street and road network operation, it is necessary to consider only the nodes where the traffic direction changes depending on the increased number of vehicles, and the elements of the street and road network to which the main traffic flows are directed.

In modern network theory, the number of links of a node is called its degree. The degree of a node is a quantitative measure of its importance based on the number of links belonging to that node. The degrees of vertices characterise the number of possible directions of routes that can be laid through the corresponding vertex. Hence, the following formula is used to calculate the number of directions for routes that can pass through the corresponding bottleneck:

$$n_r = (k_j - 1) \tag{4}$$

where

n_r is the number of directions for routes, passing through the corresponding bottleneck;

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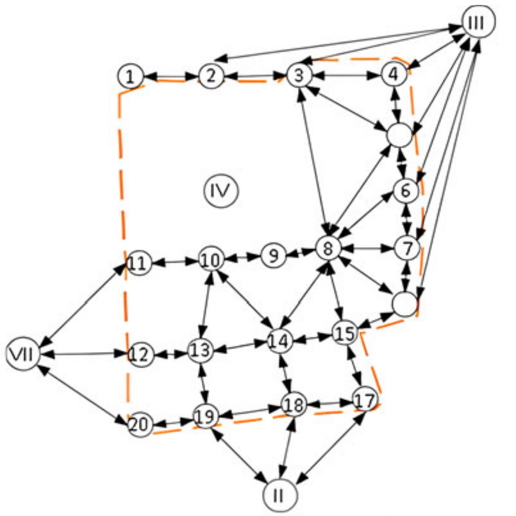

Figure 3. *Graph of connections of bottlenecks on the street and road network of Dniprovskyi District. II-Darnytskyi District; III-Desnianskyi District; IV-Dniprovskyi District; VII-Pecherskyi District.*

k_i is the number of sections of streets and roads that approach the corresponding bottleneck or the degree of the vertex.

Based on the above, all bottlenecks can be distributed according to the appropriate levels of the hierarchy, which will characterise their functional values within the system of the urban street and road network. The hierarchy levels of bottlenecks indicate their importance in ensuring transport links between the planning elements of the city. In other words, it shows the degree to which the failure of a bottleneck deteriorates the transport situation and how many alternative routes remain under certain conditions (Figure 3).

It is also possible to represent the minimum distances between the bottlenecks of the Kyiv street and road network in the form of a graph. A weighted graph shows the actual distance between bottlenecks for the Dniprovskyi District of Kyiv (Figure 4). A similar graph can be designed for the entire street and road network of any city, regardless of its planning.

The remoteness of bottlenecks can be represented as a distance matrix, where the minimum distance from one vertex of the graph (bottleneck) to another is clearly traced. Thus, the presented matrix, which determines the remoteness of all bottlenecks in the city, should be taken as the basis for ensuring the efficient distribution of traffic flows on the street and road network. The appropriate distance matrix, based on Dijkstra's algorithm (Barrat et al., 2004), can help to find the shortest path and consider the basic indicator of the minimum time spent moving between the corresponding points of attraction.

When the individual edges are loaded, the throughput capacity of each edge is considered, and the Ford-Fulkerson algorithm is applied. It is then possible to determine the maximum possible flow between the corresponding start and end nodes (bottlenecks). The Ford-Fulkerson algorithm is based on the important 'max-flow min-cut' theorem, which determines the maximum possible flow with the help of cuts to the transport network. For this purpose, we compiled a matrix of distances between the bottlenecks of the district under study (Table 1).

We studied the data on commuting trips of Kyiv residents by personal car and established the loading of bottlenecks. Based on the graphs of bottlenecks for each city district, it is possible to determine the polynomial rank graph using the technique. The polynomial rank graph makes it possible to analyse many spanning subgraphs, thereby creating conditions for considering enlarged transport districts, which

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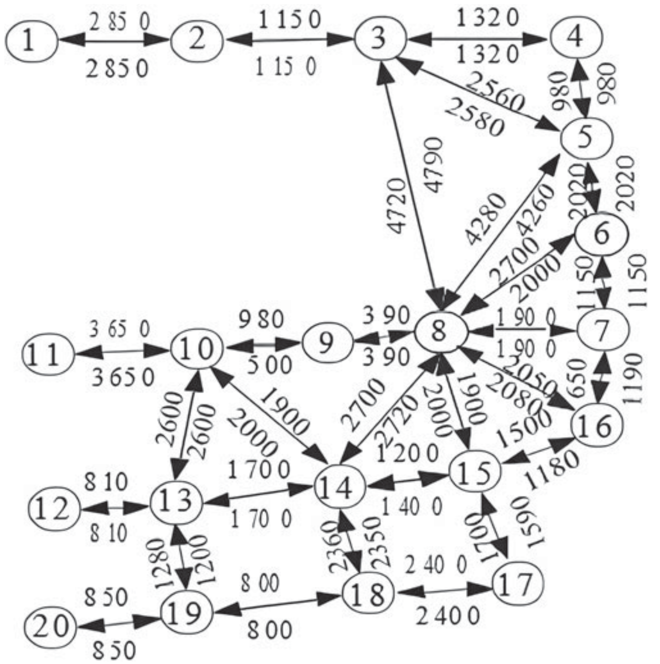

Figure 4. *Minimum distances between bottlenecks in the Dniprovskyi District.*

can be reduced in size, for example, to the existing administrative city districts. The polynomial rank graph G has the following formula:

$$P_{\upsilon}(x,\ y) = \Sigma x^{\upsilon^{*}_{G} - \upsilon^{*}_{H}} y^{\upsilon_{H}} \tag{5}$$

where

v_H is the corank of the spanning graph, which includes all vertices of the graph, subgraph H;
v^*_H is the rank of subgraph H;
v^*_G is the rank of graph G.

The appropriate technique makes it possible to build a polynomial for any graph that reproduces the relationship between the elements on the urban street and road network. The following formula is used to build the polynomial graph of bottleneck connections of the street and road network of the Dniprovskyi District of Kyiv, which has 20 vertices and 30 arcs:

$$\begin{aligned}
&(x+1)^5(x^{14} + 25x^{13} + 8x^{12}y + 6x^{11}y^2 + 5x^{10}y^3 + 4x^9y^4 + 3x^8y^5 + 2x^7y^6 + x^6y^7 + 300x^{12} + 185x^{11}y \\
&\quad + 156x^{10}y^2 + 131x^9y^3 + 102x^8y^4 + 71x^7y^5 + 41x^6y^6 + 15x^5y^7 + 4x^4y^8 + x^3y^9 + 2292x^{11} + 2028x^{10}y \\
&\quad + 1864x^9y^2 + 1576x^8y^3 + 1186x^7y^4 + 766x^6y^5 + 392x^5y^6 + 156x^4y^7 + 52x^3y^8 + 13x^2y^9 + 4xy^{10} \\
&\quad + y^{11} + 12465x^{10} + 13952x^9y + 13631x^8y^2 + 11511x^7y^3 + 8330x^6y^4 + 5022x^5y^5 + 2463x^4y^6 \\
&\quad + 998x^3y^7 + 335x^2y^8 + 106xy^9 + 25y^{10} + 51096x^9 + 67199x^8y + 68234x^7y^2 + 56833x^6y^3 \\
&\quad + 39319x^5y^4 + 22346x^4y^5 + 10429x^3y^6 + 4011x^2y^7 + 1306xy^8 + 296y^9 + 162992x^8 + 239201x^7y \\
&\quad + 246954x^6y^2 + 200153x^5y^3 + 130680x^4y^4 + 68967x^3y^5 + 29317x^2y^6 + 9895xy^7 + 2194y^8
\end{aligned}$$

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$$+ 411632x^7 + 646893x^6y + 663284x^5y^2 + 511904x^4y^3 + 308023x^3y^4 + 144566x^2y^5$$
$$+ 51255xy^6 + 11331y^7 + 828612x^6 + 1343485x^5y + 1330403x^4y^2 + 947313x^3y^3 + 500778x^2y^4$$
$$+ 190399xy^5 + 42899y^6 + 1326268x^5 + 2135044x^4y + 1966584x^3y^2 + 1225264x^2y^3 + 515876xy^4$$
$$+ 121782y^5 + 1666708x^4 + 2544505x^3y + 2056904x^2y^2 + 1011792xy^3 + 259982y^4 + 1601000x^3$$
$$+ 2172014x^2y + 1383644xy^2 + 410548y^3 + 1116838x^2 + 1201668xy + 458960y^2 + 509711x$$
$$+ 329090y + 115772) \quad (6)$$

Based on the model of connections between bottlenecks, polynomials were determined for each district of Kyiv. A similar graph can be designed for each district of any city. These graphs indicate the possible traffic connections between districts and existing main routes within each district, which makes it possible to redistribute traffic flows efficiently throughout the urban street and road network with the help of an intelligent traffic management system. Then, a model of the street and road network of the city is created based on the number of its nodal points (bottlenecks) to which traffic flows are naturally drawn. When deciding on the redistribution of traffic flows along the street and road network of the city, the primary focus should be on the capacity and the number of bottlenecks.

It is possible to analyse the capacity of the street and road network of the district and the whole city, considering bottlenecks as sections of the main transport links, separating them as a transport node, and comparing the total number of traffic lanes directly included in this node. When the relevant information is considered, nodes can be distributed by the number of lanes, which ranks the bottlenecks of the street and road network according to their traffic capacity. Each bottleneck has geometric coordinates and the total number of traffic lanes that directly enter and exit it. Hence, the capacity of the street and road network can be determined according to the technique for distributing its elements by multiplicity factor (Stoilova and Stoev, 2015).

When the capacity of elements of the street and road network is established, the relation between their traffic capacity and traffic demand can be determined. This helps to identify the need to construct additional elements of the street and road network, or the existence of alternative traffic routes with less traffic load, which is the main thing to consider when designing intelligent traffic control systems. The efficiency of the operation of the urban street and road network also depends on its reliability, which is an important indicator of the operating condition of the urban street and road network. The reliability of the street and road network as an urban engineering structure is a system of probabilities, such as its failure-free operation, the speed of vehicles corresponding to the road traffic regulations, and the safe speed of the traffic flow (Stepanchuk et al., 2020). The concept of reliability of the street and road network includes the reliability of its individual elements.

Reliability is closely related to the failure probability or accident risk. The problem of network reliability is well studied nowadays. As a rule, a graph is used as a model of the network, the elements of which are subject to failure. A graph considers various clarifications of this system, such as elements subject to communication failures or nodes, the network nodes that require to connect one element with another. However, the key factor for ensuring the reliability of the operation of city nodes is their connection. Therefore, the appropriate total number of traffic lanes in bottlenecks that provide communication between city districts in a particular direction is required to ensure reliable conditions for street and road network operation. In order to determine the optimal routes for the redistribution of vehicles, it is necessary to consider the probability of occurrences (RTA, road maintenance, vehicle breakdown, etc.) that can lead to the partial or complete exclusion of certain elements and sections of the street and road network on possible routes. However, when a vehicle stops moving over some lanes, there is a risk of a lack of the necessary number of lanes. In this paper, we examine the lack of traffic lanes precisely in the bottlenecks of the urban street and road network. Therefore, the efficient operation of the street and road network requires ensuring the necessary traffic capacity of traffic lanes during peak hours. The traffic capacity is a qualitative characteristic of the roadway operation of all street and road

Table 1. *Matrix of distances between the bottlenecks of the Dniprovskyi District of Kyiv.*

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	0·0	2·9	4·0	5·3	6·3	8·3	9·5	8·7	9·1	10·1	13·7	13·5	12·7	11·4	10·7	10·1	12·4	13·8	14·0	14·8
2	2·9	0·0	1·2	2·5	3·5	5·5	6·6	5·9	6·3	7·3	11·0	10·7	9·9	8·6	7·9	7·3	9·6	11·0	11·2	12·0
3	4·0	1·2	0·0	1·3	2·3	4·3	5·5	4·7	5·1	6·1	9·7	9·5	8·7	7·4	6·7	6·1	8·4	9·8	10·0	10·8
4	5·3	2·5	1·3	0·0	1·0	3·0	4·2	5·3	5·7	6·6	10·3	10·0	9·2	7·5	6·3	4·8	8·0	9·9	10·5	11·4
5	6·6	3·7	2·6	1·0	0·0	2·0	3·2	4·3	4·7	5·7	9·3	9·1	8·3	6·5	5·3	3·8	7·0	8·9	9·5	10·4
6	8·3	5·5	4·3	3·0	2·0	0·0	1·2	2·7	3·1	4·1	7·7	7·0	6·2	4·5	3·3	1·8	5·0	6·9	7·5	8·3
7	9·5	6·6	5·5	4·2	3·2	1·2	0·0	1·9	2·3	3·3	6·9	5·9	5·1	3·4	2·2	0·7	3·9	5·7	6·3	7·2
8	8·8	5·9	4·8	5·2	4·3	2·0	1·9	0·0	0·4	1·4	5·0	4·8	4·0	2·7	2·0	2·6	3·7	5·1	5·3	6·1
9	9·2	6·3	5·2	5·6	4·7	2·4	2·3	0·4	0·0	1·0	4·6	4·4	3·6	3·0	2·4	2·9	4·1	5·3	4·9	5·7
10	9·7	6·8	5·7	5·6	5·2	2·9	2·8	0·9	0·5	0·0	3·7	3·4	2·6	2·0	2·9	3·4	4·6	4·4	3·9	4·7
11	13·3	10·5	9·3	9·8	8·8	6·5	6·4	4·5	4·2	3·7	0·0	7·1	6·3	5·7	6·5	7·1	8·2	8·0	7·5	8·4
12	13·1	10·2	9·1	9·3	8·3	6·3	6·2	4·3	3·9	3·4	7·1	0·0	0·8	2·5	3·9	5·1	5·3	2·9	2·1	2·9
13	12·3	9·4	8·3	8·5	7·5	5·5	5·4	3·5	3·1	2·6	6·3	0·8	0·0	1·7	3·1	4·3	4·5	2·1	1·3	2·1
14	11·5	8·7	7·5	7·7	6·7	4·7	4·6	2·7	2·4	1·9	5·6	2·5	1·7	0·0	1·4	2·6	3·1	2·4	3·2	4·0
15	10·7	7·8	6·7	6·5	5·5	3·5	2·4	1·9	2·3	3·1	6·8	3·7	2·9	1·2	0·0	1·2	1·7	3·6	4·2	5·0
16	10·7	7·8	6·7	5·3	4·4	2·3	1·2	3·1	3·5	4·5	8·1	5·2	4·4	2·7	1·5	0·0	3·2	5·1	5·7	6·5
17	12·3	9·4	8·3	8·1	7·1	5·1	4·0	3·5	3·9	4·7	8·3	5·3	4·5	2·8	1·6	2·8	0·0	2·4	3·2	4·1
18	13·9	11·0	9·9	10·1	9·1	7·1	6·1	5·1	5·1	4·6	8·3	2·8	2·0	2·4	3·8	4·9	2·4	0·0	0·8	1·7
19	13·5	10·6	9·5	9·9	9·0	6·7	6·6	4·7	4·3	3·8	7·5	2·0	1·2	2·9	4·8	6·0	3·2	0·8	0·0	0·9
20	14·3	11·5	10·3	10·8	9·8	7·5	7·4	5·5	5·2	4·7	8·3	2·9	2·1	3·8	5·2	6·3	4·1	1·7	0·9	0·0

network elements. Thus, the effective operation of the street and road network is ensured when the traffic capacity of its section or element is greater than or equal to the maximum traffic volume ($P_c \geq N_{max}$).

Traffic jams in the bottlenecks of the urban street and road network can be considered as the probability of an undesirable event that poses a risk of potential danger and has a significant impact on its operation.

$$R = \frac{K_{BN}}{K_{total}} \tag{7}$$

where

R is the probability of an undesirable event that poses the risk of a potential traffic jam;
K_{BN} is the number of traffic jams caused by insufficient traffic capacity of the bottlenecks;
K_{total} is the total number of traffic jams on the street and road network of the city. Risk refers to the probability of an event caused by increased traffic, poor road conditions, etc.

The mathematical relationship of the risk theory is based on the summation of the density of the distribution of physically defined or experimentally obtained values. It is a theoretically probabilistic model for comparing the average value (A) and root-mean-square deviation ($GÆ$) of the dangerous parameter of a transport construction with the same characteristics of this parameter (A_r, G_r), which are in a critical state with a risk of damage of 50%. When summing the normal, lognormal, and Gram-Charlier distributions, the Laplace function leads to a probability of $0 \cdot 5$ in the structure of calculation formulas of the risk theory. Using risk theory, the probability of traffic jams due to inconsistency in traffic lane capacity can be determined by the following formula:

$$r = 0 \cdot 5\Phi\left(\frac{P_a - P_1}{\sqrt{G_{P_a}^2 - G_{P_1}^2}}\right) \tag{8}$$

where

P_a is the actual traffic capacity of bottlenecks between city districts;
$G_{P_a}^2 = C_V^{P_a} \times P_a$ is the root-mean-square deviation of actual traffic capacity of one traffic lane;
C_V is the coefficient of variation.

In order to optimise the efficiency of the urban street and road network, it is necessary to optimise the number of traffic lanes on each main street (especially in bottlenecks) since the number of traffic lanes on all streets does not correspond to the traffic volume or will not be optimal. An optimisation tool can be an analysis of the risk of lack or overabundance of traffic lanes. The increased number of traffic lanes makes it possible to eliminate traffic jams and increase the efficiency of the street and road network. When analysing the efficiency of the urban street and road network, the question is always raised of how it is possible to effectively distribute traffic flows along it, subject to the failure of some sections of the streets, or rather, to ensure the reliability of its functioning in difficult operating conditions.

The optimal route is characterised by the movement of the vehicle bypassing the places of transport congestion according to the criterion of minimising time. It is almost impossible for drivers to choose the optimal route on their own. A driver cannot objectively assess the traffic situation that has developed on the street and road network of the corresponding transport area since there is a lack of complete information about the state of other sections of the network that can be used as alternative routes.

Relying on their considerations and interests in choosing a route, drivers become hostages of circumstances that do not allow them to change driving direction and force them to move only in the direction where the traffic flow is directed. Therefore, the management of the distribution of traffic flows along the urban street and road network should be reduced to a solution to the problem of minimising the total travel along the route between the two transport nodes. The efficiency of the street and road network is

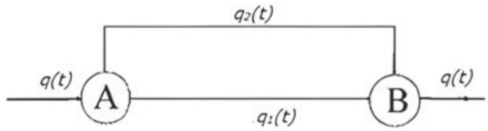

Figure 5. *Distribution of flow (q) at vertex A into two alternative routes directed to vertex B.*

determined by indicators of time savings when moving over it under particular conditions of its loading, characterised by minimising the time spent on a certain route ($t_{\text{route}} \rightarrow$ min). Under difficult road conditions, the efficiency of the route does not mean the shortest path per distance but the minimum time of movement over a particular route.

Since modern conditions are characterised by an intensive increase in the number of cars on city streets, there is a need to distribute the traffic flows that predominantly consist of cars. The task set in this study can be solved by distributing traffic flows in different driving directions based on indicators of vehicle engine volume. This can help to redirect the transit vehicles, the engine volume of which is larger than an established indicator, along other parallel streets, thereby reducing the traffic load on the problem sections of the street and road network.

The traffic flow consisting of cars should be distributed at the intersection since the traffic becomes complicated straight after it. Therefore, a multi-position road sign is installed at the entrance to the intersection, prohibiting the movement of vehicles whose engine volume exceeds the established indicator. This road sign indicates that (for this section of the street) transit vehicles, the engine volume of which exceeds the established distribution indicator, must pull off the main traffic flow direction and move over a different (alternative) route. Moving over a separate traffic flow should be facilitated by road signs and information boards on further movement over this route.

A feature of this traffic flow distribution method is the ability to distribute the traffic flow, consisting of 70–95% of light vehicles, into two flows, etc. We consider the approach to traffic flow distribution and the direction of vehicles to alternative routes. For example, there are two possible routes between points A and B (Figure 5). A distribution indicator (regulator) is installed in point A that decides the path for each driver based on optimisation principles and information about the density of the traffic flow $q(t)$ at point A.

In this case, a traffic flow with density $q_1(t)$ will move over the first route, and a traffic flow with density $q_2(t)$ will take the second path. It can be assumed that vehicles whose engine volume is less than the established distribution indicator should move over the first route, and vehicles with a larger engine volume should take the second path, respectively. Thus, the forced distribution of vehicles is performed, characterised by such conditions as $q_1(t) = K_{n \leq W}$ and $q_2(t) = K_{n > W}$. $K_{n \leq W}$ is the number of vehicles in the flow, the engine volume of which is less than or equal to the established distribution indicator. $K_{n > W}$ is the number of vehicles in the flow, the engine volume of which exceeds the established distribution indicator. The total number of vehicles ($K_{n \leq W}$ and $K_{n > W}$) that move over to the first and second alternative routes should not exceed the traffic capacity of those routes. In other words, this condition can be represented by the formulas: $Kn \leq W \leq P_1$ and $Kn > W \leq P_2$.

However, the principal condition is to ensure approximately the same time expenditures for moving over a route, i.e., $t1 \approx t2$. Hence, it is possible to achieve the same time values at different path lengths ($S_1 < S_2$) only by providing an appropriate speed of flow along the first and second routes. It should be noted that the proposed method for the distribution of traffic flows, consisting of cars, helps to separate one-quarter, one-third, one-half, or two-thirds of the main flow and direct it to another alternative route. Based on the obtained indicator of the traffic volume of the bottleneck, it is possible to determine the priority and long-term measures to ensure its traffic capacity. Thus, the main measures for improving the efficiency of the street and road network operation in Ukraine have both local and global natures. Local measures involve the following: improving the parameters of traffic-light regulation; ensuring the efficient traffic control of vehicles and pedestrians at intersections; ensuring the compliance of traffic capacity of bottlenecks with the traffic demand and safety headway; optimal distribution of vehicles

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along lanes; allocating separate lanes for public transport; and constructing or reconstructing road sections, bridges, tunnels, overpasses, intersections, etc. Global measures imply the following: ensuring compliance between the number of available workplaces in the city and its demand; determining the optimal traffic route; ensuring the adequate number and optimal placement of elements of transport communication between the city districts; directing vehicles to alternative traffic routes; introducing an intelligent traffic control system; imposing tolls on overloaded sections of roads; and improving operating conditions of public transport.

It is worth noting that three main measures are applied in the largest cities of Ukraine that ensure the efficient operation of the urban street and road network (Stepanchuk et al., 2021). These measures differ significantly in their complexity and cost and involve the following:

(1) Increasing the traffic capacity of bottlenecks by expanding the roadway at signal-controlled and uncontrolled intersections, reconstructing existing obsolete overpasses, and constructing new multilevel interchanges, bridges, tunnels, overpasses, etc.;
(2) Designing and implementing an intelligent traffic control system, which instantly processes and rapidly adopts an appropriate decision on the optimal distribution of traffic flows; notifying drivers of the need to change their direction of movement and choose an alternative route with the help of multi-position road signs, electronic information boards, radio communication, and GPS navigation system;
(3) Expanding and developing the public transport network (city train, subway, high-speed tram, etc.) and ensuring its comfort conditions (Figure 6).

The adoption of a reliable decision to ensure the effective operation of the street and road network lies in its economic justification. In order to confirm the decision, it is necessary to determine the economic feasibility of the construction or reconstruction of a particular element of the street and road network. The decision can be considered cost-effective if the benefit exceeds the construction or reconstruction cost (Britchenko et al., 2022).

Empirical research shows that the main approach to the methods for improving the efficiency of the street and road network operation involves designing a traffic flow management system based on an operational solution to the problem of reducing traffic jams and the possibility of their occurrence. Furthermore, such a system obtains reliable information on the most efficient routes and calculates and determines the optimal routes in real-time mode. All the above makes it possible to distribute traffic flows rationally along the urban street and road network. Such an approach provides solutions to problems both local and global in nature (for the entire network) (Figure 7).

The economic effect and type of optimisation should also be considered. The introduction of measures for increasing the efficiency of the street and road network operation opens up new opportunities for the economic development of the city, accompanied by the following socio-economic effects:

– reduce the travel time for personal transport vehicles;
– public transport will be able to adhere to its schedules;
– increase road safety and decrease the number of RTA;
– timely delivery of cargo will increase the efficiency of transportation and the work of enterprises;
– emergency vehicles will be able to move faster and will not interfere with other road users;
– less operating time of internal combustion engines will decrease emissions of harmful substances into the environment;
– the absence of frequent changes in acceleration, braking, or parking modes will reduce the physical wear of vehicles;
– decrease in psychological irritation (stress and transport fatigue) of drivers and passengers caused by prolonged downtime in traffic jams.

The values of indicators of the socio-economic effect show how much the costs of developing the street and road network are offset by the benefits that the population or enterprises of the city receive.

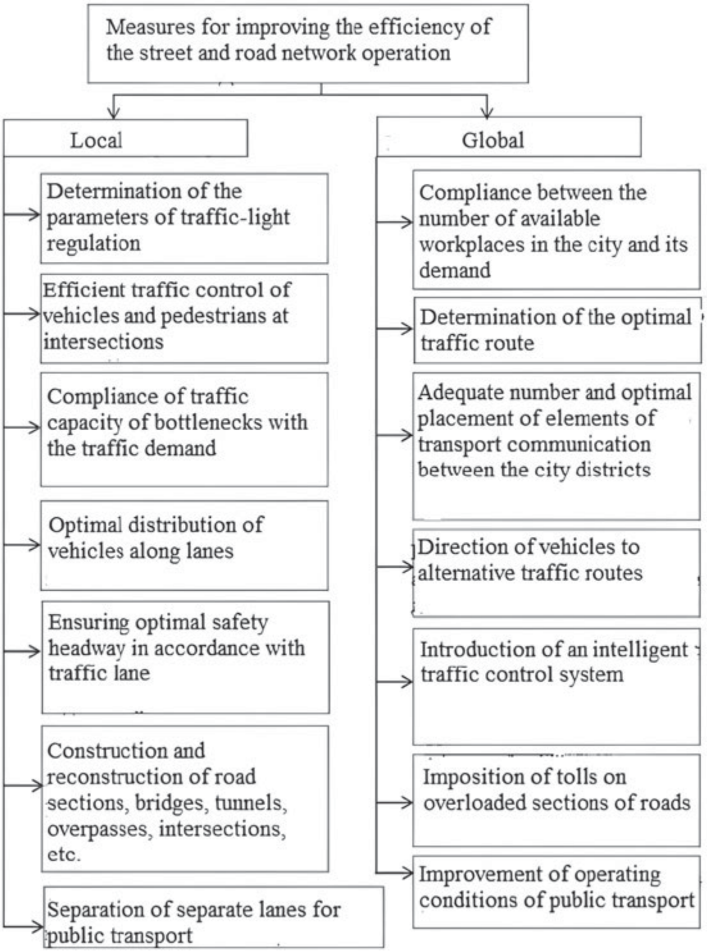

Figure 6. *Measures to ensure the effective operation of the urban street and road network.*

4. Discussion

Today, Ukraine has an average level of motorisation that has not reached a dangerous limit. However, this indicator differs significantly in the largest cities in Ukraine, where it is approaching a critical value. In all countries of the world, the level of motorisation of large cities exceeds the overall level of motorisation of the country. The street and road networks of cities are overloaded by vehicles due to a significant concentration of the population in urban and suburban areas.

Ukraine is no exception to this situation. In particular, the number of cars is rapidly growing in Kyiv, constituting 308 cars per 1,000 inhabitants. The annual growth rate of highway transport in Kyiv is 10% (Figure 8) (Voznyuk, 2014). The volume of highway transport in Kyiv almost doubled from 2005 to 2016. The number of highway transport vehicles in Kyiv was 899,200 units in 2016, and the distribution was as follows: personal vehicles (746,800), buses (10,500), freight vehicles (34,900), and special transport vehicles (107,000). Moreover, more than 25,000 transit vehicles pass through Kyiv daily (Brykailo, 2018). Passenger car is one of the most intensively developing modes of transport in Ukraine. This situation is caused by the following factors:

– relative ease of vehicle operation without considerable costs (e.g., the owner does not need to design a road network);
– relatively low cost of vehicles and insignificant costs for their maintenance;

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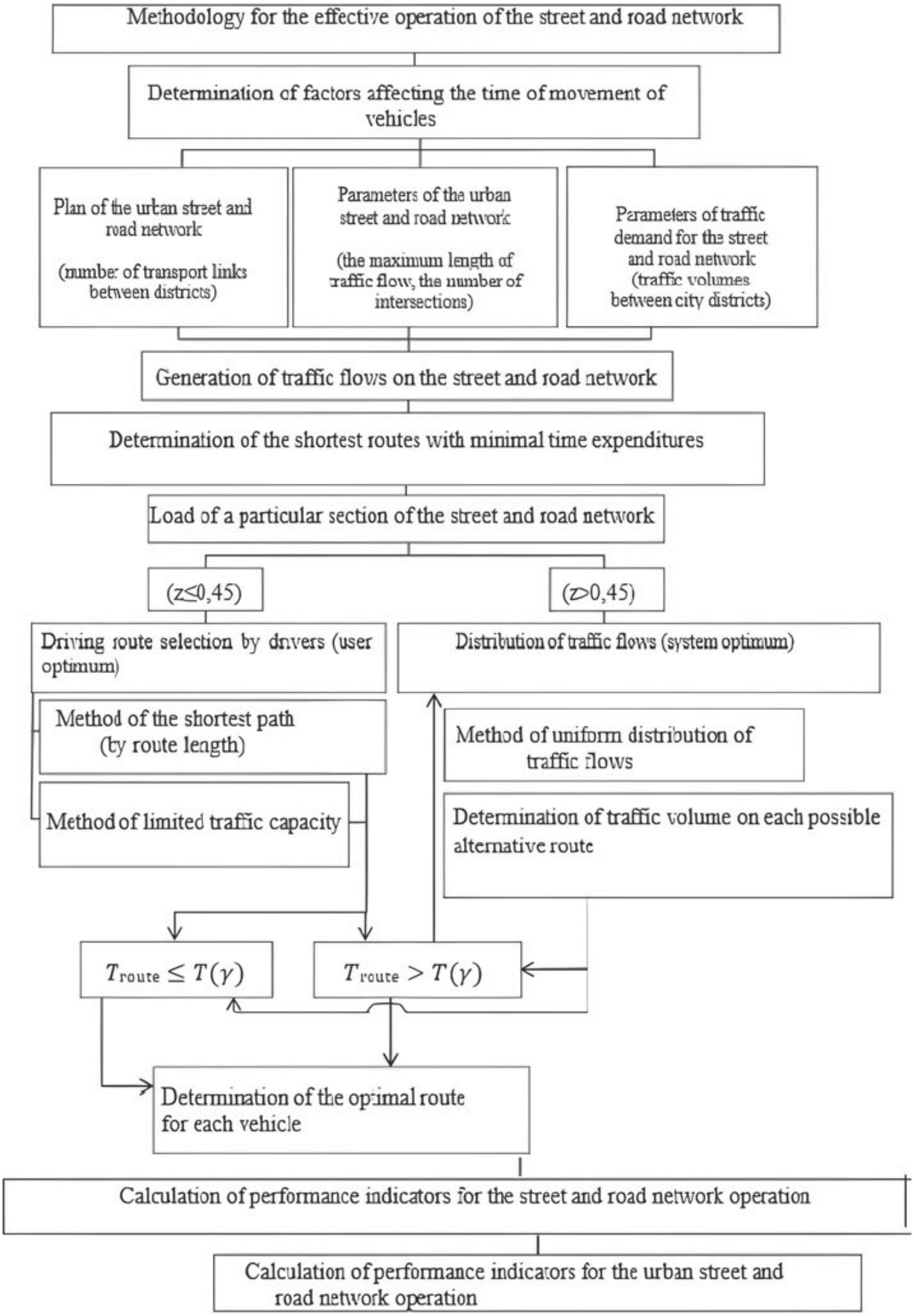

Figure 7. *Methodology for the effective operation of the urban street and road network.*

– less travel time compared with public transport;
– comfort when transporting passengers;
– transportation of passengers and cargo from the origin to destination for many modes of transport;
– enhancing the personal image of the owner of a vehicle;
– creation of conditions for independent spatial flows and the provision of personal space.

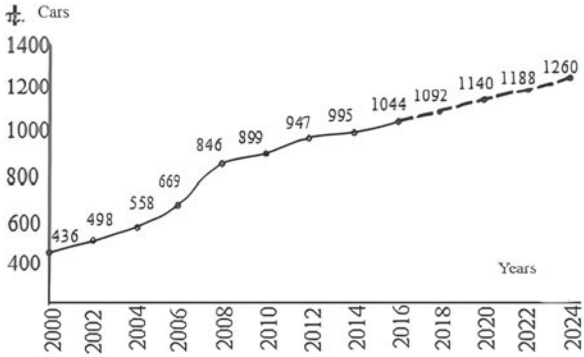

Figure 8. *Dynamics of growth in the number of highway transport vehicles in Kyiv, 2000–2024.*

Table 2. *The share of movement of people in different countries by transport mode, %.*

Country	By car	By public transport	By bicycle	On foot	By other modes
Austria	39	13	9	31	8
United Kingdom	62	14	8	12	4
Denmark	42	14	20	21	3
Canada	74	14	1	10	1
Netherlands	44	8	27	19	1
Germany	52	11	10	27	0
USA	84	3	1	9	2
France	54	12	4	30	0
Switzerland	38	20	10	29	3
Sweden	36	11	10	39	4

It is the car that provides freedom of choice of movement, creates personal space and comfort, and ensures maximum mobility and speed. The car was designed to improve the quality of life, but it has also become one of the primary causes of global crises. Moreover, even significant financial contributions to the development of the street and road network do not always provide a positive effect on the problems created by the growth of car use.

The number of cars has dramatically increased in recent years in Ukrainian cities and caused the overloading of the street and road network; moreover, a significant part of passenger traffic has switched to cars. The use of passenger cars without regard to the operation of urban public transport (i.e., the traffic capacity of some road sections or intersections is not considered) has led to 'transport paralysis' in many cities of Ukraine. It is worth noting that traffic delays during peak hours can be observed both in the central city areas and in more remote residential areas.

In many countries, the percentage of use of personal cars is very high (more than half of all movements are carried out by car). The car is least used in European countries, where people prefer to make trips on foot (Table 2). The share of foot traffic differs, and its percentage can significantly vary even in cities of one country (Table 3). The share of foot traffic depends on the layout and development of the city. The convenience and safety of foot traffic is one of the most important measures, but this area of traffic management is still insufficiently developed.

It is more difficult to regulate the behaviour of pedestrians than the behaviour of drivers since psychophysiological factors, with all the deviations inherent in individual groups of people, can hardly be calculated in regulatory regimes. The problems of design, construction, and operation of highways and urban streets associated with the influence of various factors were studied in scientific works

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Table 3. *The share of movement of people in European cities, %.*

City	On foot and by bicycle, %	By public transport, %	By car, %	Population
Amsterdam	47	16	34	718,000
Groningen	58	6	36	170,000
Delft	49	7	40	93,000
Copenhagen	47	20	33	562,000
Aarhus	32	15	51	280,000
Odense	34	8	43	102,000
Barcelona	32	39	29	1,643,000
Hospitalet	35	36	28	273,000
Vitoria	66	16	17	215,000
Brussels	10	26	54	952,000
Gent	17	17	56	226,000
Bruges	27	11	53	116,000

by the following scholars: V. F. Babkov, A. O. Bieliatynskyi, H. F. Bohatskyi, S. A.Waksman, B.D. Greenshields, V. I. Huk, V. K. Sudba, D. Drew, V. H. Zhyvosmotrov, H. I. Klynkovshtein, Y. M. Lobanov, O. A. Lobashov, O. I. Mykhailov, M. M. Osetryn, V. P. Polyshchuk, O. O. Poliakov, Y. O. Reitsen, F. Kheit, V. V. Filipov, A. S. Sardarov, D. S. Samoilov, V. V. Silianov, A. V. Sihaiev, V. P. Starovoida, A. E. Stramentov, M. S. Fishelson, V. O. Cherepanov, V. V. Shestokas, Y. V. Khomiak, M. R. Yakymov, etc.

A great deal of experience has accumulated worldwide in solving problems related to traffic queues and traffic jams. A very simple system, introduced in Athens in 1982, allows cars with licence plates ending in even numbers to drive on even-number days of the month and vice versa for odd numbers. The historical area of Rome has been a zone of limited car traffic since 1994; the ban is valid from 06:30 to 18:00 on weekdays and from 14:00 to 18:00 on Saturdays. As a result, the traffic volume decreased by 20%, and the load on public transport increased (Stepanchuk, 2017). There is a system of priority lanes for public transport traffic in Paris, introduced on the main city streets. They are bus-only and taxi-only lanes, separated by markings or a low kerb from the main roadway. The average fine for departure to and moving over this lane is 35 euros. There are 41 km of such priority lanes in Paris, and buses run exactly to the timetable. Since 1990 the problem of traffic jams in Vienna has been solved by freeing the rightmost lane from cars and limiting parking by time. Parking is allowed from 09:00 to 20:00 in the central city district but limited to an hour and a half; in other areas, parking time can last for no more than two hours. The city has 17 intercept parking lots for long-stay parking, which are located near highways and public transport stops.

Stepanchuk (2012) notes that traffic organisation in cities, as a rule, is very far from perfect. The introduction of modern methods and means of traffic management will increase traffic discipline but will not change the transport situation in the city significantly. The experience of Europe and the United States shows that the effect of traffic management in the direction of increasing capacity and reducing transport costs does not exceed 10%. However, traffic management measures are most necessary at the first stage because they consume less time and cost than other measures.

The method to cope with traffic jams introduced in Singapore in 1990 is still one of the most effective in the world. The state limits the number of car sales in the country by high prices, taxes, and quotas. Only very rich people can afford to buy a personal car, the city's car fleet is growing as programmed (3% per year), and the level of motorisation is 178 cars per 1,000 inhabitants (State Statistics Service of Ukraine, 2016). All roads are under constant video surveillance. The public transport system (metro, bus, and cheap taxi) is convenient and works smoothly.

There are also various ways to encourage city residents to use public transport. For example, local authorities abolished fares on public transport in the Belgian town of Hasselt (74,000 people) in 1997.

Later, such measures were taken in Lubben and Templin (Germany), Overtornea and Kiruna (Sweden), Aubagne and Châteauroux (France), and Tallinn (Estonia). The process of switching to the free transport system began in Tallinn in the spring of 2012. Analysts calculated that this transport reform helped to reduce the number of vehicles visiting the central city zone daily by 15%. In the first week after these measures were introduced, automatic traffic flow sensors recorded that car activity decreased by 7% in the city centre, and the number of passengers on public transport increased by 11–12%. The congestion of major intersections decreased by 14% (Rudenko, 2015). Since the introduction of these measures, the number of personal cars has decreased by 15–18% in the city centre (Full ULEZ, 2021).

In the United Kingdom, 70% of travel is done by car, with the exception of London, where public transport serves 43% of movements. The government of the United Kingdom pays much attention to urban public transport systems. It implements projects for their development, which has already led to the stabilisation and increase in passenger volumes. The restoration of tram services in several cities has significantly increased the volume of traffic by public transport.

In the German city of Dresden, the share of use of bicycle as a mode of transport increased by 8% in 2008 compared with 1994. In 2008, the total distribution by modes of transport, in comparison with 2003, was as follows: public transport 21% (+1%); bicycle 16% (+4%); on foot 22% (−2%); car 41% (−2%). The share of public transport increased, and that of personal cars decreased. The number of bicycles increased from 689 to 750 units per 1,000 inhabitants (Dubova et al., 2009). These data show that it is possible to change the vehicle chosen by many people (from personal car to public transport or bicycle), provided the appropriate comfort is assured. However, it requires ensuring the most acceptable conditions for all road users (Lutsyk and Stepanchuk, 2014).

Many papers and monographs present the domestic and foreign experiences of such measures. Recommendations for developing the street and road network should first be focused on improving the efficiency of servicing the existing transport links system. The optimisation of the street and road operation is solved based on mathematical methods and modelling, considering economic and social criteria. The improvement of traffic conditions of the urban street and road network requires a comprehensive study and justification.

5. Conclusion

We determined the features of the development of the street and road network of the largest cities and generalised the measures for ensuring the efficient operation of the network. The results of the study indicate that the set goal was achieved, and the formulated tasks were solved.

Based on the analysis of scientific works, the relevance of the problem of methodology and methods in the given field has been established. The priority area to address the problems of urban transport systems is the improvement of the street and road network operation. We have established that the street and road network is the primary subsystem of the entire urban transport system. The discrepancy (failure) of its work in providing a comfortable and safe connection between its planning elements leads to a deterioration in the quality of life of the population and the functioning of enterprises and organisations.

We updated the classification of external and internal factors affecting the operation of the street and road network. This classification includes road, urban planning, operating, natural and climatic, human, and socio-economic factors. Based on the established internal relationships, we developed a model of the influence of factors on the level of their priority, which made it possible to divide them by hierarchy levels and, accordingly, the level of their impact on independent components.

We analysed the existing methods for improving the operating conditions of the street and road network and developed their classification of these methods, highlighting legislative and regulatory, urban planning, technical, traffic control, and administrative measures. The study establishes that the system for evaluating the efficiency of the street and road network determines four main effects: economic, social, environmental, and functional. The analysis of scientific papers made it possible to establish the criteria for evaluating the functional effect, which formed the basis of the methodology for improving the efficiency of the street and road network operation.

The spontaneous generation of traffic flows on the street and road networks of cities is accompanied by significant temporary and financial losses for society. If the residents of Kyiv could spend less time driving, it would have a positive economic effect. The efficient operation of the urban street and road network implies managing and controlling traffic flows based on the observance of conditions for maximum traffic safety and capacity of roads and intersections. Improvement of vehicle traffic conditions involves their optimal distribution along traffic routes.

In order to ensure the maximum efficiency of the city's traffic control system, it is necessary to introduce an intelligent traffic control system, which instantly responds to traffic problem situations and rapidly adopts an appropriate decision on the optimal route at the level of individual vehicles. The unified system of automatic movement of vehicles should monitor the general conditions, thus preventing the formation of traffic jams (transport congestion). We conducted experimental work on monitoring street and road networks in urban areas in Ukraine. It was found that 75–85% of transport queues and traffic jams were formed daily in the same places and for the same reason. We established that traffic jams on the street and road network of the city of Kyiv typically occur at signal-controlled intersections (69%), bridges (13%), multilevel intersections (9%), roundabouts (3%), and pot-holed roads (6%).

The analysis indicates that the traffic jams can be eliminated at a speed of 150–180 m of the queue in one minute under the condition of control and management of the entrance of new vehicles in the direction of the existing transport congestion. The system for monitoring traffic flows according to the loading of sections of the street and road network helps to determine the expected number of vehicles at an intersection and predict and decide quickly on their redistribution along parallel alternative routes, which, in turn, minimises the time of traffic delays.

Movements due to labour needs (commuting) influence the formation of transport and passenger flows in the cities of Ukraine. The corresponding distribution of traffic volumes between city districts lies in the availability of jobs in the relevant area and its placement in the city zone, which establishes the strength of inter-territorial communication. The corresponding indicator of trips to the workplace in Kyiv was as follows: within the area of residence (19 · 2%), between districts bordering on each other (39 · 9%), and between remote areas (40 · 9%). Movements between districts exceed movements within a district. Urban inter-district movements require the provision of appropriate transport connectivity between them.

We developed a methodology for constructing a model for the distribution of traffic flows along the street and road network. It is based on the compliance of qualitative and quantitative indicators of bottlenecks that act as two adjacent nodes providing traffic movements over a particular area of the city in accordance with established transport loading. The number of bottlenecks that provide transport links between city districts and their traffic capacity make traffic management and control even more relevant and must be considered as places where traffic flows are directed. Optimisation of the urban street and road network is impossible without optimising the number of traffic lanes on the elements that provide transport links between city districts. The number of lanes in bottlenecks should provide the necessary traffic capacity, corresponding to the traffic volume on this element of the street and road network during peak hours.

Economical transport operation largely depends on the efficient use of the urban street and road network. Since motorisation is growing dramatically, the optimal balance between the transportation of people by public transport and the personal vehicle should be considered as a condition for the optimal operation of the entire urban transport system. As a result of this research, it was found that the economic effect of the introduction of measures to improve the efficiency of the street and road network was reduced time spent in queues, which were estimated as the cost of time for passengers, drivers, and vehicles. If the efficiency of the street and road network is increased, it will decrease fuel consumption and thus achieve positive economic and environmental effects.

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