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Ievgen Medvediev, Sergiy Soroka
Volodymyr Dahl East Ukrainian National University
59-a, Tsentralnyi pr., Sieviebrodonetsk, 93400, Ukraine

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THE ROAD NETWORK TRAFFIC CAPACITY TAKING INTO ACCOUNT PUBLIC TRANSPORT STOPS LAYOUT METHOD

Summary. *The vigorous motorization process is taking place in a growing number of countries year by year, and the number of people involved in road traffic is constantly increasing. The growth of the vehicle fleet and the volume of transportation lead to an increase in traffic that in the context of cities with a historical build-up leads to a traffic problem. It is particularly acute at the junctions of the road network. There is an increase in transport delays, queues, and congestion, causing reduce in speed, excessive fuel consumption, and increased wear-out of vehicle components and assemblies. These questions are constantly analyzed both in theoretical and practical terms. Today, the negative effects of motorization cannot be eliminated, and effective measures need to be developed to reduce their negative impact on the urban environment. An irrational location of public transport stops leads to a significant increase in transport delays. Respectively, the objective is to determine the optimal layout of the public transport stops on the street network, taking into account the existing and designed traffic conditions.*
Key words: *public transport, traffic capacity, public transport stops, traffic delays.*

1. INTRODUCTION

The very name "urban public transport" indicates the main operational differences in this type of transport. In particular, the transportation of passengers is localized within the city (settlement). Public transport is characterized by a significant, in comparison with individual transport, vehicle capacity, and large carrying capacity and is oriented to serve the entire population of the city. This type of transport performs the bulk of all passenger traffic in the city.

The urban passenger transportation organization, the public transport planning, the national and local public transport development support programs are based on the various general information (population, size of the city, etc.) and special transport information. To obtain the latter, transport companies organize an accounting system for the relevant indicators. Concerning the objectives, accounting is divided into operational, accounting, and statistical. The reporting documentation is formed on the results of accounting, which contains the established data which can be used to manage the process of operation of this enterprise, as well as to implement various national and city policies. [1].

As for the road network (RN) of the city, this is one of its most stable elements and therefore it should be designed for a sufficiently long period of use without significant changes. Insufficient urban traffic planning in the street network causes serious consequences such as a decrease in the traffic speed and safety, additional time losses by the population on travel, increased transport costs, etc. [2].

A close connection between the coherent street network planning and the rational urban traffic organization is demonstrated in many large cities of the world. The main tasks of the city RN rational construction are reduced to the selection of the most suitable network characteristics for the given conditions, concerning its configurations, structure, and density, and its most important elements. The established characteristics of the network and its parameters should ensure maximum safety and speed of the various modes of transport [2, 3].

The main disadvantage of the existing RN in the old cities is the discrepancy between their technical characteristics (structure, density, and capacity of the most loaded elements) with contemporary and forecasted needs of the urban traffic. Therefore, it is needed to pay attention to the following:

- development of the indicators of the optimal structure and density of the street network to the conditions of its use;
- analysis of the relationship between the planning of the street network and the organization of transportation (primarily passenger) by various modes of transport;
- methods for determining the optimal traffic lane width of the main streets;
- methods for calculating the capacity of street network elements.

It should be noted that a proper traffic management process and appropriate engineering solutions for RN planning will ensure the necessary level of road safety and reduce the level of traffic on the streets and roads of the settlement.

2. RESEARCH STATEMENT

This paper aims to identify the regularities of changes in the RN capacity depending on the way the public transport stops are located. Accordingly, to achieve the above objective, it is necessary to solve the following tasks:

- to select the same-type sections of the RN on which the necessary indicators will be recorded;
- to establish the primary indicators of the traffic flows and characteristics of the RN using the field research;
- to process and analyze the obtained values of the field studies and generate the necessary input data for the modelling and calculations implementation;
- create the necessary transport models with the different designed traffic conditions in
- the RN;
- analyze the obtained modelling data and establish a change in the RN traffic capacity depending on the method of public transport stops location.

It should be noted that the paper considered two different conditions for the placement of the stop, in particular:

- the stops with and without the bays;
- the stops located before and after the intersections.

3. ROAD NETWORK TRAFFIC CAPACITY AND ITS PECULIARITIES

From the planning point of view, the indicators characterizing the RN of the city include [1, 4, 5]:

- density;
- coefficient of nonlinearity;
- average remoteness of the city districts;
- coefficient of traffic capacity use;
- volume-capacity ratio;
- the degree of complexity of the main streets intersections.

Quite an important indicator in the urban transport system functioning is the density of the arterial street network. This is the main indicator that characterizes the development of the arterial urban RN, determined by the ratio of the total length of the arterial streets to the city built-up area. Also, the RN analysis is carried out based on the nonlinearity degree of the connections. It characterizes the convenience of the city network communication and is determined by the ratio of the distance between the areas of departure and areas of arrival by the street roads to the distance between them by direct distance. The urban roads network can be considered as favourable if the non-linear degree is less than 1.15, the average – within 1.15–1.25, and unfavourable – more than 1.25. An increase in the coefficient of correspondence non-linearity can lead to significant overruns and, respectively, to an increase in transport and operating costs and in the time spent by the population in travel [2, 5].

No less important indicator reflecting the quality of the RN functioning is the capacity and volume-capacity ratio. The network capacity is determined by the capacity of the main directions at their entrances and exits. Each of the directions is a separate element of the network. Their assessment should be carried out for each area separately. For the successful operation of one RN element, it is necessary to exclude sections where capacity is lower than at the entrances and exits. Otherwise, the direction will not operate effectively, and systematic congestions will be observed in the "bottlenecks".

An indicator of the quality of these elements operation is the waste of time by any type of transport. The total time losses can be quite large. The less the loss is observed in one section at different times of the day, the better the traffic organization, and the higher the degree of reliability of the RN. However, to determine the criteria for assessing the performance of a particular section of the network, extensive research is required, associated with significant material and technical costs.

The travel duration is a widely used criterion today. To assess RN efficiency, it is recommended to apply simulation methods using computer technology. In this case, the total travel time of the flow can be divided into separate intervals, during which the vehicles move from element to element, from zone to zone, from intersection to intersection. The capacity of the urban RN is one of the main indicators that allows assessing the transport and operational qualities of the network itself [6, 7].

There is a well-known definition of the road capacity as the maximum number of cars that can pass it (through its cross-section) per unit of time. However, since the traffic flow moves in lanes in several rows, the most universal indicator is the capacity of the lane, which can be calculated using the following formulas [8, 9]:

$$P_c = \frac{3600}{\Delta t_{\min}}, \tag{1}$$

$$P_c = \frac{3600 \cdot V}{l_i}, \tag{2}$$

where P_c – a lane traffic capacity, vehicle/h; $\Delta t_{\min}$ – the minimal interval between the vehicles, s; V – vehicle velocity, km/h; l_i – the linear interval between the vehicles, m.

The capacity varies depending on the traffic area. Its values can be obtained in different ways at each site separately. So, for example, at intersections, it will decrease due to delays. Such coefficient takes into account this reduction [9]:

$$\delta = \frac{T_1}{T_2}, \tag{3}$$

where T_1 and T_2 – the duration of the vehicle's passage through the intersection following the design speed without delays and taking into account stops and speed reduction at the end of the intersection, s.

The value of the coefficient δ is influenced by the distance between intersections. The research conducted by the transport scientists has shown that the spacing between the stops from 200 to 800 meters results in an 80 % increase in capacity.

Taking into account the aforesaid, the capacity of the street roadway with traffic light control is determined by the formula [9]:

$$P_{np} = P_{\max} \cdot K_c \cdot n \cdot \delta, \tag{4}$$

where $P_{\max}$ – capacity in ideal road conditions; K_c – multilane coefficient; n – the number of lanes of the carriageway.

In this case, the probability of a delay at a traffic light is [8, 9]:

$$P(\Delta) = \frac{t_r}{T_c} = \frac{t_r}{t_g + 2 \cdot t_y + t_r}, \tag{5}$$

where T_c – the duration of the traffic light cycle, s; t_g, t_y, t_r – the duration of the green, yellow, and red traffic lights respectively, s.

At a controlled intersection, traffic on the main road has a priority. Each intensity on the main road corresponds to a certain number of cars in the secondary direction, which can flow into the main stream. In this regard, the capacity of an intersection means the possibility of the ratio of intensity on streets or roads that intersect. The interval in the main flow is sufficient for the vehicle maneuver in the secondary direction if $\Delta t_m \geq t_{lim}$ (Δt_m – the time interval between cars in the main direction; t_{lim} – the time interval between cars of the main direction, sufficient for the passage of one car from the secondary direction). Often, the calculation of the capacity of the uncontrolled intersection is carried out according to the following formula [9]:

$$P = N_m \frac{e^{-N/3600\Delta t_m}}{1 - e^{-N/3600\delta_t}}, \tag{6}$$

where N_m – traffic intensity in the main direction, vehicle /h; δ_t – the time interval between cars in the secondary direction.

As a result, the traffic capacity of the street is determined by the intersection capacity. And in case the study will prove the necessity to increase the number of the lanes, then the road could be divided into 2 lanes: the main one and secondary (for the public transport and urban traffic). The peculiarity of the public transport movement needs special consideration of the scales of possibilities and a targeted volume-capacity ratio of the road lanes, which are used for buses or trolleybuses pass. The capacity of the public transport lane is limited both by the roads and streets junctions and the public transport stops.

4. THE PUBLIC TRANSPORT STOPS AND REGULATION ASPECTS FOR THEIR DESIGN

The public transport stop is the engineering constructions designed for boarding and alighting of the passengers. The public transport stops are classified according to [10, 11]:

- a kind of public transport which uses the stop (bus, tram, trolley-bus, combined);
- the type of the route vehicles (for general, two-link, twin and three-wagon vehicles);
- the number of public transport vehicles that can conduct the boarding and alighting of the passengers at the stop (single, double);
- the nature of the stop use (permanent, at which the route vehicles stop every time during the operation on the route; temporary, at which the route vehicles stop only at predetermined time periods, “on request”, at which the route vehicles stop only when there are passengers at the stop, and when passengers in a vehicle want to get off at this stop, notifying the driver in advance with the appropriate signal);
- the location of the stop on the route (endpoints and intermediate).

The stopping place of a bus or trolleybus can be normal with a constant width of the roadway or with the arrangement of an open “bay” by expanding the roadway. According to the domestic regulations, the bus stop bays should be arranged at least 2.5 m wide using technical and dividing lanes between the roadway and the sidewalk, as well as lanes of greenery. In limited conditions, the arrangement of the bus stop bays can be carried out at the expense of the sidewalk, if its width, which remains after the widening of the roadway, ensures the proper functioning of the boarding and alighting area and appropriate conditions for pedestrians. [12].

As a rule, stops are placed near the junctions of the city streets and roads, as well as in the centre of the large span, if there are objects of mass attendance nearby. In each case, when placing stops, one should take into account the planning of intersections of the city streets and roads, the width of the roadway and sidewalks, the conditions of the traffic and pedestrian flows, and so on.

Bus and trolleybus stops should be located, as a rule, after the intersection, and tram stops – before the intersection. Placing bus and trolleybus stops before the intersection of streets and roads is allowed in exceptional cases when [12]:

- there is a large public object or an entrance to an underground pedestrian before the intersection;
- the traffic capacity reserve of the street (road) roadway before the intersection is larger than behind it;

- the time spent by passengers on a transfer in the main transfer directions of the intersection is significantly reduced;
- there is an approach to an artificial structure (bridge, flyover, tunnel, overpass) directly or a railway crossing begins after the intersection.

The placement of tram stops after the intersections of city streets and roads is allowed in exceptional cases when [12]:

- there is a large public object or an entrance to an underground pedestrian crossing after the intersection;
- the traffic capacity reserve of the street (road) carriageway before the intersection is larger than after it.

Implementation of additional stopping points in central districts and at junctions with large passenger flow can also be beneficial to increase the line capacity since it is often limited by the long stops of the vehicles with passengers' concentration.

The placement of public transport stops near intersections must meet the following requirements [10, 11, 13]:

1. Passengers transferring conditions at the junction should be as easy as possible, respectively, the stopping points of public transport lines that intersect should be located closer together to reduce the walking distance for passengers and save the time spent by them on the transfer;
2. Safety and comfort of waiting, boarding and alighting of public transport passengers should be ensured, if possible, without interfering with the movement of pedestrians on the sidewalk and vehicles on the roadway.
3. With a high traffic intensity on public transport lanes, it is necessary to ensure the possibility of more efficient use of the intersection capacity. For this, stopping points could be removed from the intersection borders by the length of the tramcar or vehicle with a small margin for the possibility to put a tram or bus (trolleybus) already prepared for the pass right in front of the intersection.

While planning intersections and squares, it is necessary to take into account the specified basic requirements for the rational organization of public transport. Also, it is necessary to take into account the interests and needs of road traffic in the area of the same junctions. Fig. 1 shows typical schemes for the rational planning of intersections and the public transport stops layout in their zone [10, 11].

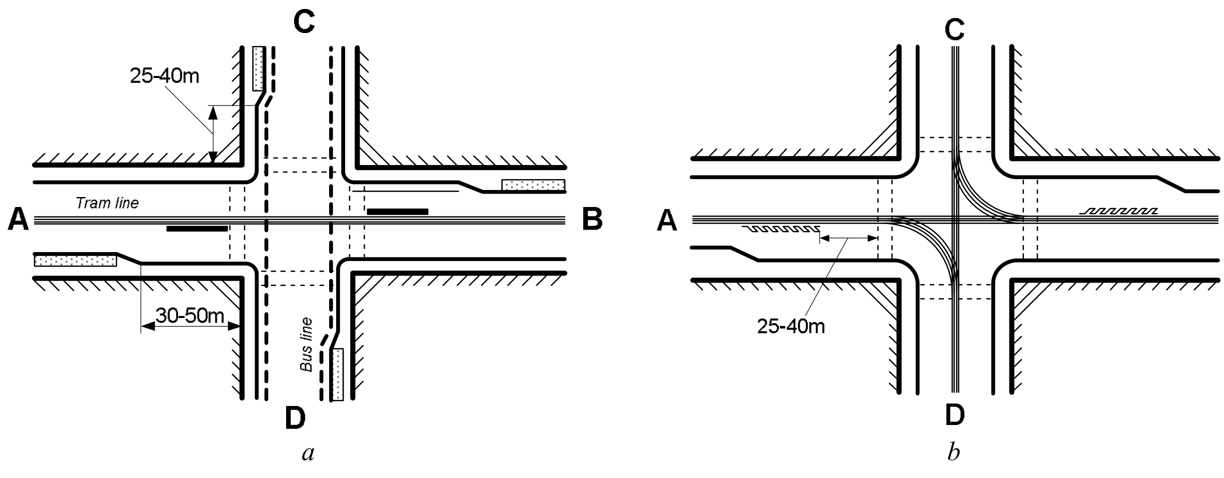

Fig. 1. The layout of the tram and bus stops: a – immediately before the intersection; b –when moved away from the intersection.

Diagram *a* shows the regular layout of the tram stops on the main street A-B at the intersection with a traffic frequency which is not exceeding 40 trains per hour and bus (or trolleybus) stops on C-D street, which has a smaller carriageway width and less extensive passengers and transport flows. To avoid narrowing the roadway along the street A-B in the areas where the tram stops are located or narrowing of the cars and trucks movement along the street C-D in the area where the bus stops are located, the necessary expansion of the roadways (by 2.5–3 m) is arranged on the approaches using the vegetation lanes while maintaining the same width of the sidewalk on the approach to the intersection and the span.

Within a large area, it is advisable to arrange stopping points for public transport both at the approaches to it and at the exits, which significantly reduces the size of pedestrian flows, areas that intersect, and contributes to increasing the safety and convenience of pedestrian traffic and all types of transport.

Usually, the location of stopping points should correspond to certain methods and tasks of traffic organization at a given transport junction. Fig. 2 gives the various ways of location public transport stops, which facilitate the unloading of some transport approaches or ensure the convenience for transferring passengers in the most active transfer directions [10, 11].

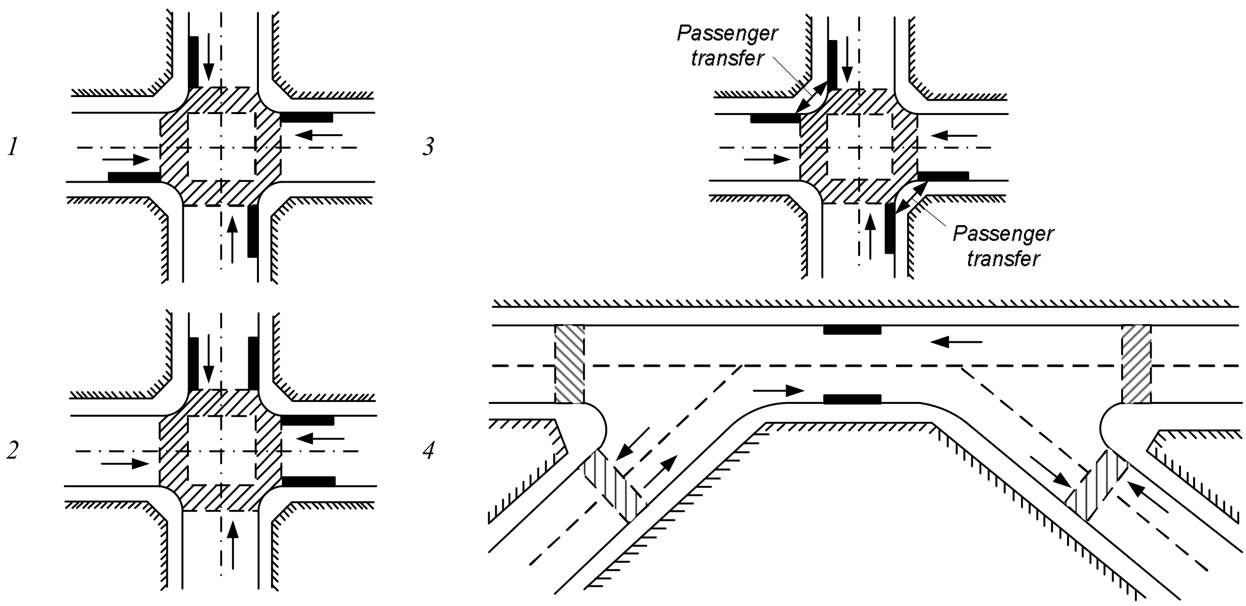

Fig. 2. Possible ways of locating the stops in the transfer junctions:
1 – in front of the intersection; 2 – in one corner, to unload approaches;
3 – for the convenience of transferring passengers; 4 – to combine different routes at one stop.

It should be noted that the method of locating public transport stops significantly affects the duration of passenger travel.

5. CONDUCTED RESEARCH AND ANALYSIS OF THE OBTAINED RESULTS

Transport research is a set of activities that collect information about the road or other modes of transport. Its purpose is to obtain initial data for planning, design, and modernization of roads and constructions, as well as for the project of improvement operating modes on existing transport networks, taking into account safety, continuity, convenience, economy, and its impact on the environment, etc.

The results of such studies can often be used for the following [5, 7, 8]:

- assessment of transport system current state;
- identification of needs in passenger and freight transportation and the dynamics of their changes;
- development of perspective measures for the transport system improvement following the increasing population needs;
- technical and economic studies for the gradual development of the urban transport system elements or other facilities design considering real investments;
- proposals to improve goods and passenger transportation and urban traffic management.

Field research is in the recording of the specific conditions and indicators of traffic for a given period. This method is currently the most common and has a great variety.

When studying and designing the traffic organization, the traffic flow is described by mathematical models. The primary tasks that facilitated the development of traffic flow modelling are the study and justification of the arterials and traffic capacity of their intersections. The traffic flow behaviour is probabilistic and depends on various factors and their combinations. Together with technical factors (vehicles, road), human behaviour (drivers, pedestrians) has a significant impact as well as the environment. Transport networks and systems modelling can be carried out using both mathematical formulas and appropriate software (PTV VISSIM, PTV VISUM, TransCAD, etc.) [14, 15, 16]. Simulation of road traffic in cities allows analysing existing traffic flows, simulating predicted traffic flows, analysing and planning public transport infrastructure, analysing and predicting traffic congestion, choosing the optimal traffic control scheme at intersections, optimizing the operation of signalling devices, etc.

The PTV VISSIM software is designed for simulation of the individual vehicle travel and traffic flows in the settlements and beyond. Also, pedestrian traffic can be simulated in it. This program includes seven general functions [14]:

1. Building a road network;
2. Modeling the traffic flows taking into account various parameters;
3. Simulation of traffic conditions;
4. Modeling public transport traffic;
5. Traffic simulation (the model of each vehicle movement is based on the Wiedemann car-following model);
6. Displaying the parameters of the created model on the screen;
7. Ability to edit parameters in real-time.

To study the impact of public transport stops location on the urban road network capacity, the PTV VISSIM software environment was chosen. The input data was obtained at streets and road network using the field research methods. The following values of the traffic flow parameters were investigated: traffic intensity, velocity, composition.

Based on the data obtained in the PTV VISSIM software, the traffic flows moving in a given section are modeled. The simulation was carried out at various distances between public transport stops (300–500 m, with 10 m by foot). To determine the time intervals between cars, automatic measurement points were set, and the average value of the obtained data is given in the Table. 1.

Table 1

Time intervals between cars

Equipped public transport stops				Non-equipped public transport stops			
Distance between stops	Time Intervals	Distance between stops	Time Intervals	Distance between stops	Time Intervals	Distance between stops	Time Intervals
300	2.97	410	4.01	300	3.55	410	4,51
310	2.99	420	4.09	310	3.63	420	4,59
320	3.01	430	4.11	320	3.68	430	4,67
330	3.04	440	4.14	330	3.72	440	4,70
340	3.19	450	4.15	340	3.77	450	4,73
350	3.37	460	4.35	350	3.80	460	4,81
360	3.59	470	4.43	360	3.99	470	5,11
370	3.72	480	4.55	370	4.10	480	5,16
380	3.76	490	4.69	380	4.20	490	5,36
390	3.92	500	4.96	390	4.28	500	5,38
400	3.99	–		400	4.49	–	

Based on the simulation results, the capacity of the simulated section of the street is determined. The calculations were performed in the Microsoft Excel software according to the formula (1). The results are given in the Table. 2.

Table 2

The capacity of the simulated street section

Equipped public transport stops				Non-equipped public transport stops			
Distance between stops	Time Intervals	Distance between stops	Time Intervals	Distance between stops	Time Intervals	Distance between stops	Time Intervals
300	725	410	917	300	669	410	841
310	768	420	958	310	672	420	858
320	792	430	965	320	698	430	877
330	812	440	1002	330	705	440	902
340	827	450	1067	340	748	450	948
350	867	460	1128	350	761	460	955
360	869	470	1189	360	766	470	967
370	875	480	1199	370	771	480	978
380	881	490	1207	380	784	490	992
390	897	500	1213	390	799	500	1013
400	902	–		400	802	–	

Based on the data in Table 2 a graph of the traffic capacity dependence on the distance between public transports stops is constructed (Fig. 3).

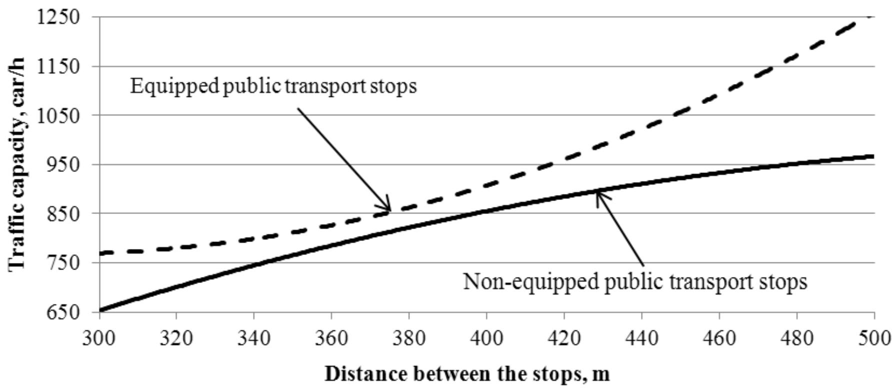

Fig. 3. Traffic capacity dependence on the distance between public transport stops

The second stage of the research is to establish the impact of the public transport stops layout on the capacity of the uncontrolled intersections. Data on the limitary intervals between vehicles passing the intersection are taken from the simulated network (Table 3).

Table 3

Intervals between cars on the main and secondary directions of the simulated uncontrolled intersection

Public transport stop before the intersection		Public transport stop after the intersection	
Simulated intensity, un/h	Limitary interval on the main road, s	Simulated intensity, un/h	Limitary interval on the main road, s
600	6	600	2,99
575	6,2	575	3,09
550	6,5	550	3,29
525	6,9	525	3,49
500	7,2	500	3,73
475	7,6	475	3,99
450	8,1	450	4,38
425	8,4	425	4,66
400	9,1	400	4,78
375	9,6	375	4,98

The calculation of the uncontrolled intersection capacity was performed according to the formula (6), and the calculation results are given in Fig. 4.

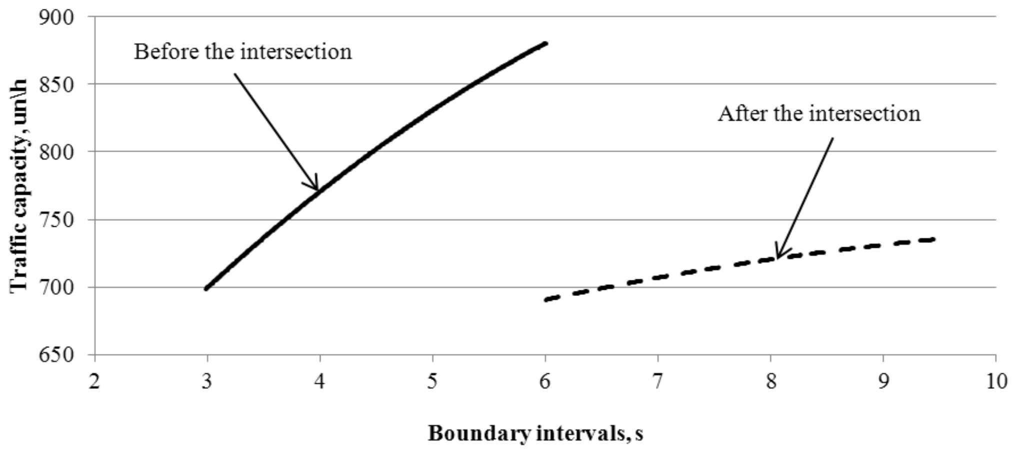

Fig. 4. Dependence of the uncontrolled intersection capacity depending on the public transport stop layout

The graph, shown in Fig. 4, is built using polynomial approximation. The mathematical relationship is shown below:

– after the intersection:

$$P = -1{,}4012\Delta t_{гр}^2 + 34{,}599\Delta t_{гр} + 533{,}3\,, \tag{7}$$

– before the intersection:

$$P = -5{,}4264\Delta t_{гр}^2 + 109{,}18\Delta t_{гр} + 420{,}86. \tag{8}$$

According to the graphical dependence shown in Fig. 3, it can be stated that with an increase in the distance between public transport stops, the traffic capacity of the section also increases. This is because, at a greater distance between stops, the vehicles with high dynamic characteristics can manoeuvre overtaking slow-moving vehicles. By this, the traffic density decreases, and the intervals between cars in the traffic increase. With an increase in the intervals in the flow, the traffic safety also improves, which is one of the main tasks for traffic organization.

Fig. 4 shows that with the increase of the limitary interval on the main road, the uncontrolled intersections capacity increases. This is because public transport, when boarding and alighting passengers at the stop, blocks the direct flow but allows manoeuvring turns, and therefore reduces the interval between cars.

In general, within the public transport stop, the flow is condensed and traffic safety declines. This is due to a decrease in velocity, intervals, and traffic safety in the traffic flow, and therefore capacity. Thus, it is recommended to arrange public transport lanes in overcrowded areas of the city.

6. CONCLUSIONS AND RESEARCH PERSPECTIVES

1. The traffic capacity is one of the key indicators that reflects the level of the RN functioning. Consequently, it was the RN that was selected in the paper to determine the influence of the public transport stops placing method. At the same time, two options for the layout of the stop were considered, in particular: with the bus stop bays and without, and the stops before and after intersections.
2. Similar sections were selected at the RN of the city, where the necessary indicators were taken into account by the field research method. They are input data for creating a traffic model in the PTV VISSIM software. It should be noted that the created transport models varied in different designed traffic conditions.
3. Based on the PTV VISSIM simulation of the traffic flows, the dynamics of changes in the traffic capacity were established depending on the distance between public transport stops and depending on the location of a public transport stop close to the uncontrolled intersection.

4. It has been established that the roads with the stops with the bus stop bays have higher traffic capacity than those without bays. It should be noted that with a distance between stops of up to 400 m, the value of the difference in capacity ranged from 7 to 14 %, however, with an increase in distance, this discrepancy grew rapidly.
5. During the analysis of the results of the second stage of the study, it was found that the arrangement of a stop after an uncontrolled intersection often leads to a decrease in traffic capacity. At the same time, public transport stops were created without bays during the simulation.

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