This study examines the issue of traffic organization on sections of city streets, in which there are public transport stop zones of different configurations (with a drive-in pocket and along a traffic lane). Accordingly, the object of research is the parameters of traffic flows; the subject is the regularities in their change on such specific sections of the street-road network, taking into account the configuration of stops, the number of traffic lanes, and priority conditions for the movement of public transport.

The task addressed in this work was the quantitative assessment of the efficiency of traffic management in public transport stop zones. It was also important to compare different configurations of street segments in terms of their impact on delays of private and public transport.

As a result of the research, the speed and time characteristics of the traffic flow and their dependence on its composition and intensity for different number and specialization of traffic lanes, as well as the location of the public transport stop, were determined.

The resulting quantitative indicators of delays of all types of transport for each modeling option made it possible to determine the best of them according to the criterion of minimal time loss. This applies to both private and public transport, as the values of delays may differ from each other by 10–50 %.

An applied aspect related to using the scientific result is the possibility of justifying the number of traffic lanes, or their allocation for public transport, as well as determining the appropriate configuration of stops. This constitutes the prerequisites for the transfer of the scientific results to the relevant interested structures in the field of transport, which are responsible for the organization and safety of traffic under urban conditions

Keywords: public transport stops, simulation modeling, transport delay, composition of traffic flow

UDC 656.13

DOI: 10.15587/1729-4061.2024.313636

IDENTIFYING PATTERNS OF CHANGE IN TRAFFIC FLOWS' PARAMETERS DEPENDING ON THE ORGANIZATION OF PUBLIC TRANSPORT MOVEMENT

Taras Postranskyy
PhD*

Maksym Afonin
Corresponding author
PhD*
E-mail: maksym.o.afonin@lpnu.ua

Mykola Boikiv
PhD*

Romana Bura
PhD*

*Department of Transport Technologies
Lviv Polytechnic National University
S. Bandery str., 12, Lviv, Ukraine, 79013

Received date 09.09.2024
Accepted date 14.10.2024
Published date 30.10.2024

How to Cite: *Postranskyy, T., Afonin, M., Boikiv, M., Bura, R. (2024). Identifying patterns of change in traffic flows' parameters depending on the organization of public transport movement. Eastern-European Journal of Enterprise Technologies, 5 (3 (131)), 72–81. https://doi.org/10.15587/1729-4061.2024.313636*

1. Introduction

The concept of transport systems sustainability was introduced into scientific and professional circles relatively recently, but its meaning is revealed by a number of new techniques and practices that radically change the paradigm of movement of residents of cities and agglomerations. Sustainable urban mobility is based on the principles of abandoning trips by private vehicles, more use of micromobility, and increasing the share of public transport (PT) in the overall distribution of urban correspondence [1, 2].

Taking into account the fact that the automobile-centric society is formed as a result of improved purchasing power and the need for quick and universal movements in the city, activities aimed at strengthening the sustainability of city transport systems are perceived negatively.

An additional challenge to achieving the goals of sustainable urban mobility plans is also a combination of public disapproval of such methods and the often flawed and unfounded actions of local authorities. This is illustrated by the implementation of unpopular measures on street sections where the road infrastructure does not have enough capacity to accommodate traffic flows. An example of this is the introduction of traffic lanes or the elimination of stops for the sole purpose of complying with the principles of sustainable mobility, neglecting the analysis of the road situation in the design areas. Under such conditions, the total loss of time of drivers and passengers of private transport significantly exceeds the time saved due to the traffic of HT in separate lanes for its passengers.

Methods for conditionally improving the level of traffic organization at the expense of significant infrastructural solutions, which primarily include increasing the number of traffic lanes, are also unpopular at this time. The reason for this is the high cost of construction and expansion of the roadway under urban conditions, even from the point of view of the complexity of laying engineering communications, which must already meet modern standards of strength and durability [3, 4].

All this leads to the fact that the decision regarding the selection of the parameters for street infrastructure elements for PT should be clearly justified and based on research and modeling data. It is also worth evaluating the usefulness of such measures, taking into account both the time spent by passengers of the public transport system and the time losses incurred by other traffic participants during the passage of such sections. An additional issue that requires further study is the economic feasibility of certain measures since the cost of capital construction works is constantly increasing with the development of the latest technologies in this area. Therefore, the study and comparison of different configurations of city streets in PT stop zones is a relevant task that has significant applied value in the field of street environment design.

2. Literature review and problem statement

The implementation of measures to improve the priority in the PT movement is a rather debatable issue both among practicing engineers and scientists since the criteria by which such decisions are implemented are poorly described in many norms and standards. The search for the optimal solution for prioritizing traffic on the city street network is described in [5]. It analyzed changes in traffic flow indicators on a conditional section of the street with two lanes of traffic in one direction. However, the authors considered the diversion of one of these lanes for route vehicles. The research was carried out by means of micro-modelling, and its results indicate that when a separate traffic lane is allocated to PT, the delay of buses is reduced by 40–60 %, depending on traffic intensity. However, certain problems remain unsolved as such measures significantly worsen the conditions of individual transport, as time losses for this type of movement increase more than twice on a 200 m long street section. Such results indicate the need to clarify the ratio between time losses for private cars and its savings for PT.

Work [6], which focuses on determining the safety criteria for bus stops, highlights the type of their location as a factor of indirect influence from among more than thirty others. According to this method of auditing the safety of bus stops, those located along the dedicated highway lanes better meet the general safety criteria. However, it is extremely difficult to differentiate the weight purely of the stop configuration criterion. The authors of work [7] considered the issue of changing speed regimes in the zones of PT stops. According to their data, depending on the type of stop location (in a pocket or on a lane), the speed of the main traffic flow varies in different ways. Moreover, if the stop is located on the traffic lane, the average speed of the car decreases by 20–25 %, and if the stop is located in the entry pocket – only by 5–10 %. It is also worth noting that an additional factor that affects the speed of private cars is the presence of buses at the stop since this situation leads to a decrease in speed in both cases. However, the loss of time of traffic participants in the zone of influence of PT stops is not considered in the work.

The influence of the type of stops on the traffic flow using simulation modeling tools was studied in [8]. The authors of the work developed a micromodel of a street section with and without a drive-in pocket. The results from determining the speed regime on the site did not differ, in contrast to work [7]. However, analysis of the total time delays of private transport showed their reduction by almost three times when arranging a drive-in pocket. It is worth noting that the model assumed one traffic lane in each direction, and the total intensity of the traffic flow was less than 400 cars/hour. In view of this, there is a fundamental impossibility of extrapolating such results for urban highways.

Work [9], which reports a study on the risks of emergencies in PT stop zones, investigated a multi-lane carriageway. The authors identified the most dangerous zones and maneuvers on the section of the carriageway, which is equipped with a bus stop with a drive-in pocket. The results indicated that the greatest risks of accidents occur not in the lane closest to the pocket but in the adjacent one. It was also determined that the maneuver of buses exiting the entry pocket is much riskier than entering it. The authors of study [10] also conducted a safety assessment of bus stop zones using artificial intelligence systems, which is an effective method for minimizing the risks of traffic accidents. However, the methods of applying artificial intelligence and modern telematics are quite complex and expensive to implement.

There are also studies that consider the placement of stops of different configurations near intersections. For example, in work [11], an analysis of the advantages and disadvantages of placing PT stops before and after the intersection was carried out, the list of which is quite comprehensive. After conducting research, the authors are inclined to the conclusion that bus stops, which are located directly on the traffic lane, significantly affect the level of passenger service. But from the point of view of other road users, this option is effective only on a multi-lane carriageway in front of intersections. This is the approach used in work [12], in which the use of drive-in pockets for PT stops in the intersection area is substantiated. The simulation results indicated an increase in the carrying capacity of city street intersections, but the issues related to traffic modes of the sections between them remained unresolved.

In study [13], an analysis of the effectiveness of grouping buses of different routes at railway station stops was carried out. The results showed that this method increases the level of delays of private transport, in contrast to the individual arrival of buses at stops. It should be noted that the work considered the modeling of traffic at regulated intersections without reference to the type of stops and the share of PT in the total traffic flow.

A systematic approach to conflict management in PT stop zones was proposed by the authors of work [14]. Researchers have proposed a strategy to avoid accidents between buses and private cars, which involves exchanging signals between vehicles and combining them together with telematics devices into a single system. Such solutions are ahead of their time and could be applied only in the case of sufficiently widespread distribution of autonomous vehicles in order to minimize the effect of the human factor.

In general, our review of the literature reveals that the question of the ratio of benefits for public transport and negative consequences for private transport in the sections of multi-lane streets and zones of stop points is open. First of all, this applies to studies that are aimed at substantiating the usefulness of the introduction of traffic lanes and do not focus on the time losses of other traffic participants when implementing such measures.

Summarizing the above body of research, worth highlighting are those studies that consider the positioning of PT stops only from the point of view of their potential danger with less attention to the delays of all types of transport and the throughput capacity of the street section as a whole [9, 14]. There are also studies that highlight the change in the speed regime in the area of traffic stops [7, 8] but such results are more helpful for assessing the overall picture of the road situation. In separate papers [11, 12], a comparison of the effectiveness of the use of different configurations of PT stops is performed, but in the intersection zones, and not on the spans of city streets. According to available publications in this research area, there is a need to take into account not only safety aspects and speed regimes in the area of PT stops but also a detailed analysis of time delays of traffic participants for different configurations of stop points.

Therefore, on the basis of the reviewed scientific works, we can conclude that to tackle the issue of placement of PT stops, it is necessary to conduct studies that evaluate their various configurations. In this case, it is important to take into account the number of traffic lanes, the presence or absence of dedicated lanes for PT, the share of this type of transport in the general flow, as well as the general intensity of the traffic flow. Based of these studies, it would be possible to draw conclusions regarding the justification of a specific type of traffic stop (in a pocket or on a traffic lane), having effective data on time losses of all types of transport. Taking into account the possibilities of simulation modeling, the issue of comparing different variations of traffic organization on such specific sections of the street-road network is a good opportunity to solve the dilemma of a fair and justified priority in the traffic of PT.

3. The aim and objectives of the study

The aim of our study is to identify patterns of changes in traffic flow indicators in the zones of PT stops under different configurations of traffic management schemes using simulation modeling. This will make it possible to substantiate the optimal parameters for sections of city streets where there is an intensive traffic flow.

To achieve the goal of the work, it is necessary to solve the following tasks:

– to conduct experimental studies on the main traffic flow indicators under actual conditions;

– to build a simulation model of the operation of the PT stop zone and carry out its calibration;

– to determine the average value of duration of the traffic delay and the speed of movement of vehicles for different options for the organization of traffic and the share of PT in the flow.

4. The study materials and methods

Parameters of traffic flows along sections of streets and roads between intersections were chosen as the object of our study. The subject of the study is the patterns of changes in traffic flow parameters on the above-mentioned sections of the street network, taking into account the organization of traffic and the configuration of PT stops.

Our structural-logical analysis of the research object made it possible to reveal close relationships between the indicators of traffic flows along the sections of the street and road network and the conditions of movement and their quantitative reflection. The research hypothesis assumed that the duration of the traffic delay directly depends on the share of slow-moving vehicles in the flow, in particular PT, and the traffic organization scheme. Its validity was checked using the law of sufficient grounds, in particular by analyzing empirical data obtained during experimental research (simulation modeling).

The basis of the VISSIM program is a model that simulates following a car in front with the possibility of changing the traffic lane. This software environment uses the WIEDEMANN model, which assumes that the driver does not maintain a constant speed (as in simpler models) but accelerates or decelerates depending on the distance to the car in front. Since the driver cannot accurately estimate the speed of the car in front, s/he gradually increases her/his speed until s/he catches up with the car in front of her/him. The speed will increase to the set maximum, which is set according to the maximum permissible value on the road section. This behavior makes it possible to more accurately simulate and reflect real traffic conditions [15].

This paper examines the influence of location of the PT stops, taking into account the planning features of the street, on traffic flow indicators. In particular, for the time of passage of the traffic stop zone, the average speed, and the maximum length of the queue of vehicles on the traffic lanes. Such a micro-level model will make it possible to investigate various scenarios of the interaction of traffic participants in the zone of PT stops.

Travel time and traffic delays are important indicators of PT operation in cities. The purpose of this study is to investigate the impact of PT stops under different planning features of streets on the main parameters of traffic flow. Accordingly, it is important to find optimal solutions to reduce travel time and minimize traffic delays in the area of PT stops. Such delays are a key factor in assessing the availability of PT and the overall quality of services of these systems in cities.

The construction and operation of transport models in PTV VISSIM involved taking into account the features of the structural modules of the program:

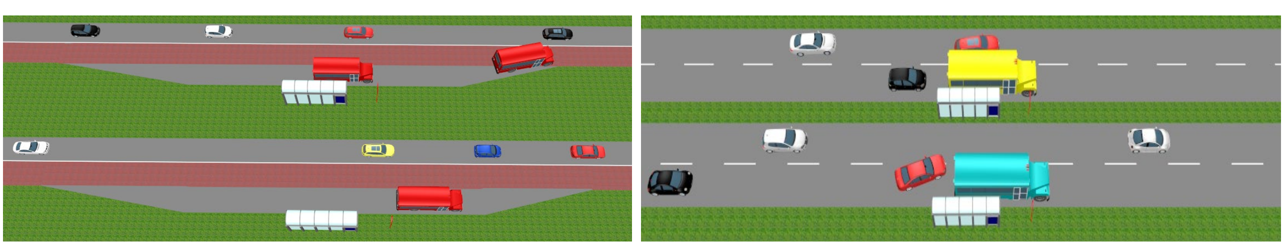
– planning features of the street (number of lanes, width of the traffic lane, presence or absence of a traffic lane);

– PT stops (in the presence and absence of a "drive-in pocket" on the carriageway);

– parameters of the traffic flow (traffic flow intensity, speed of movement and share of PT in the flow).

On the basis of such input data, counters measuring traffic delays on the approaches to highway stops and indicators of traffic flow in traffic lanes under different traffic conditions were installed on the road section (Fig. 1).

This method for simulating the influence of traffic lanes for PT is based on the processing of an already existing database and the construction of a forecast regarding the features of the model's behavior under various scenarios of placement of PT stops on the street-road network.



a *b*

Fig. 1. Simulation model of street sections in the area of public transport stops in the PTV VISSIM environment: *a* – under the conditions of a 2×2 traffic lane, a separate lane for public transport, and the presence of an "entry pocket" for public transport; *b* – under the conditions of 2×2 traffic lanes and the absence of an "entry pocket"

An important stage in the construction of a traffic flow model in PTV VISSIM is the introduction of input information about traffic flow parameters. Their quantitative value was obtained directly on the street and road network using the field research method. Traffic accounting was carried out using research forms, which recorded the number and type of rolling stock. Observations were carried out during periods of peak load, in particular: in the morning (8:00–9:00) and evening (18:00–19:00) peaks. Sections of streets between intersections in the city of Lviv (Ukraine) were chosen as objects on which observations were recorded. At the same time, typical street cross-sections had the following parameters:

– option I: 1×1 traffic lane with traffic stops both in "entry pockets" and directly on the carriageway (Fig. 2, *a*);

– option II: 2 lanes of traffic in one direction with PT stops both in "entry pockets" and directly on the carriageway (Fig. 2, *b*);

– variant III: 1×2 traffic lanes, one of which is intended for the traffic of PT (Fig. 2, *c*);

– option IV: 2×2 traffic lanes with traffic stops both in the "entry pockets" and directly on the carriageway (Fig. 2, *d*).

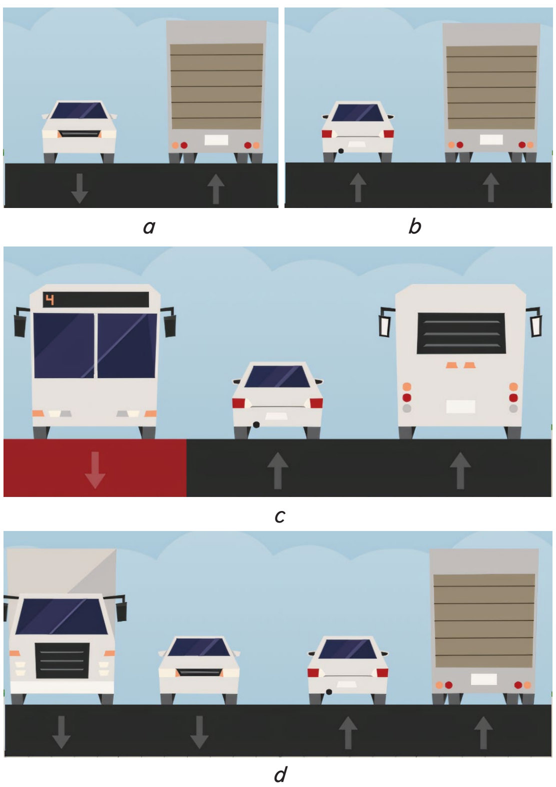


Fig. 2. Typical transverse profiles of streets on which traffic flow parameters were studied: *a* — 1×1 traffic lane; *b* — 2 traffic lanes in one direction; *c* — 1×2 traffic lanes with a lane for public transport; *d* — 2×2 traffic lanes

The width of the traffic lanes on the investigated sections of the street-road network ranged from 3.5 to 3.75 m, and the road surface was made of asphalt concrete. The roadway was in satisfactory condition, in particular, there were no potholes, overflows, etc., which could lead to a decrease in movement speeds. As for the traffic flows, they included the movement of passenger cars and trucks and heavy-duty vehicles, in particular trolleybuses and/or buses.

The processing of research results involved obtaining experimental points based on simulation data for three simulation scenarios followed by regression analysis. In the process of approximating the obtained dependences, the curves of the second power polynomial were selected as those that well visualize the dynamics of changes in the studied traffic indicators using a simple mathematical function.

Statistical analysis was performed using Google Sheets spreadsheets as they are a convenient means for both visualizing results and generating approximation curves based on experimental points.

The assessment of adequacy of the selected dependences was carried out by defining the coefficient of determination. The visualization of the data involved representing the dependences of average delay and speed of different types of vehicles on the share of PT in the flow in one plane for each simulation scenario. Thus, it is possible to compare the dynamics of changes in the investigated indicators for all types of vehicles in the stream.

5. Results of investigating traffic flow conditions using simulation modeling

5. 1. Results of field studies on the main indicators of traffic flow as input data for constructing a traffic model

In accordance with the above-mentioned methodology of field studies, data on traffic flow parameters were obtained in two peak periods of the day on streets with typical cross-sections. Based on this, the averaged values of the actual traffic intensity of vehicles were derived (Table 1).

Also, according to the results of on-site research and analysis of the composition of traffic flows, their distribution on each of the typical sections was established (Fig. 3).

Table 1

Mean values of vehicle traffic intensities on streets with typical cross-sections

Type of vehicles	Mean values of the actual intensity of traffic flows in one direction on typical sections, cars/hour			
	I	II	III	IV
Passenger cars	378	996	648	819
Trucks	39	34	53	49
Public transport	63	90	45	97
Sum	480	1120	746	965

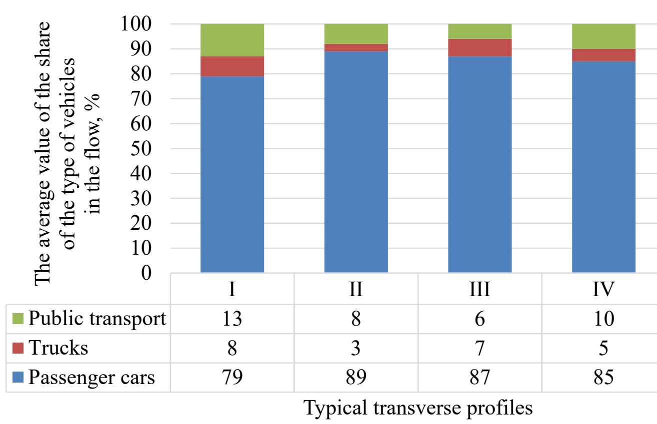


Fig. 3. Averaged values of the composition of traffic flow along the typical investigated sections of the street-road network

According to the results of our study, it was established that passenger cars predominate in the flows in each of the sections, and the share of PT on average ranges from 6 to 13 %. It was also established that the lowest values of the traffic intensity were observed on the road traffic lane of the typical cross-section I, and the highest on the lanes of the typical cross-sections II and IV.

5. 2. Construction of simulation models of traffic flows under different conditions of movement

The process of building models (simulating the movement of vehicles) in the PTV VISSIM environment involved the formation of street segments between intersections with the setting of their planning parameters. In particular, six scenarios were devised to simulate the movement of traffic flows in the above-mentioned areas. Each simulated segment has a straight section, and the width of the traffic lane is 3.5 m. In turn, the variable indicators during the simulation were:

– traffic intensity and composition of traffic flow;
– arrangement of PT stops;
– the presence and absence of lanes for traffic.

The first simulation scenario assumed the presence of a 1×1 traffic lane on the carriageway with the location of PT stops directly on one of them. At the same time, the modeling process was carried out both in the presence and in the absence of an additional lane for the traffic of PT (Fig. 4).

In this case, the model predicted that when the bus stops, the cars moving behind have the opportunity to enter the oncoming lane and make a detour maneuver. For this purpose, they need a sufficient interval between cars moving in the oncoming lane. If there is no such interval, the vehicles behind waited for the completion of boarding and disembarking of passengers.

The second simulation scenario (Fig. 5):

– the presence of two traffic lanes in one direction;
– availability of one lane for general traffic and one lane for traffic.

In both cases, the PT stops were located directly on the traffic lanes.

In the case shown in Fig. 5, *a* cars move without obstacles, reducing the speed of movement in front of slow-moving vehicles, if necessary, perform an overtaking maneuver. According to the scenario shown in Fig. 5, *b*, the general traffic flow moves in one lane, and the speed of movement depends on the "leader car".

The third simulation scenario implied (Fig. 6):

– the presence of two traffic lanes in one direction;
– availability of one lane for general traffic and one lane for PT traffic.

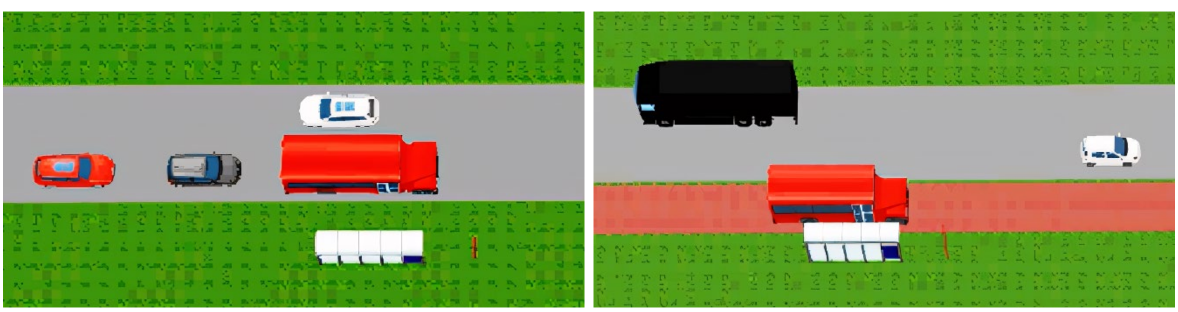
Each of these cases implied the arrangement of a PT stop in the form of a "drive-in pocket". At the same time, the geometric parameters of the "pocket" are as follows:

– the length of the driving wedge for braking – 20 m;
– the length of the driving wedge for acceleration – 15 m;
– the width of the "pocket" is 3.0 m.

The conflict zones are arranged in such a way that the cars have priority over the PT that leaves the pocket. This makes it possible to bring the simulation process closer to real conditions of movement. In addition, trucks and cars do not enter the drive-in pocket.

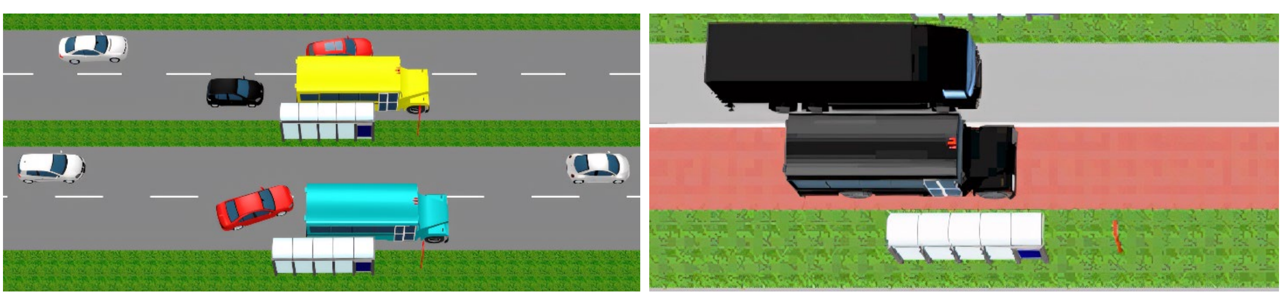
The next stage of our work was the implementation of the process of calibration of the constructed simulation micromodels (individual simulation scenarios) in the PTV VISSIM environment. It involved the process of adjusting the input parameters and elements of the transport models, in particular so that the conditions of movement correspond to those observed during field observations. Average values of distances between vehicles in queues, time intervals between cars, acceleration, and deceleration, etc., were used as indicators used to enable this process.

Based on the constructed simulation micromodels in the PTV VISSIM environment (the above simulation scenarios), experimental studies were conducted. They involved the identification of regularities in the impact of street planning parameters in the area of PT stops on indicators of traffic flows.



a *b*

Fig. 4. First simulation scenario: *a* – in the absence of a public transport lane; *b* – if there is a public transport lane



a *b*

Fig. 5. Second simulation scenario: *a* – in the absence of a public transport lane; *b* – if there is a public transport lane

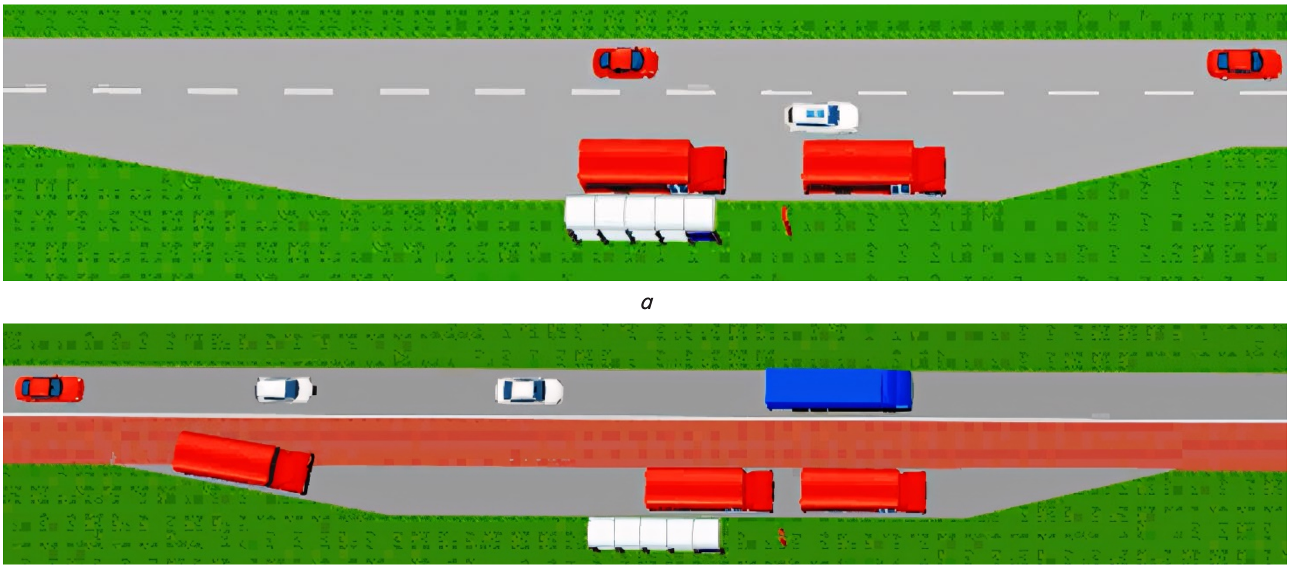


Fig. 6. Third simulation scenario: *a* – in the absence of a public transport lane; *b* – if there is a public transport lane

5. 3. Influence of the share of public transport and the traffic organization scheme on the duration of transport delay and the speed of movement

With the help of the PTV VISSIM software, traffic flow simulation was carried out under the six aforementioned scenarios. At the same time, the input parameters were changed, which included both the modification of the planning parameters and the change in the intensity of traffic and the composition of traffic flows. At the same time, the main variable was the share of PT, which varied from 1 to 16 %. It should be noted that the maximum in this case is due to the results obtained during one of the studies conducted directly on the street-road network. In turn, the share of freight transport in the flow was 5 % in all simulation scenarios. This value is due to the averaged data obtained from field studies. In accordance with this, the redistribution of the composition of the traffic flow was carried out due to the change in the proportion between PT and passenger cars. As for traffic intensities, their value ranged from 300 to 500 cars/hour along one traffic lane with a step of 100 units. Such values were chosen based on averaging the results of field observations.

The constructed models implied the installation of counters that measured the duration of the average delay of various types of vehicles and determined the average value of their speed. On the basis of the obtained above-mentioned values, a corresponding database was formed. After carrying out its statistical and mathematical analysis, the average value of the studied values for different values of movement intensities was established. On the basis of this, for the first version of the simulation, graphical dependences of the influence of traffic share and the planning characteristics of street on the traffic parameters of vehicles were plotted (Fig. 7, 8).

In our studies, one of the indicators that describes the quality of the built model is the coefficient of determination R^2, which indicates the value of the approximation reliability. During the study of the influence of the share of public transport in the flow on the parameters of the traffic flows under all simulation scenarios, the coefficient of determination ranged from 0.72 to 0.85. This indicates that there is a relationship between the share of PT on the street-road network and the average delay and speed of the traffic flow. Such results of statistical processing indicate the correspondence of the original data and the regression model, as well as to what extent the obtained observations are confirmed by the simulation model.

As can be seen from these simulation results, passenger cars experience the greatest effect on the conditions of movement while increasing the share of PT. In this case, the arrangement of an additional lane for the traffic of the PT makes it possible to reduce the average duration of delay of other types of transport in the flow and to practically not change the speed modes of the traffic.

For the second modeling option, graphical dependences of the influence of the traffic share and the planning characteristics of the street on the traffic parameters are shown in Fig. 9, 10.

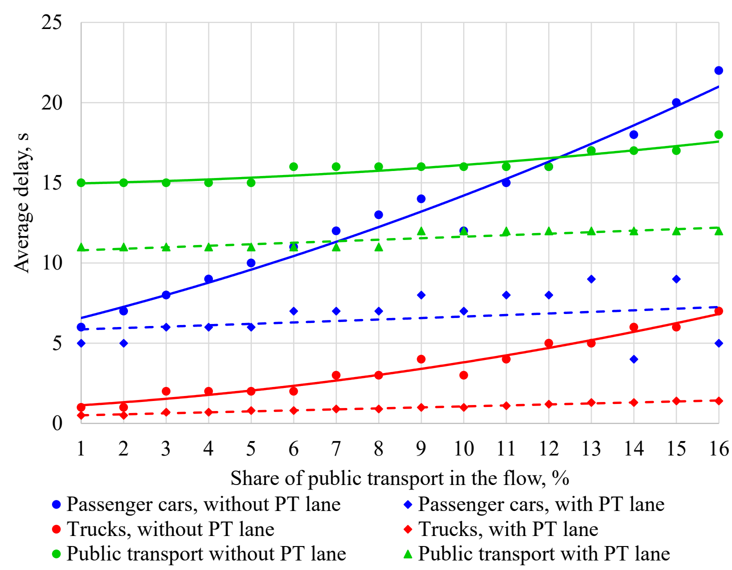


Fig. 7. Influence of the share of public transport in the flow on the average value of the duration of traffic delay in the first simulation scenario

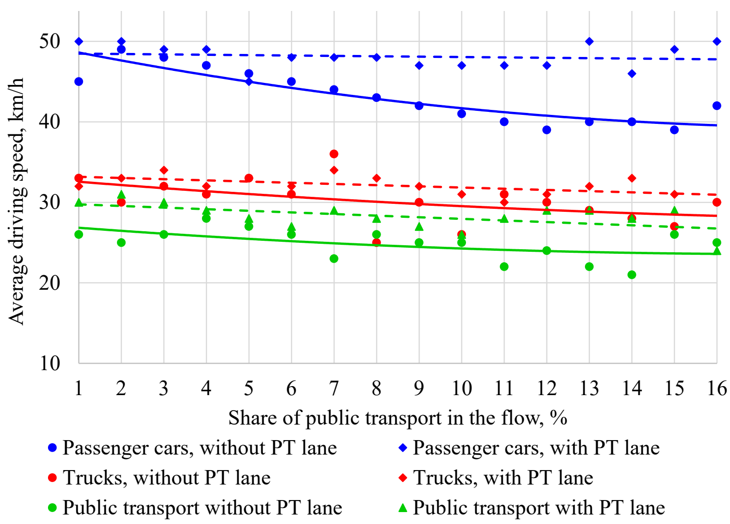


Fig. 8. Influence of the share of public transport in the flow on the average speed of vehicles in the first simulation scenario

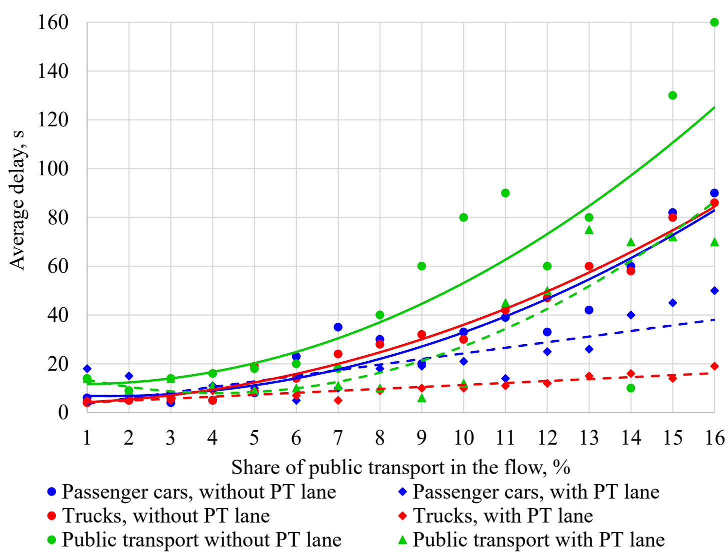


Fig. 9. Influence of the share of public transport in the flow on the average value of the duration of traffic delay in the second simulation scenario

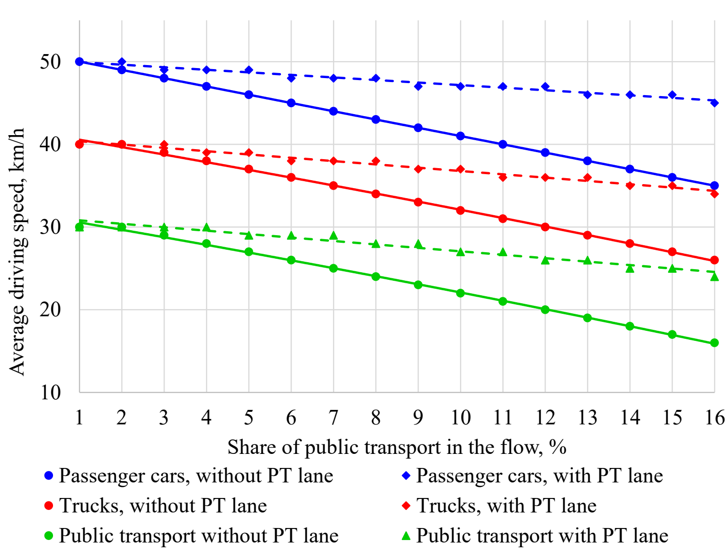


Fig. 10. Influence of the share of public transport in the flow on the average speed of vehicles in the second simulation scenario

Based on the results of the simulation according to the second option, it was found that with a small share of PT in the flow (up to 4 %), the arrangement of the dedicated lanes would lead to an increase in the average duration of the delay in the movement of cars and trucks. In turn, the adoption of such engineering decisions would not lead to the desired result, in particular, speeding up the movement of PT. Also, the increase in the traffic delay of passenger cars and trucks for the shares of PT over 4 % and the lack of dedicated lanes is explained by the increase in the frequency of obstacles to traffic in the form of stopping buses and trolleybuses on the carriageway. These stops are related to the boarding and disembarking of passengers. In addition, from the data shown in Fig. 10, it becomes obvious that the speed of the traffic flow is significantly affected by the presence of PT. Thus, the arrangement of the dedicated lanes would reduce the variation in the speed of movement of vehicles in the flow and they would be closer to the average value of the speed modes of the movement of trucks. As for both the speed of movement and the duration of PT delay during the arrangement of dedicated lanes, these values largely depend on the number of such rolling stock. In particular, with their significant increase, the transport delay would increase. This is due to the formation of queues, which are caused by waiting for the possibility of boarding and disembarking passengers at PT stop.

For the third modeling option, graphical dependences of the influence of the traffic share and planning characteristics of the street on the traffic parameters are shown in Fig. 11, 12.

The results show that the absence of lanes for traffic on street and road networks and the share of traffic in the total flow significantly affect the average delay of traffic flows in the stop zone.

The simulation of the movement of traffic flows on the street section under the third variant of modeling shows the positive influence of traffic lanes on the parameters of the entire traffic flow. Under these traffic conditions, the average duration of delay of all types of transport does not exceed 65 seconds. It should also be noted that a particularly significant effect can be obtained if there is a PT share of more than 11 % in the stream. Under such conditions, it is recommended to unambiguously implement the allocated lanes.

Having analyzed the data shown in Fig. 7–12, it was established that public transport and its share in the flow affect the average length of traffic delays at the approaches to public transport stops. At the same time, an equally important influencing factor is the traffic organization scheme and arrangement of public transport stops.

After processing the resulting values with the help of Google Sheets electronic tables, the corresponding mathematical dependences were established (Table 2). They reflect the dynamics of changes in the average duration of delay (t_d) depending on the share of public transport in the flow (p). At the same time, the variety of traffic organization schemes (simulation scenarios) and the type of vehicles are taken into account.

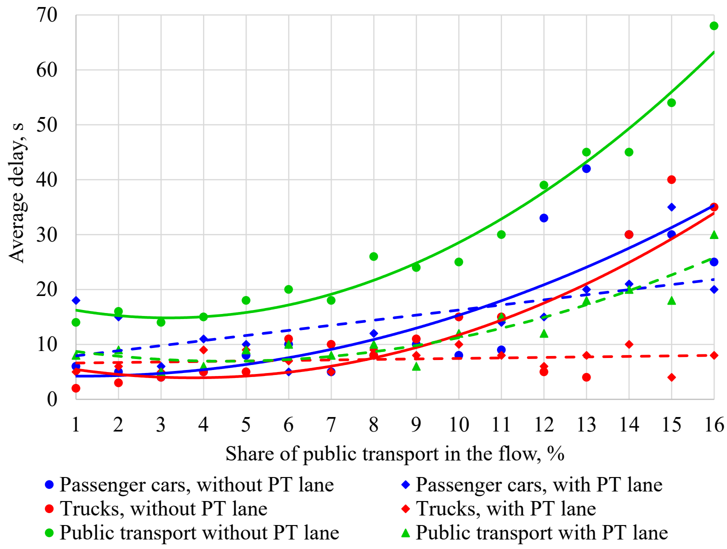


Fig. 11. Influence of the share of public transport in the flow on the average value of the duration of traffic delay in the third simulation scenario

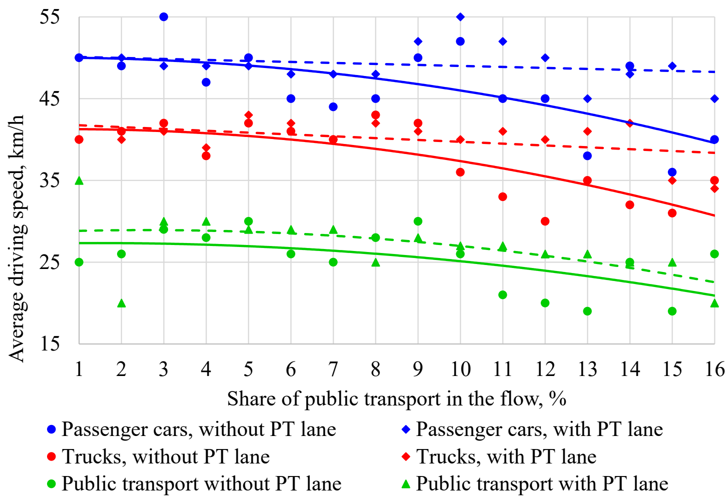


Fig. 12. Influence of the share of public transport in the flow on the average value of the speed of vehicles in the third simulation scenario

Table 2

Mathematical dependences of changes in the average duration of traffic delays on street sections under different simulation scenarios

Type of vehicles and presence/absence of lanes for PT traffic	Dependence of change in the average duration of movement delay		
	Simulation scenario I	Simulation scenario II	Simulation scenario III
Passenger cars, without PT lane	t_d=0.0189p^2+0.6403 p+5.9143	t_d=0.3633p^2–1.1035p+7.6018	t_d=0.1401p^2–0.3074p+4.3929
Passenger cars, with PT lane	t_d=–0.0172p^2+0.5299p+4.225	t_d=2.2985p+1.275	t_d=0.1968p^2–2.4188p+17.036
Trucks, without PT lane	t_d=0.0137p^2+0.1473p+0.9714	t_d=0.3022x^2+0.2013p+3.7857	t_d=0.1998p^2–1.4973px+6.7375
Trucks, with PT lane	t_d=0.0616p+0.445	t_d=0.8029p+3.3	t_d=–0.0956p+8.75
PT, without PT lane	t_d=0.1735p+14.525	t_d=0.4928p^2–0.8118p+12.009	t_d=0.2943p^2–1.8692p+17.809
PT, with PT lane	t_d=0.0941p+10.7	t_d=0.5571p^2–4.5996p+17.511	t_d=1.1382p+2.575

Based on our calculations and constructed dependences (Fig. 8, 10, 12), it was established that the change in the speed of the traffic flow for the first two simulation scenarios is better described by linear regression. The limits of range of variations in the indicator of average delay of the traffic flow for different share of PT, which are represented by the minimum and maximum values, respectively, are better visualized by a group of numerical values, which is described by a polynomial dependence. The influence of the PT share on the average movement delays, according to mathematical dependences (Table 2), can mostly be described by a second power polynomial. However, it is worth noting that in many cases of simulation, the patterns of changes in the indicators of traffic flows moving through sections with existing PT lanes are linear.

6. Discussion of results of investigating the influence of organization of public transport traffic on the parameters of traffic flows

Our work defines a basic model, which includes the construction and configuration of street sections and equipped public transport stops. Features of the network itself, such as model inputs for peak periods, different types of vehicles, desired traffic speed and driver behavior, etc., were also taken into account.

In general, the procedure for assessing the impact of PT on traffic flow parameters proposed in this study consisted of the following main stages.

The results of field studies of traffic flow parameters were used to build traffic simulation models using the PTV VISSIM software environment. They make it possible to change the planning parameters of the straight sections of the streets between the intersections through which traffic is carried out by both PT and cars and trucks. Based on the simulation results, graphical dependences of changes in the average duration of the delay and the speed of movement of vehicles in the stream were derived. Based on the analysis of data shown in Fig. 7–12 it has been established that the share of PT in the flow affects the conditions of movement of other types of transport.

The proposed models made it possible to establish that in the presence of 1×1 lanes of traffic in each of the directions, the arrangement of an additional dedicated lane for traffic makes it possible to improve the conditions of movement and increase the carrying capacity of the street section. At the same time, according to the results of modeling the scenario shown in Fig. 4, *a*, it was established that the increase in the share of PT in the flow leads to the formation of significant delays in the movement of transport. This is due to the fact that passenger cars and trucks often do not have sufficient intervals to make maneuvers to bypass the PT, which has stopped for boarding and disembarking passengers. In turn, under such conditions, the construction of an additional dedicated traffic lane (Fig. 4, *b*) would allow separating the PT from the general flow and, accordingly, leveling its influence. However, it should be noted that the construction of an additional lane is a financially costly process, and under the conditions of dense urban infrastructure, it is often impossible.

During the simulation of traffic scenarios shown in Fig. 5, it was established that a positive effect from the introduction of dedicated lanes could be obtained only if the share of PT in the flow is more than 4 %. This is explained by the fact that with a small number of buses and trolleybuses on the modeled section of the street, there are no significant delays in traffic, which are caused by the stop of PT during the boarding and disembarking of passengers. However, the growth of the share of PT leads to the deterioration in the conditions of movement, in particular, when their share increases from 4 % to 16 %, the duration of the delay of other types of transport increases by approximately 75 % (63 seconds on average). The introduction of lanes for PT traffic makes it possible to reduce their negative impact, and the average duration of the traffic delay increases significantly only for buses and trolleybuses, when their share in the flow is more than 12 %. This phenomenon is explained by the significant accumulation of rolling stock of PT on the dedicated lane in the area of the stop point.

Analyzing the results of traffic simulation according to the scenarios shown in Fig. 6, it was established that, in the absence of a dedicated traffic lane, there are significant delays in the movement of PT (ranging from 18 to 71 seconds). This situation is due to the fact that often buses and trolleybuses were forced to wait for a sufficient interval between cars in the flow to leave the "entry pocket". At the same time, with the increase in the share of PT, the duration of the delay of this type of transport increased. The introduction of dedicated lanes avoids this effect and reduces PT delays by an average of 47 %. In addition, it should be noted that for the share of PT in the flow of more than 11 %, there is a critical need for the introduction of a dedicated lane. In the opposite case, the duration of the transport delay of cars and trucks increases rapidly (on average from 4 to 36 seconds). Also, under such conditions, a decrease in the speed of cars by approximately 19 % was observed. However, for the share of PT in the flow of less than 11 %, the introduction of lanes for PT traffic leads to an increase in the duration of vehicle delays by more than 3.5 times.

Thus, in the presence of two or more traffic lanes in one direction and a significant number of traffic lanes in the flow, it is recommended to implement a dedicated lane of traffic lanes. Often, the advantage of this method of traffic organization is the absence of significant financial costs for the design and construction of a new traffic lane (reconstruction of the street and road network). However, for the share of PT in the flow of less than 11 %, the introduction of the dedicated lane leads to an increase in the duration of delay in the movement of cars. This may have a more negative effect than obtained for PT agents.

Based on the results of statistical analysis, the obtained data were approximated. Thus, it was established that the existing dynamics of changes in the average delay and speed of traffic flows can be described using polynomial and linear laws. This is confirmed by the obtained statistically significant coefficients of determination. The latter can be justified by the fact that the patterns of changes in traffic flows are stochastic, and the calculated values of the coefficient of determination are acceptable.

Thus, the research results indicate that when choosing planning and organizational measures, it is necessary to take into account not only the benefit obtained for PT. This trend can be traced in a significant number of scientific works [5, 8]. However, their authors often do not take into account the increase in the duration of delays of other types of rolling stock and, as a result, the increase in emissions of harmful substances, the increase in the consumption of fuel and lubricants, the formation of significant traffic jams, etc.

So, our work establishes a connection between the composition of the traffic flow and the planning parameters of streets and the values of average duration of delays. In general, the research was carried out under idealized conditions and along separate straight sections of city streets. Thus, the resulting dependences can be used only on runs where there is no significant influence of intersections and their planning parameters on traffic flow indicators. In accordance with this, a task for further research appears, in particular, regarding the in-depth study of the issue of traffic organization with ensuring the priority of PT along sections of considerable length and taking into account the influence of intersections and traffic lights.

In practice, our results could be applied both in the design of new sections of the street and road network, and under the conditions of reconstruction of existing ones. This would make it possible to choose the best option for organizing traffic along the sections of city streets where a PT stop is planned.

7. Conclusions

1. In the work, a series of field studies were carried out along sections of city streets with existing stopping points.

As a result of observations, it was established that the share of PT in the total flow varied from 6 % to 13 %, trucks – from 3 % to 8 %, and passenger cars – from 79 % to 89 %. Thus, the share of slow-moving vehicles in the flow varied from 3 % to 13 %. As for traffic intensities, the lowest values were observed on streets with a typical transverse profile I, and the highest on streets II and IV.

2. On the basis of information on the configuration of the road environment and primary indicators of traffic flow, simulation models of the work of straight sections of city streets were built. The calibration process involved taking into account the average values of distances between vehicles in queues, time intervals between cars, and their dynamic indicators. This is due to the need to bring the simulation model closer to actual conditions of movement.

3. The models constructed in the PTV VISSIM software environment have made it possible to establish the average values of duration of delay and the speed of movement of vehicles under different simulation scenarios. With the increase in the share of PT in the flow from 1 % to 16 %, the delay values varied from 2 to 160 s, and the speed of movement – from 15 to 52 km/h. Such a variation is due to the given planning parameters of the streets and techniques for arranging PT stops.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

Funding

The study was conducted without financial support.

Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

References

1. Soczówka, P., Żochowska, R., Karoń, G. (2020). Method of the Analysis of the Connectivity of Road and Street Network in Terms of Division of the City Area. Computation, 8 (2), 54. https://doi.org/10.3390/computation8020054
2. Zhuk, M., Pivtorak, H., Kovalyshyn, V., Gits, I. (2024). Simulation of Transfer Probability in the City Route Network: Case Study of Lviv, Ukraine. Periodica Polytechnica Transportation Engineering, 52 (3), 282–291. https://doi.org/10.3311/pptr.22322
3. Rybak, R., Kovalchuk, V., Parneta, B., Karnakov, I. (2023). Investigation of Reinforced Concrete Pipe Deformability by Reinforcement Frame Under Static Loads. Proceedings of CEE 2023, 351–361. https://doi.org/10.1007/978-3-031-44955-0_35
4. Kovalchuk, V., Rybak, R., Hnativ, Y., Tkachenko, V., Onyshchenko, A., Kravets, I. et al. (2022). Assessment of the stressed-strained state of a reinforced transport pipe under the combined effect of ambient temperature and static loads. Eastern-European Journal of Enterprise Technologies, 6 (7 (120)), 6–12. https://doi.org/10.15587/1729-4061.2022.268904
5. Fornalchyk, Y., Vikovych, I., Royko, Y., Hrytsun, O. (2021). Improvement of methods for assessing the effectiveness of dedicated lanes for public transport. Eastern-European Journal of Enterprise Technologies, 1 (3 (109)), 29–37. https://doi.org/10.15587/1729-4061.2021.225397
6. Tubis, A. A., Skupień, E. T., Rydlewski, M. (2021). Method of Assessing Bus Stops Safety Based on Three Groups of Criteria. Sustainability, 13 (15), 8275. https://doi.org/10.3390/su13158275
7. Zhang, J., Li, Z., Zhang, F., Qi, Y., Zhou, W., Wang, Y. et al. (2018). Evaluating the Impacts of Bus Stop Design and Bus Dwelling on Operations of Multitype Road Users. Journal of Advanced Transportation, 2018, 1–10. https://doi.org/10.1155/2018/4702517
8. Barua, S. (2020). Influence of bus bay and curbside bus stop in an urban road. International Journal of Students' Research in Technology & Management, 8 (3), 14–19. https://doi.org/10.18510/ijsrtm.2020.833
9. Qi, W., Ruan, L., Zhi, Y., Shen, B. (2021). Risk Area Identification Model of Bus Bay Stops Based on Distribution of Conflicts. Discrete Dynamics in Nature and Society, 2021, 1–11. https://doi.org/10.1155/2021/9663966
10. Murawski, J., Szczepański, E., Jacyna-Gołda, I., Izdebski, M., Jankowska-Karpa, D. (2022). Intelligent mobility: A model for assessing the safety of children traveling to school on a school bus with the use of intelligent bus stops. Eksploatacja i Niezawodność – Maintenance and Reliability, 24 (4), 695–706. https://doi.org/10.17531/ein.2022.4.10
11. Cvitanić, D. (2017). Joint Impact of Bus Stop Location and Configuration on Intersection Performance. PROMET – Traffic&aTransportation, 29 (4), 443–454. https://doi.org/10.7307/ptt.v29i4.2338
12. Medvediev, I., Soroka, S. (2020). The road network traffic capacity taking into account public transport stops layout method. Transport Technologies, 2020 (2), 13–22. https://doi.org/10.23939/tt2020.02.013
13. Liang, S., Ma, M. (2018). Analysis of Bus Bunching Impact on Car Delays at Signalized Intersections. KSCE Journal of Civil Engineering, 23 (2), 833–843. https://doi.org/10.1007/s12205-018-2043-x
14. Yu, J., Liu, Y., Chen, W. (2024). Conflict management at urban bus stops through cooperative trajectory planning. Transportation Research Part C: Emerging Technologies, 165, 104696. https://doi.org/10.1016/j.trc.2024.104696
15. Park, B. (Brian), Schneeberger, J. D. (2003). Microscopic Simulation Model Calibration and Validation: Case Study of VISSIM Simulation Model for a Coordinated Actuated Signal System. Transportation Research Record: Journal of the Transportation Research Board, 1856 (1), 185–192. https://doi.org/10.3141/1856-20