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Modeling of Passenger Flows in Agglomerations of Large Developing Cities (on the Example of Kyiv)

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Abstract

Based on the analysis of the fundamental impact of transport infrastructure, the city and the agglomeration are increasingly interpreted as a set of historically composed residential and industrial districts formed in the areas of interchanges of different modes of transport. On the example of the City of Kyiv, the modeling of passenger flows in agglomerations of large developing cities is considered, in order to implement the provisions of a modern urban environment, based on transport analysis of the urban area, with further forecasting of passenger flows on the street-road network and choice of main types of citywide passenger transport in the city. Based on the calculation of the population and passenger formation of transport areas, a model of the city's transport infrastructure is represented, the distribution of passenger traffic by modes of transport is estimated. The results of experimental studies of the intensity of existing passenger flows and models of their definition in the agglomeration of the most valuable city are determined. And the ways to solve the problems of conflict between the city and transport are proposed.

Keywords

urban area, street-road network, public transport, passenger traffic

1 Introduction

"The Kyiv City Development Strategy Until 2025", as the main normative document defining the goals and objectives of long-term city development, provides a process of strategic planning of local development following modern socio-economic realities and societal requirements (Kyiv City State Administration, 2017).

In particular, in the sector of transport development and urban mobility, the principles of sustainable urban mobility should be implemented, including: improving road safety; the development of public transport and space for pedestrians and non-motorized vehicles; improving the efficiency of the city's transport system management.

Optimization of transport demand should be implemented by increasing transport efficiency through the implementation of public transport systems (Mass Rapid Transit) and increasing the transport efficiency of sections of the street-road network.

The development of public transport and ensuring a quality transport offer can be achieved through the implementation of the following goals, objectives, and measures of the strategy:

- priority development of high-speed rail transport systems;
- priority development of high-speed trolleybus/bus services;
- establishment of transport interchanges;
- high-quality renewal of public transport rolling stock by introducing high-capacity rolling stock with the low floor;
- increasing the comfort and safety of public transport stops, territory, and objects of transport interchanges;
- development of night and weekend routes in the public transport system based on the analysis of the corresponding demand;
- development of second railway station;
- creation of a fast and convenient transit transport hub through the construction of suburban, long-distance, and international bus stations, integrated with railway stations and airports.

This requires a change in the management model of the city's transport infrastructure by improving systems for

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monitoring, analyzing, and forecasting the development of the city's transport system based on static and dynamic transport models (collection of statistics, updating of geoinformation data); implementation of the geoinformation system of accounting and management of infrastructural objects of the city with the town-planning cadastre; introduction of the obligatory procedure of coordination of plans on reconstruction and reorganization of the city transport system, determination of the priority of their realization at drawing up of branch programs of social and economic development based on the analysis carried out with the use of actual transport model of the city.

An integral part of urban planning documentation is the transport part of the master plan of the city, which is developed in detail in the complex transport scheme and complex schemes of traffic organization.

In particular, the Master Plan as concept for the strategic development of the City of Kyiv and its suburban area until 2025 (Kyiv Institute of the Master Plan, 2017) provides for the main directions of development of transport and street network:

- priority of all types of public passenger transport in the performance of urban transportations;
- high-speed off-street modes of rail transport (subway, high-speed tram, railway) development;
- creation of a system of complex interchanges at the intersections of high-speed public transport lines;
- providing fast, comfortable, and safe transport connections between all functional zones of the capital based on increasing the density of the street network;
- construction of underground and above-ground multi-story car parks in residential areas of the city, near interchanges;
- creation of the street network of lanes for bicycle traffic, pedestrian traffic during the design, construction, and reconstruction as well as conditions for the movement of the low-mobility population;
- restriction of movement of cars on city streets, blocking the traffic on certain streets, squares and their transformation into a pedestrian zone, the implementation of the paid entrance to the central planning zone of the city;
- creation of separate lanes on the streets for unimpeded movement of buses, trams, and trolleybuses.

The implementation of these provisions is impossible without modeling passenger flows in agglomerations of large cities, based on transport analysis of the urban area, with further forecasting the size of passenger flows on the road network and the choice of major types of urban passenger transport in the city.

2 Analysis of recent research and publications

There is still no clear definition of what a "city" is. Most concepts are interpreted as a place of concentration of certain urban planning functions to meet different human needs. In any case, no one will deny that at the current stage of development of society, the city is the most perfect form of human settlement. When considering the issue in terms of existing regulations, the city is presented as a territory of maximum satisfaction of human needs in three forms of life: housing, work, and leisure.

Accordingly, in each city there are the following functional areas: residential, industrial, and recreational. Collectively, they represent "urban matter". The urban matter exists within the street and road network that has developed and represents the urban framework that supports the urban matter in certain dimensions. The street-road network is an area of the city territory, where pedestrians and vehicles inevitably count as road users.

Population growth and the role of cities in public life or urbanization has been slow throughout history but has intensified significantly in the early 19th century. From 1800 to 1900, the part of the urban population increased from 10 to 13%. The population of large cities at this time did not exceed one million inhabitants: in London – 865,000, Beijing – 800,000, Constantinople – 570,000, Paris – 550,000, Naples – 340,000, St.Petersburg – 330,000, Vienna – 230,000.

The history of the formation and development of cities has shown that when the area of the city exceeds the possibilities of pedestrian accessibility (Daniels and Mulley, 2013), there is a need for vehicles to move around its territory. From this moment on, the city and transport are constantly pushing each other in their development.

Theoretical and practical aspects of the elasticity of demand for urban transport are studied in the article (Pupavac et al., 2020) on the example of the city of Rijeka, which shows the change in the required volume of transport services in urban traffic. As a result, there is a change in overall demand for transport services or the transfer of various entities.

The growth of the city territory causes the need for transport, transport causes further development of the city, etc. As a result, at a certain stage of development of each city, depending on the population, a transport system is formed (Table 1), which requires the use of high-powered

Table 1 Transport classification of cities

N	City type	Population of the city, thousand	Basic transport		Pick-up transport	
			Type of transport*	Share of transportation type, percent	Type of transport*	Share of transportation type, percent
1.	The largest	More than 800	CR	10	LRT	20
			S	20	TL	25
			LRT		B	25
2.	Large	500–800	LRT	20	TM	30
			MR		TL	25
					B	25
3.	Big	250–500	TM	25	TL	25
					B	50
4.	Medium	100–250	TM	5	TL	15
					B	80
		50–100	TM	1	B	94
			TL	5		
5.	Small	Less than 50	B	100	–	–

*Note: B – bus, CR – city railway, LRT – light rail transport, MR – monorail transport, TL – trolleybus, TM – tram, S – subway

types of urban passenger transport with a population of 100 thousand inhabitants and more. The quantitative growth of cities is also characterized by the accumulation of vehicles on the street-road network of cities. This leads to a mismatch between network capacity and traffic load, which is manifested in an increase in time spent on movement to primary areas and facilities, an increase in accidents, violation of the ecological balance of the city environment, economic losses. At the present stage, one of the ways to solve the problem is the priority use of city-wide passenger transport in daily transportation of the population in the city, where the main position should be given to vehicles with high capacity. In this case, the viability of the city directly depends on the efficiency of the system of citywide passenger transport and road network, which is adapted to its features.

Table 1 was developed on the basis of multiyear researches and long-term prospects for the use of passenger public transport in the cities of Ukraine and Eastern Europe (Dubova, 2006), and further researches for modeling of passenger flows are based on Table 1. Designations indicated in Table 1 are presented and fixed in the modern regulatory document of Ukraine – "DBN B.2.2-12:2019 Planning and development of territories" (State Building Standards, 2019).

The emergence of urban agglomeration is the result of urbanization when population growth in a given area is manifested in the territorial concentration of settlements, united in a complex urban system of intensive labor, cultural and recreational ties. The formation of the agglomeration at the first stage causes the concentration of functional areas, zones, and facilities along the existing railways and suburban highways.

In the conditions of the modern city and its agglomeration, it is difficult to demarcate the settlement, industrial and recreational territories that permeate each other. Given the fundamental impact of transport infrastructure, the territory of the city and the agglomeration is increasingly interpreted as a set of historically composed residential and industrial zones, formed in the areas of interchanges of different modes of transport. The function of the system of the forming framework is performed by rail transport (Bolonenkov, 1973) - it can be railway lines, light rail, or monorail transport, working on the principle of coordination of the general and supply routes. The integrity of the system is ensured through transport terminals, where different types of transport are integrated. Further directions for the development of cities based on forecasting passenger flows, determining the need for transport, and analyzing the problems of motorization of cities and ways of its urban planning solution had been obtained in the work (Zablotskiy, 1986).

Compliance of the requirements of pedestrians and passengers to the transport infrastructure of the urban agglomeration at the level of normative indicators is essentially a characteristic of the level of satisfaction of the requirements of the population in terms of time spent on movement.

The sharp acceleration of the urbanization process that took place in the second half of the 20th century has led to an increase in the share of the urban population to 50% today.

Modern cities have gone through several stages in their development:

- urban growth, which is associated with population growth as a result of natural increase, migration, and changes in administrative boundaries;
- the growth of the urban area, which is associated with the strengthening of labor and cultural ties in the suburban area and the accession of nearby settlements with the formation of agglomerations with a population of more than 10 million inhabitants (Table 2);
- growth of agglomerations and the formation of large urban areas - megalopolises with a population of 25 to 70 million people (Table 3).

In the middle of the 20th century, urbanization led to problems and changes in the urban environment, poor land use, deteriorating infrastructure and services, changes in the natural landscape, lack of greenery, environmental pollution, waste disposal, congestion of road and transport.

The main consequences of the stages of the urban development process in terms of transport can be represented by the following groups:

- strengthening of city-agglomeration connections and related changes in the transport infrastructure;
- increase in travel time in the city and the agglomeration, decrease in speed, increase in road delays;
- a sharp increase in the level of accidents on the street and road network of cities and agglomerations;
- deterioration of the ecological situation.

The process of population concentration in Eastern European cities, including the cities of Ukraine, continues and is an inevitable process of urbanization with inherent changes in the scope of transport. Despite the declining population (23% over the last 25 years), the number of cities is growing, and the share of citizens is 69%. The general agglomerations with a population of 400 to 4000 people are naturally formed around the largest cities as a result of concentric growth and territorial merging of settlements. But, in fact, the process of urbanization, which should play a positive role in the development of territories over time, contradicts the primary purpose of the city - to create the most comfortable conditions for improving living standards. Inefficiently managed agglomerations become so as their transport problems worsen, which is the main reason why passengers use cars for daily travel (Department for Transport of UK, 2017). The world has accumulated sufficient experience in solving them, but, for example, the agglomeration of 4 million people, the center of which is the City of Kyiv, this experience is not taken into account. Thus, the total average daily volume of passengers' transportation in Kyiv is

Table 2 The most important agglomerations in the world

N	Agglomeration	Country	Population, million inhabitants	Area, km^2	Population density, peop./km^2
1.	Tokyo	Japan	37.7	8677	4345
2.	Mexico	Mexico	23.6	7346	3213
3.	New York	USA	23.3	11264	2068
4.	Seoul	South Korea	22.7	1943	11623
5.	Mumbai	India	21.9	2350	9319
6.	Sao Paulo	Brazil	20.8	7944	2618
7.	Manila	Philippines	20.7	4863	4257
8.	Jakarta	Indonesia	19.2	7297	2631
9.	Deli	India	18.9	1425	13263
10.	Shanghai	China	18.6	7037	2643

Table 3 The most important megalopolises in the world

N	Megalopolis	Population, million inhabitants	The length of the main axis, km	Population density, peop./km^2	Number of agglomerations
1.	Tokaido	70	700	800	20
2.	Boswash	45	800	450	40
3.	Chi-Pitts	35	900	220	35
4.	San-Francisco	18	800	180	15
5.	Rhenish	30	500	500	30
6.	English	30	400	500	30

4.3 million passengers, of which 1.7 million are off-street high-speed types: railway, subway, and high-speed tram. Thus, 2.6 million (60.5%) passengers are transported by land urban passenger transport: traditional tram, trolleybus, bus. The basis of the system (38%) is small-capacity buses - route taxis, which are extremely inefficient in terms of mass passenger traffic in urban agglomerations (Kyiv City State Administration, 2017).

Increasing the speed of citywide passenger transport can be achieved only by maximizing the reduction of overhead at regulated and unregulated intersections during acceleration and braking, at stops during boarding and disembarking of passengers, at land pedestrian crossings, at other obstacles. This means the need to eliminate as much as possible the intersections of citywide passenger transport with the flow of pedestrians and transport modes and increase the distance between stops. Given the organization of priority at intersections and a separate road, the speed increases to 30–32 km/h, which is equivalent to the speed system BRT (Dubova, 2020). This solution meets the basic needs of moving the population with the help of citywide passenger transport: time, level of comfort, and safety.

3 Problem and task statement

The transport system of the agglomeration of the City of Kyiv is practically absent. The existing railway transport infrastructure is inefficient. The use of buses, including small buses or taxis, as the main mode of transport, leads to an increase in travel time by 2–2.5 times. High filling of rolling stock, inconvenient schedule, lack of connection with other types of passenger transport, constant traffic jams during rush hours on the highways approaching the center of the agglomeration, made daily travel extremely uncomfortable.

The modern urbanization process inevitably affects the daily lives of millionaire cities, primarily in the form of additional vehicles (25–30%) arriving in the city from the suburbs in the morning and leaving in the evening.

Despite this, normative and design documents, as a rule, do not provide recommendations for calculating the amount of passenger traffic in the suburban area of the city. As a result, the level of organization of passenger transport services and especially the transfer process is spontaneous and disordered, which affects the excessive time spent by passengers on the road and the low level of travel comfort. But forecasting the size of passenger traffic is an important aspect of determining the intensity of transport links between the city and the agglomeration.

The constant increase in the number of vehicles does not correspond to the limited capacity of the city's highways and agglomerations (Reitzen, 2014). Experience has shown that the road network cannot be endlessly transformed for the benefit of the cars, which now have full priority as a vehicle. It now includes all the consequences that led to the deterioration of the quality of human life in the city and the agglomeration. Competition between individual cars and city-wide passenger transport continues and so far does not lean towards the use of the subway, tram, trolleybus, and bus, which are still considered transport for people in difficulty and pensioners.

Existing urban development projects, which form the prospects of the city and the agglomeration, present well-constructed documentation and offer large-scale projects for the construction of backup highways, additional radial exits and bypasses, tunnels, and multilevel transport facilities.

Among the options, it is necessary to give priority to the organization of mass passenger transport. For the countries of Eastern Europe, already now, at the first stage, this can be done at the level of solving organizational issues within the existing railway transport infrastructure. In the presence of the adjusted system of rail transport, it is possible to solve questions of external coordination and the organization of lines of the passenger transport. The basis for the formation of such a system is complexes of transport interchanges and intercepting parking lots in the areas of stops of rail passenger transport. This is in line with the latest trends in the world.

The global experience of organizing passenger transportation in limited territorial conditions has shown that only the use of high-quality citywide passenger transport can be a solution in the current situation. Only powerful, environmentally friendly modes of transport can perform basic transportation in modern urban areas: in cities, agglomerations, megacities. Most European cities are interconnected by high-speed rail, which was founded by Britain in the 19th century and then in the 1980s followed by Belgium, France, Germany, the Netherlands, Spain, Austria, and Italy. Technical advances and innovations on routes in these countries have shown that moving on a modern train is a serious competitor to aircraft in terms of speed and safety. The western part of Europe is now connected by a single high-speed rail network Eurostar and Thalys. At the beginning of the 21st century, China became the world leader in the use of high-speed lines and the first regular high-speed maglev, where the largest number of highways is located – 29.22% of the total length of railways and regular trains travel at 350 km/h. (Table 4).

Today, no one disputes the leading role of France in the creation of high-speed railways, but work to improve the system of high-speed express and other modes of urban passenger transport continues – modern regional express trains are moving at 160 km/h and can accommodate 220 passengers in the railroad passenger car. In the city, there is a network of underground regional subways, which branch out into the city to serve the territory of the agglomeration.

The restoration of the tram, which ceased to exist in the 1940s, began in European countries at the beginning of this century. Today, four lines connect the terminals of the Paris Subway with the suburbs and are served by modern high-speed rolling stock.

Similar systems of city-wide passenger transport, which connect the city territory and its agglomeration, also operate in other European countries and offer options for solving the problem of transporting people in highly urbanized areas.

When trains in the world are gradually catching up with aircraft at speeds of 600 km/h, high-speed railways in Eastern Europe, including Ukraine, are more of a myth than the near future. The state of railway communication and city-wide passenger transport, in general, is an illustration of the country's technological backwardness.

The speed of movement of goods and passengers by railway is one of the key indicators of the state of the railway. According to the existing standards and the existing technical infrastructure, the permissible speed on most railways cannot exceed 70 km/h. Ordinary trains run at a speed of 58 km/h, "high-speed" – 81 km/h, which is 3 times less than the global figures (200–250 km/h). Existing railway tracks serve both freight and passenger traffic when separate tracks with different technical characteristics are being built all over the world for high-speed passenger transport. The system of connecting different modes of transport and different routes in time and space is imperfect. There is no monitoring of the existing system of passenger traffic, and no clear long-term plans for further development for at least 10–15 years.

Table 4 Characteristics of high-speed railways in the world (2018)

N	Country	In operation, km	Under construction, km	Length of lines, km	Maximum speed, km/h	Average speed, km/h
1.	Austria	352	208	560	275	230
2.	Belgium	326	0	326	368	300
3.	Great Britain	113	230	343	-	-
4.	Germany	3038	330	3368	368	320
5.	Denmark	5	175	180	-	-
6.	India	0	508	508	-	-
7.	Iran	0	410	410	-	-
8.	Spain	3200	2800	6000	404	320
9.	Italy	1192	433	1625	400	300
10.	China	26869	10738	37607	501	350
11.	Taiwan	345	0	345	300	300
12.	Morocco	186	0	186	-	-
13.	Netherlands	175	35	210	300	300
14.	Norway	64	81	145	210	210
15.	Poland	0	322	322	291	200
16.	South Korea	1105	376	1481	421	300
17.	Russia	0	0	0	290	250
18.	Saudi Arabia	453	0	453	-	-
19.	USA	0	0	0	265	240
20.	Turkey	802	3798	4600	303	250
21.	France	3220	125	3345	575	320
22.	Switzerland	92	23	115	-	-
23.	Japan	2765	657	3422	603	320

Each major city has numerous industrial, labor, and cultural ties with the surrounding area, and cannot be considered in isolation from it. The development of transport and the city is interdependent and therefore transport is one of the criteria for city planning. On the one hand, the location and population of districts, the availability of places of employment and services determine the flow of passengers and the need for transport, on the other hand – the development of transport determines the greater accessibility of residential areas and places of employment. Estimation of conditions of transport service of the most significant city in the special literature (Zablotskiy, 1986) is based on a definition of quantity of movements with time expenses less than 45 minutes in a total number of labor movements.

One of the defined goals of the Strategy of the City of Kyiv is to prove that the share of the population that spends no more than 45 minutes on the implementation of transport correspondence: "home-work" and "work-home" (one way) has increased from 77% (in 2015) up to 90% (in 2025). Studies have shown that the total cost of travel time exceeds the normative value by 15% in the case of using a car and 79% in the case of using citywide passenger transport, which averages 47% (Dubova, 2016).

4 Methodology and theoretical framework

The modern city is presented as a complex organism, which is the most acceptable form of human provision of forms of life: housing, work, recreation. Accordingly, the territory of the city is a combination of hierarchically constructed functional zones (State Building Standards, 2018; 2019), territories and objects that are united into a single system by transport infrastructure of the city (TI).

Thus. from the transport point of view, the city is a system, which combines the framework of the street-road network (subsystem SRN) and functional areas, territories, and facilities that it covers. The results of the city's life are manifested in the SRN in the form of traffic flows (VH vehicle subsystem), pedestrian and passenger flows (PP subsystem). Traffic, pedestrian, and passenger flows are participants in traffic, the value of which should correspond to the capacity of the city framework. The conditioned level of functioning of the system is provided by a set of objects of transport and pedestrian service (TPS subsystem). Each of the subsystems is characterized by indicators that are regulated by normative values following the existing (State Building Standards, 2018; 2019).

The main characteristic of the system is the number of the city's population, which in terms of transport can be in two states: passengers and pedestrians, which are constantly transitioning.

The basis of the TI system is the fulfillment of three requirements:

- compliance of the number of passengers with the carrying capacity of the transport;
- compliance of traffic intensity with SRN capacity;
- compliance of the intensity of pedestrian flows with the capacity of pedestrian paths and sidewalks.

TI, as the basis of the city, should be presented in the form of a four-way complex (Fig. 1), combining systems of PP, SRN, VH, and TPS with a single purpose - to ensure the movement of passengers through the territory of the city with the normative time spent in conditions with a high level of comfort and safety.

The number of passengers is the basis for transport calculations. Each of the subsystems has an indicator that describes their common correspondence. For SRN this indicator is the capacity (C), for VH – the carrying capacity (P), for PP – the value of passenger traffic (D). There is a consistent relationship between the indicators when the number of passengers Dij loaded into vehicles should correspond to the capacity $Dij < Pi$, and the number of vehicles (Ui) per hour on the SRN, containing passengers, should correspond to its capacity $Ui < Ci$. Compliance is ensured by the system of TPS, which has the function of managing and coordinating the components of the transport infrastructure through the system of traffic control. Thus, the problem of meeting the needs of the population in transportation in the city is solved.

The transport analysis of the separate territorial-planning formation of the city is carried out based on analytical and experimental inspection of the transport infrastructure, the corresponding transport calculations, and the definition of indicators. The basis for transport analysis is the calculation of the amount of passenger traffic and the passenger traffic intensity per hour and the mapping of them on the sections of the SRN map.

The type of municipal transport and the system of routes of the city are chosen according to the map of passenger flows, which is a priority structure in the transportation of passengers in the city.

In reality, in the absence of a systematic approach to TI, this relationship is broken.

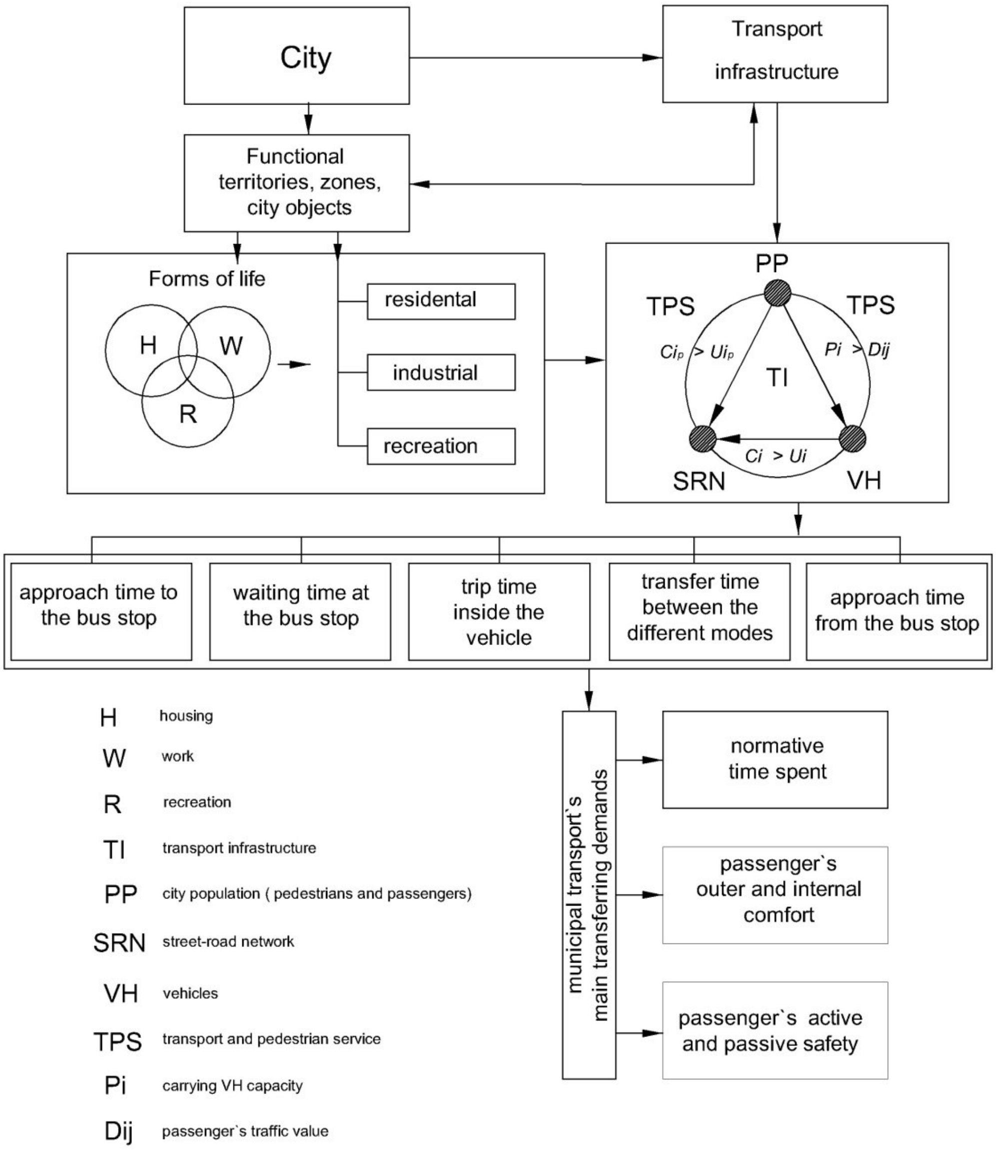

Fig. 1 Model of city transport infrastructure

Passenger demands are manifested at each stage of the components of the municipal transport's trip: when approaching the bus stop, waiting at the bus stop, while staying inside the vehicle, transfers between modes of municipal transport, approach from the bus stop to the destination.

Travel time is always a priority. Calculations have shown that concerning the maximum standard time of 45–60 minutes, which should probably be used as a guide for the city and its agglomeration, the average components of travel time at the maximum level of comfort and safety should not exceed:

- the approach time to the stop with a radius of 300–500 m and a pedestrian-passenger speed of 5 km/h will be 6 minutes;
- waiting time at the stop on average during rush hour will be 3 minutes;
- the time required to change from one mode of transport to another will be 5 minutes;
- the approach time from a stop to the destination with a radius of accessibility of 300–500 m will be 6 minutes;
- the time spent inside the rolling stock will be 25 minutes.

In such conditions, the required speed of transport reaches 32 km/h, which corresponds to the level of high-speed transport systems.

Travel time is an experimental studies of the time of rolling stock on the route and the corresponding calculations were carried out personally by the authors. The results of these studies are presented at (Zvarych and Dubova, 2006), where the main stages of the development of urban passenger transport in Ukraine and the difficulties that have appeared in our time had been described; as well as proposed options for solving the problem of the functioning of passenger transport in city centers. The continuation of this line of research is reflected at (Dubova and Zvarych, 2012), where the factors had been considered that affect the capacity of urban passenger transport lines and determine the travel time in conditions of dense traffic flows.

The processes of agglomeration development of the conditions of urbanization and suburbanization are gradually faced with the fact that most of the people living in the conditions of a "healthy" suburban area and working in the city do not want to move. Thus, transport is the most difficult issue for the further development of the agglomeration.

To solve the social problems of resettlement in the agglomeration it is necessary to significantly increase the speed of connection to 30–40 km/h. To increase this speed, it is necessary to build modern high-speed off-street transport lines: suburban railway, mini-metro, light metro, high-speed tram, monorail (Land Transport Authority, 2022). From an economic point of view, this can be done only in some areas. For settlements located far from a possible route of high-speed communication, the decision can be the usage of buses of small capacity, individual transport, the bicycle, scooters (Dolati, 2014). Thus, the problem of planning the agglomeration cannot be solved without the organization of a single transport system that takes into account the use of individual transport. In small towns and remote areas individual transport is most needed. Here its use does not create problems of parking lots, garages, or other elements of transport infrastructure.

The definition of passenger flows on the main directions of a street and road network is the demand at all stages of design of transport systems.

Perspective forecasting of the amount of passenger traffic on the SRN is most often performed using a gravitational mathematical model (Merkulov et al., 1980), which regulates the transport accessibility of the main functional areas, zones and facilities as the main indicator of the quality of transport services.

Calculation of population and passenger formation of transport districts is the algorithm when the transport areas are performed as a part of the city's territory in terms of pedestrian accessibility. It is measured on the plan and in total gives the city area, F (km^2). The territory of the city is divided into transport districts – territorial formations with an area of 0.5–3 km^2, tending to the central transport node or to the axis of symmetry of the area. The boundaries of the districts are: natural or artificial obstacles, the main street-road network. Zoning is carried out in such a way that one or two points of gravity get to one district (industrial districts, city and shopping centers, railway stations, city parks). The size of the districts should be approximately the same, the central district can be 20–30% smaller.

For calculations in cities with a population of 250–500 thousand, 500–800 thousand, and more than 1 million, 35–50, 60–70, and more than 100 districts are allocated, respectively.

The area of transport areas is measured on the plan and in total is the total area of the city F (km^2). The population of the city is determined by the task N (thousand inhabitants).

The calculation of the population in transport districts is determined by the formula Eq. (1):

$$N_i = \frac{N}{F} \times f_i , \qquad (1)$$

where N is the population of the city; F is city's square; f_i is the area of the i-th transport district; N_i is the population of the i-th transport district.

The value of the total passengers P in the city is obtained depending on the population of the city N, distributing it in proportion to the transport districts Eq. (2):

$$P = M \times N , \qquad (2)$$

where P is the value of total passengers formation in the city, million passengers; M is total mobility of the population, movements per capita per year; N is population of the city, thousand inhabitants (Fig. 2).

The next step is tracing of the trunk transport network, which connects the main objects in the city: the centers of transport areas, industrial enterprises, the city center,

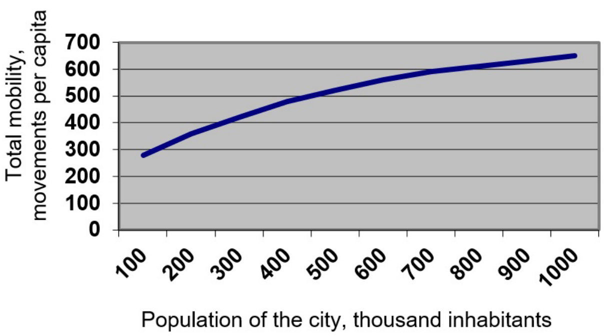

Fig. 2 Dependence of mobility on the population of the city

the railway station, the city park, the shopping center, etc. To check its compliance, we find the density of the transport network by the Eq. (3):

$$\delta = \frac{L}{F}, \quad (3)$$

where L is the length of the transport network, km; F is area of the city, km^2.

The density index must meet the requirements of the standard: $\delta = 1.5 - 2.5$ km/km^2.

In case of non-compliance with regulatory requirements, the adjustment of the trunk transport network is necessary by its reducing or lengthening.

We determine the centers of gravity of transport areas, which should coincide with intersections or should be located at the races of the city's road network.

The calculation of the number of passengers following between the centers of transport districts of the city is performed according to the gravity model:

$$D_{ij} = P_i \frac{N_j \frac{100}{t_{ij}^2}}{\sum_{i=1}^{n} N_j \frac{100}{t_{ij}^2}}, \quad (4)$$

where D_{ij} is the value of passenger traffic, million people; n is the number of transport districts; t_{ij} is time spent on movement between districts, min; N_j is population of the district, thousand inhabitants; P_i is passenger formation of the area, million people.

Preparation of initial information for calculations includes data on the number of employees of the city-forming base enterprises and capacity in service maintenance institutions. The calculation of the number of passengers following between the centers of transport districts is performed according to the above formula in Eq. (4).

Distances between districts, l_{ij}, km in Eq. (5):

$$l_{ij} = 0.7 \times \sqrt{F_i}. \quad (5)$$

Based on these data, the time spent on movement between districts is determined, taking into account the time for approach, waiting, transfer and movement on transport. The accepted time spent on intra-district movements is 10 minutes.

The Tables 5, 6 consistently make calculations:

- time spent on movement between districts in Eq. (6):

$$t_{ij} = 12 + 4 \times l_{ij}, \quad (6)$$

- coefficients of social assessment of the mutual location of districts in Eq. (7):

$$d_{ij} = \frac{100}{t_{ij}^2}, \quad (7)$$

- distribution of weights (c) of the probability of distribution of passenger formation on areas of a residence in Eq. (8):

$$c = N_j d_{ij} \Big/ \sum N_j d_{ij}, \quad (8)$$

- population movements between districts D_{ij};
- coefficients of transport use, φ_{ij} and travel between districts in Eq. (9):

$$D_{ij}^{mp} = \varphi_{ij} \times D_{ij}, \quad (9)$$

- passenger work on transport in Eq. (10):

$$A_{ij} = D_{ij}^{mp} \times l_{ij}, \quad (10)$$

- definition of the main indicators: average distance of a trip l_{av}, general mobility M and transport mobility M_{tr};
- obtained as a result of calculations of the main document – a cartogram of the intensity of passenger traffic at the SRN of the city;
- adjustment of the pre-planned transport network according to the map of passenger flows;
- choice of mode of transport, determination of the routing scheme, interval, and organization of traffic, the number of rolling stock of passenger transport on the routes;
- determination of costs for the organization of selected modes of transport.

5 Results of the research

Forecasting of passenger flows is a significant aspect of determining the city's external relations. For this purpose there are additional transport areas at the exit highways of the city, characterized by the number of suburban population to which it is attracted, and the number of city residents who leave the city for work, business, cultural and other purposes. Thus, each transport area has a characteristic that consists of the number of inhabitants of the city center and the number of inhabitants of the suburban area, forming the amount of passenger formation and the amount of passenger absorption. But this method is associated with a complex procedure and time-consuming calculations at the city level.

To determine the flow of suburban passengers a model based on determining the size of passenger traffic through surveys and according to the schedule to the annual or daily mobility of the population for work, cultural and

Table 5 Determination of the amount of passenger traffic in the agglomeration of the City of Kyiv

N	Name of the settlement	Population, thousand inhabitants	Distance to the City of Kyiv, km	Transport mobility of the population, one person' trips per year	Transport accessibility, min.	Passenger flow per year, million passengers
1.	Boryspil	60.271	37	223	44	13.44
2.	Brovary	98.895	26	265	39	26.21
3.	Boyarka	35.32	30	213	47	7.52
4.	Bucha	28.729	39	128	59	3.7
5.	Vasylkiv	21.03	38	128	59	2.7
6.	Vyshneve	37.457	30	285	35	10.7
7.	Vyshhorod	26.536	27	213	46	5.7
8.	Irpin	42.924	33	155	54	6.65
9.	Ukrainka	14.163	36	155	55	2.2
10	Fastiv	48.237	75	53	86	2.6
11	Novosilky	3.234	16	213	30	0.7
12	Obukhiv	33.102	37	213	47	7.05
13	Kotsiubynske	15.038	20	285	37	4.3
14	Gostomel	14.304	38	128	59	1.83
15	Vorzel	5.648	45	60	69	0.34
16	Vel. Dymerka	9.606	39	151	55	1.45
17	Nemishaevo	7.052	41	128	61	0.9
18	Glevaha	12.00	30	261	39	3.13
19	Borodyanka	13.086	64	54	83	0.71
20	Makariv	10.362	66	47	88	0.49
21	Chabany	7.650	18	328	31	2.51
22	Kalynivka	5.292	40	213	46	1.13

Table 6 The passenger traffic estimation by transport mode

N	Destination	The amount of passenger traffic by mode of transport, passengers per hour				Calculated passenger flow, passengers per hour	Deviation, %
		railway	car	mini bus shuttle	total		
1.	Kyiv - Brovary	340 3.0%	7298 70.0%	10750 27.0%	18388 100%	25700	12.4
2.	Kyiv - Boryspil	90 1.3%	4198 62.5%	2430 36.2%	6718 100%	6782	1.0
3.	Kyiv -Vasylkiv	300 13.8%	1327 61.2%	540 25.0%	2167 100%	2127	1.8
	The average share	6.0%	64.6%	29.4%	100%	–	5.1

household purposes can be used (Fig. 3) according to the number of settlements in a given time zone of the agglomeration relative to the city center.

These criteria should be used and determined in the development of urban design documentation. Regulatory requirement (State Building Standards, 2019:p.66): "The time spent on moving from places of residence to places of employment for 90% of workers (one way), as a rule, should not exceed: in cities with a population of more than 800,000 people – 45 minutes, from 500,000 to 800,000 people – 40 minutes, from 250,000 to

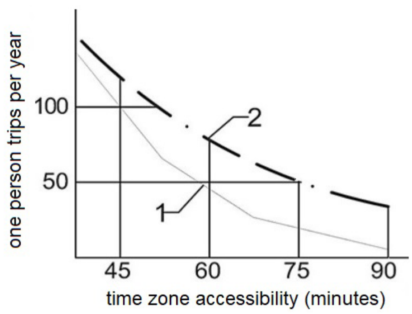

Fig. 3 Mobility changes of the population in areas of accessibility: 1 – mobility by work purposes; 2 – mobility by cultural and household purposes

500,000 people – 35 minutes, up to 250,000 people – 30 minutes" exists, as a recommendation, for movement within the city and does not apply to the agglomeration zone. There are 11 cities and 11 urban-type settlements in the agglomeration of Kyiv (Kyiv City State Administration, 2017) (Table 5). Research has shown that in non-stop traffic conditions, the average transport accessibility between cities in the agglomeration of the City of Kyiv is 48–50 minutes. Taking into account the additional time spent on approach, waiting, transfer, possible traffic jams and accidents, the travel time for passengers increases by 2–2.5 times.

The magnitude of passenger traffic on the border of Kyiv as a result of modeling in different directions is (Fig. 4) from 2,000 to 14,000 passengers per rush hour, which indicates the need for a balanced approach to the choice of the transport mode in each case.

Experimental studies of the traffic intensity and passenger traffic for the three directions Kyiv-Brovary, Kyiv-Boryspil, and Kyiv-Vasylkiv were performed to verify the obtained data (Table 6).

The obtained values of passenger traffic coincide with the simulation results in all cases. Directions 1 and 2 primarily require the usage of powerful electrified modes of urban passenger transport: railways, light rail transport, monorail systems, which is consistent with modern trends in the organization of passenger transport in the suburban area.

Unfortunately, the existing transport scheme does not meet this requirement. According to the research, the advantages in passenger transportation belongs to private cars (64.6%) and vans – 29.4%, the share of rail transport is only 6.0% (Table 6).

Existing railways and highways, which are the basis for an efficient transport system, cannot be fully used in suburban areas without a systematic approach to the organization of the entire transport process. The priority should belong to the infrastructure of rail transport, which has already developed, but it requires maximum costs for reconstruction according to the latest world standards.

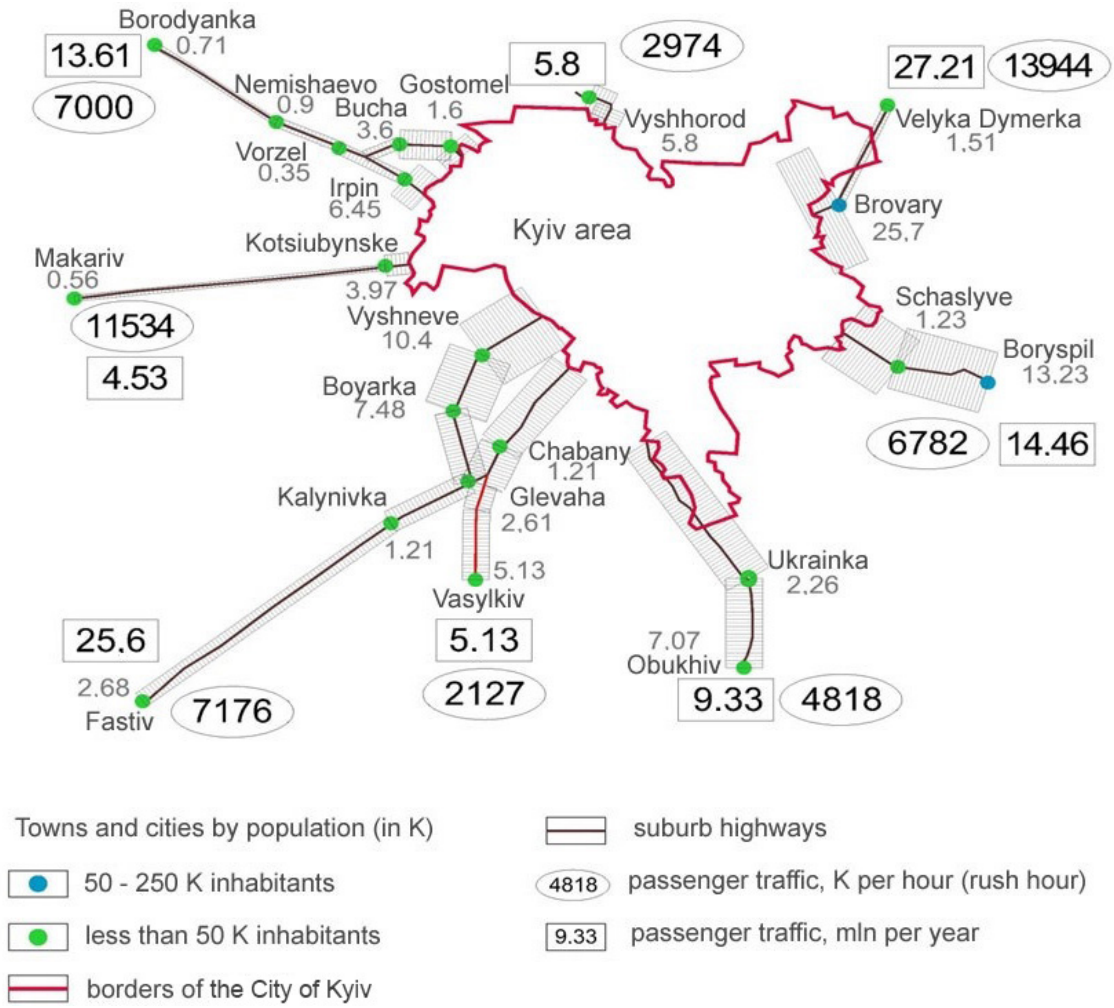

Fig. 4 The magnitude of passenger traffic in the agglomeration of the City of Kyiv

6 Conclusions

The problem of the conflict between the city and transport can be solved in several ways. The first is to increase the capacity of streets, create streets and highways, which are specialized carriageways entirely for transit, regional and local traffic. The busiest traffic intersections are represented by road structures at different levels. The experience of road construction makes it possible to create the traditional ring-type junctions. When the traffic intensity increases to maximum on the levels, the overpass over the intersection or underground tunnel are required. In this case, all the main directions of movement intersect at different levels and the complete allocation of traffic flows is carried out in several stages with a gradual adaptation to the growth of traffic flows. Construction of transport junctions at different levels in combination with the network of highways and roads connecting the city and the city agglomeration allows to increase the capacity of the primary road network and increase the amount of traffic flow, increase speed from 50–60 inside the city up to 80–100 km/h in high-speed areas.

The second way to solve the traffic problem is to prohibit or restrict the private cars in certain urban regions. Urban spaces that connect pedestrian areas, streets for the public passenger transport, bicycle paths, combined with infrastructure for rest and relaxation, have existed since the second half of the 20th century and have proven their necessity. This transformations force drivers to change to public transport, to leave their car at home or in the parking lot.

The third way, at first sight, is not connected with transport, but as a result, decisively influences the formation and distribution of transport streams. This is the rational placement of infrastructure elements that attract the largest number of visitors, the dispersal of city centers and recreation cities, changing the location of cities of employment, etc. This solution to the traffic issue is most effective using rational planning of the territory - based on managing the development of the city agglomeration it is possible to manage its transport. Complex issues require a comprehensive system solution.

Moreover, the integrated approaches and scientific substantiation, analysis of the experience of the modern urban space reconstruction should be taken into account. It needs to build the holistic system of interactions between scientific (research) and engineering (design) approaches (Prusov, 2012), considering features of the streets and urban roads greening (Tkachenko et al., 2021).

Only in such a complex, it is possible to substantiate the need to build high-class highways, the possibility of allocating zones without transport, to place elements of transport service: garages, parking lots, gas stations, service stations, etc. With the growth of the level of motorization, the demand for the organization of transport space is complicated by the lack of free territories in cities and on radial directions in agglomerations. Therefore, along with the creation of conditions that improve the use of the car, it is necessary to introduce restrictions on its usage for the benefit of pedestrians, cyclists, citywide public transport.

References

Bolonenkov, G. V. (1973) "Планировочная организация пригородных сообщений большого города" (Planning organization of suburban communications in a large city), State Research Institute of Scientific and Technical Information, Moscow, Russia. (in Russian)

Daniels, R., Mulley, C. (2013) "Explaining walking distance to public transport: The dominance of public transport supply", Journal of Transport and Land Use, 6(2), pp. 5–20. https://doi.org/10.5198/jtlu.v6i2.308

Department for Transport of UK (2017) "Transport Statistics Great Britain 2017", [pdf] Crown, London, UK. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/661933/tsgb-2017-report-summaries.pdf [Accessed: 30 December 2021]

Dolati, H. (2014) "Biking Distance: Exploring Gender, Race, and Climate", Master Thesis, Master of City and Regional Planning, Ohio State University. [online] Available at: http://rave.ohiolink.edu/etdc/view?acc_num=osu1388725654 [Accessed: 30 December 2021]

Dubova, S. V. (2006) "Об исследовании времени нахождения городского пассажирского транспорта на маршрутах в центральной части города" (On the study of the time spent by urban passenger transport on routes in the central part of the city), [pdf] Urban Development and Spatial Planning, 25, pp. 69–76. Available at: https://library.knuba.edu.ua/books/zbirniki/02/200625.pdf [Accessed: 24 August 2023] (in Ukrainian)

Dubova, S. V. (2016) "Оценка качества функционирования городского пассажирского транспорта общего пользования." Assessment of the quality of functioning of public urban passenger transport), [pdf] Modern Problems of Architecture and Urban Planning, 44, pp. 147–154. Available at: http://library.knuba.edu.ua/books/zbirniki/01/201644.pdf [Accessed: 30 December 2021] (in Ukrainian)

Dubova, S. (2020) "Transport priorities of urban development", presented at IX International Scientific Conference from the Series "Phenomena of Borderland": Scientific Review in the Discipline of Architecture and Urban Studies – Principles, Practice Expectations, Szczecin, Poland, Nov. 27.

Dubova, S. V., Zvarych, O. A. (2012) "Дослідження впливу особливостей організації дорожнього руху на пропускну здатність ліній міського пасажирського транспорту" (Study of the impact of traffic organization features on the capacity of urban passenger transport lines), [pdf] Urban Development and Spatial Planning, 45(1), pp. 265–268. Available at: https://library.knuba.edu.ua/books/zbirniki/02/2012451.pdf [Accessed: 24 August 2023] (in Ukrainian)

Kyiv City State Administration (2017) "The Kyiv City Development Strategy Until 2025", [pdf] Executive Body of the Kyiv City Council (Kyiv City State Administration), Kyiv, Ukraine. Available at: https://dei.kyivcity.gov.ua/files/2018/1/11/Strategia.pdf [Accessed: 24 August 2023]

Kyiv Institute of the Master Plan (2017) "Генеральний план м. Києва до 2025 року. Концепція стратегічного розвитку м. Києва та його приміської зони" (The City of Kyiv Master Plan and Concept of strategic development of the city of Kyiv and its suburban area until 2025), [online] Available at: https://kga.gov.ua/generalnij-plan/genplan2025 [Accessed: 30 December 2021] (in Ukrainian)

Land Transport Authority (2022) "Land Transport Master Plan 2040", Government of Singapore. [online] Available at: https://www.lta.gov.sg/content/ltagov/en/who_we_are/our_work/land_transport_master_plan_2040.html [Accessed: 24 August 2023]

Merkulov, E. A., Turchikhin, E. Y., Dubrovin, E. N., Yudin, V. L., Samoilov, D. S., Zaitsev, L. K. (1980) "Проектирование дорог и сетей пассажирского транспорта в городах" (Design of roads and passenger transport networks in cities), Stroyizdat, Moscow, Russia. (in Russian)

Prusov, D. (2012) "Numerical Research of the Retaining Constructions during Reconstruction of the Transport Structures", Transport, 27(4), pp. 357–363.
https://doi.org/10.3846/16484142.2012.750623

Pupavac, D., Maršanić, R., Krpan, L. (2020) "Elasticity of Demand in Urban Traffic Case Study: City of Rijeka", Periodica Polytechnica Transportation Engineering, 48(2), pp. 173–179.
https://doi.org/10.3311/PPtr.11750

Reitzen, E. O. (2014) "Організація і безпека міського руху: навчальний посібник" (Organization and safety of urban traffic: a textbook), Sic Group Ukraine. ISBN 978-617-709-243-7 (in Ukrainian)

State Building Standards (State Building Codes of Ukraine) (2019) "ДБН Б.2.2-12:2019 Планування і забудова територій" (DBN B.2.2-12:2019 Planning and development of territories), Ministry of Regional Development of Ukraine, Kyiv, Ukraine. (in Ukrainian)

State Building Standards (State Building Codes of Ukraine) (2018) "ДБН В.2.3-5:2018 Вулиці та дороги населених пунктів" (DBN V.2.3-5:2018 Streets and roads of settlements), Ministry of Regional Development of Ukraine, Kyiv, Ukraine. (in Ukrainian)

Tkachenko, I., Lytvynenko, T., Prusov, D., Hasenko, L. (2021) "Features of Streets and Urban Roads Greening in Ukraine and other Countries of the World", Periodica Polytechnica Transportation Engineering, 49(2), pp. 170–181.
https://doi.org/10.3311/PPtr.14980

Zablotskiy, G. A. (1986) "Транспорт в городе" (Transport in the city), Budivelnik, Kyiv, Ukraine. (in Ukrainian)

Zvarych, O. A., Dubova, S. V. (2006) "Напрямки розвитку наземного пасажирського транспорту у містах України" (Development directions of ground passenger transport in Ukrainian cities), Urban Development and Spatial Planning, 25, pp. 96–103. Available at: https://library.knuba.edu.ua/books/zbirniki/02/200625.pdf [Accessed: 24 August 2023] (in Ukrainian)