EVALUATION OF BUS LANE IMPLEMENTATION EXPEDIENCY ON STREETS WITH DIFFERENT LANE NUMBERS: CASE STUDY

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Resume

The introduction of bus lanes on streets may not be feasible from the standpoint of reducing the overall time loss for road users. The goal of this study was to develop a method for checking the effectiveness of bus lane implementation. Using simulation experiments, conducted in PTV VISSIM, for a different number of traffic lanes, the speeds of buses and vehicles were determined both when buses are moving in the general flow and after the introduction of a bus lane, at different values of flow intensity and bus frequency. Regression equations, describing the dependence of speed on the traffic flow intensity and frequency of buses for different numbers of traffic lanes, are formulated. A mathematical model has been developed to calculate and compare the time losses of road users before and after the introduction of a bus lane, based on determining the average speed of traffic flow and buses.

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1 Introductıon

In cities, comprehensive provision of mobility is envisaged, which is the most appropriate. The measures taken in this direction influence each other and are interdependent. Bicycle trips and walking are effective for certain short distances. Therefore, one of the main measures, aimed at increasing mobility for longer trips in cities, is to stimulate the use of public transport with an increase in the quality of services provided. The main indicators of the quality of service in public transport are considered to be travel time, travel comfort and traffic safety. To improve the quality of travel on public transport, it is first necessary to consider organizational solutions, such as events for reducing the travel time. One of the main ways to achieve this goal on congested streets is to create lanes for buses. Lanes organized for buses can be used in different ways depending on the conditions and needs. For example, there is experience in using bus lanes that allow only buses to travel, serve only buses at certain hours of the day, allow the general use of buses, taxis, bicycles and allow the movement of other vehicles. The following main methods for creating the bus lanes are distinguished [1]:

- Exclusive (dedicated permanently) - only for buses, all day.
- Part-time (temporary) - valid only during rush hours.
- High-occupancy vehicle lanes (HOV) - for buses and cars with ≥ 2-3 passengers.
- Queue jump lanes - short sections with priority at intersections.

Fast passenger travel by buses should not lead to a significant increase in the time lost by private vehicle owners. Like other mobility solutions, the creation of bus lanes should be carried out on the condition that they do not create additional problems in accordance with the traffic patterns on city streets. For example, bus lanes lead to a narrowing of the area of use for other vehicles. The introduction of bus lanes can be more effective in combination with various other solutions. For this reason, it is especially important to evaluate the way they are used and their effectiveness before creating bus lanes. It is advisable to use the time lost by road users for comparison. Thus, the main criterion for choosing a specific type of bus lane is the minimum number of traffic participants.

The proportion of private car users in different cities may differ. This may be due to local conditions, mental characteristics and other factors. With the expansion of the bus network, a certain number of private car owners may prefer public transport.

The aim of this article was to develop a method for checking the effectiveness of the implementation of dedicated lanes for public transport on streets with different numbers of lanes based on the total time lost by road users under given conditions. The criterion for selecting a lane type in mixed-use corridors, or those with spatial restrictions, is the simulated time loss. Both passenger and vehicle throughput are taken into account. Due to statistical indicators and road conditions, solving this problem on a real street network is an extremely labor-intensive and lengthy process. Therefore, it is proposed to implement an operational solution to the problem by processing the results of a simulation experiment. Modern simulation tools make it possible to accurately account for dynamic changes in the behavior of road users, including after the introduction of bus lanes. The PTV VISSIM, used for scenario modelling, allows for the modelling of vehicle behavior on different traffic lanes and the generation of lost time data for each mode of transport. The results of the simulation experiments are based on data on traffic flow speed and bus speed, allowing for dynamic changes in traffic flow due to changes in flow intensity and bus frequency. Based on flow intensity and bus arrival frequency for given conditions on a given road section, the speed and lost time are estimated.

2 Literature review

In the research of Cesme et al. (2018) is noted that the introduction of bus lanes should have sufficient public support and the traffic rules on the lanes should be strictly enforced. The work, based on the experience of implementing the bus lanes, proposes a reliable traffic management plan for bus lanes and presents a strategic plan [2].

Since the cars and buses are the main means of transportation in most major cities, more and more attention has been paid to the distribution of road space between them. Giving priority to buses, i.e., creating the bus lanes, is considered a generally accepted method for relieving traffic congestion. However, when implementing the bus lanes, previously studied strategies in this direction should be carefully examined. Dadashzadeh and Ergun (2018) summarized the studies conducted for this purpose, determined the minimum requirements for a bus priority system, and divided the studies devoted to the advantages and disadvantages of a bus priority system in terms of time and space [3].

Russo et al. (2022) also noted that bus transport is the main mode of transport in most cities, but it is a subject to delays due to the impact of general traffic. A study conducted in Rome, Italy, found that the introduction of bus lanes reduced the overall travel time of buses by approximately 18%. The authors noted that the number of bus lanes in the city is small [4]. In another study, conducted in Thessaloniki, Greece, was examined the feasibility of introducing a bus lane on an one-way road connecting the city centre to the outskirts with a low bus frequency on a real city route [5]. The measurements showed that the introduced bus lane was fully justified, reducing the time buses spent on the road and ensuring a smooth bus flow. The researchers noted the importance of enforcing parking and other traffic regulations when introducing bus lanes.

Bayrak and Guler (2021) noted that, although the use of bus lanes is generally considered the best strategy to improve bus performance, it can lead to significant bottlenecks and queues for other vehicles [6]. They proposed a two-level optimization algorithm aimed at reducing the overall time loss of all users when introducing bus lanes. The results show that the introduction of bus lanes can lead to a reduction in the overall time loss only in certain strategic locations.

When buses move in the general traffic flow, their reliability becomes dependent on the general flow. However, sometimes it is impossible to create bus lanes due to lack of space on the roads or restrictions on the traffic flow or its excessive impact on the flow. As an alternative solution, the authors proposed the introduction of dynamic bus lanes, which are reserved for buses only when necessary [7]. For this purpose, a simulation model of traffic management was built and calibrated using an urban highway with several bus lanes based on real indicators. In this paper, the variants with introducing dynamic lanes, the variants with buses moving in the general flow, and the variant with introducing exclusive bus lanes were compared. The results show that despite the positive effect of introducing dynamic lanes, the time passengers spend on the road increases slightly. At the low bus traffic intensity, the lanes remain unused for a long time. The dynamic use of bus lanes is a new strategic approach and allows the use of lanes in the absence of buses. Othman et al. (2023) noted that the implementation of dynamic bus lanes is promising, but its effectiveness needs to be tested under different traffic conditions [8]. To do this, they compared the impact of implementing dynamic bus lanes with the impact of implementing conventional exclusive bus lanes under different demand levels. To do this, they modelled the Eglinton East corridor in Toronto using Aimsun Next and considered different behavior patterns. It was found that the dedicated bus lane is more effective at high bus density and high traffic flow rates. Li et al. (2025) also proposed to improve the efficiency of bus lane usage by implementing a dynamic lane usage strategy [9]. The dynamic time and space priority strategy uses infrastructure and vehicle status information to determine the available time and space resources in the bus lane. Based on these resources, a usage optimization model is developed for the vehicles that would use the bus lane.

Xue et al. (2025) analyzed various factors of bus lane sharing. After analyzing the impact of bus lane sharing strategy on commuters' sharing decisions and traffic flow pattern, the authors constructed a bus lane performance evaluation model using the TOPSIS method [10]. Zhang et al. also investigated the performance of multi-functional bus lanes and found that the proposed strategy improves the intensity balance, reduces delays by 80.56% and stops by 89.35% when CAV demand increases [11].

The use of bus lanes by cars under certain conditions may be appropriate to ensure the efficient use of bus lanes when the car demand is high and bus demand is low. To ensure the balance, Yin et al. (2024) propose a bus lane usage rule for private cars by modeling based on the speed of the adjacent lane [12]. The measured results show that the travel time is significantly reduced as a result of cars using bus lanes.

Kong et al. (2024) proposed a management strategy for intermittent bus lanes to optimize the use of road resources in small and medium-sized cities [13]. In this paper, a methodology was developed to determine the feasibility of implementing intermittent bus lane signs based on factors such as road congestion, vehicle traffic volume, and bus traffic volume.

Qiao et al. (2024) proposed a comprehensive evaluation method using a bus lane implementation priority index based on vehicle traffic volume data collected from multiple sources. A classification table of the importance of implementing bus lanes was constructed, and a corresponding range was determined for each level. In this way, bus lanes corresponding to a specific index were divided into excellent, good, average, neutral, and poor classes [14].

In the work of Tsitsokas et al. (2021), the optimal allocation of bus lanes was studied [15]. A model structure was proposed according to the dynamic characteristics of the density distribution. The problem was considered as a non-combinatorial optimization problem with binomial variables. In another work devoted to the design of bus lane infrastructure, an optimization model was developed taking into account the number of road users and the size of streets and tested in Beijing [16].

Meliti and Kadar (2011) investigated the impact of dedicated bus lanes on ridership and travel time loss [17]. The difference between the average travel time of cars and buses during the off-peak and peak hours on weekdays and weekends was determined. For this, the Student's t-test was used. It was found that the ridership of buses is generally low, and the impact of introducing dedicated lanes on ridership is very weak. Research conducted in Kuala Lumpur has shown that the time lost by buses travelling in a dedicated lane is greater than the time lost by vehicles travelling in the general flow of traffic in the adjacent lane.

Fadyushin and Zakharov (2020) studied the time losses of buses and other vehicles in the bus stop zone using field studies, microsimulation experiments and mathematical models, found that improving the parameters of bus lanes does not lead to a significant increase in the speed of buses, but has a negative impact on the travel parameters of other vehicles [18].

The introduction of bus lanes can also cause certain problems at intersections. Zhang (2023), analyzing the evaluation indicators of a discontinuous bus lane, showed that when the traffic intensity is a certain percentage of the throughput, the speed of vehicles increases, but the time losses of buses increase, as well [19].

De Oliveira et al. (2024) analyzed the change in the speed of other vehicles as a result of the creation of bus lanes in the city of Sao Paulo in 2020-2025 and concluded that this change varies depending on the area of the city and the mode of operation of the bus lane (fully separated and temporarily separated) [20]. There is also a study examining the impact of the creation of lanes reserved for public transport on the speed of buses [21].

Arasan et al. (2009) proposed to determine the ratio of vehicle traffic intensity to road capacity to assess the restriction of the traffic conditions of other vehicles as a result of creation of the bus lanes. It is noted that the introduction of bus lanes on some streets, while improving the quality of service for passengers, does not have a negative impact on the movement of other vehicles. In the research defined the initial conditions for the introduction of bus lanes [22].

There are many studies devoted to simulation experiments of the organization of bus lanes. Szarata (2021) tested the implementation of bus lanes on 4 road sections in the city of Rzeszow, Poland, using PTV VISSIM. The simulation experiment was conducted for 3 cases (no bus lane, dedicated lane, dynamic lane). The final evaluation was made on the average time loss for all vehicles. The author found out from the tests that the time spent by vehicles on the road does not increase significantly as a result of the implementation of dynamic bus lanes [23]. Tran et al. (2013) conducted a comparative analysis of 3 popular bus lanes using simulation experiments using a model created in the PARAMICS program based on the assumed input parameters. The experimental values were used in the tests for exclusive bus lanes, regular lanes and lanes with bus priority. The time-saving value that can be achieved by implementing the bus lanes on a 500-meter-long street section was determined [24]. Hawas (2013) proposed a method for estimating bus route travel times using microsimulation [25]. The parameters used are the route length, network traffic volume, specified speed limit, bus frequency, and number of passenger boardings and alightings. The regression model proposed for forecasting was calibrated taking into account the time lost on the route and in transit. The reliability of the calibrated regression model was demonstrated.

In the work of Liu et al. (2020), the joint use of bus lanes by automated vehicles was simulated using intelligent control systems. It was found that, as a result of proper organization of control taking into account the operating modes of buses on the route, it is possible to significantly increase the speed of buses and automated vehicles [26].

As can be seen from the results of the research, the effectiveness of the introduction of bus lanes significantly depends on the conditions of their use and the importance of justifying that use by taking into account the change in the main parameters under the given conditions is great. The effectiveness of bus lane implementation can be assessed using time loss, which is a universal performance indicator that takes into account delays in lanes, stops, transfers, etc.

Systematic aproach to using bus lanes usually prevents overall time losses. However, if negative impacts are observed with bus lane use, it's possible to test the effectiveness of dynamic lanes, consider reconfiguring the network, determine time losses across all streets, and model the network using macromodeling tools.

3 Methodology

In the article is developed a methodology for assessing the effectiveness of introducing bus lanes based on the total time losses of road users under given conditions (speed limit, lane width, length of a street section) in various values of vehicle traffic intensity, bus arrival frequency, and the number of bus passengers transported along a given section for different numbers of street lanes. To assess the speed of buses and vehicles when buses move in the general flow and along a bus lane, numerous simulation experiments were conducted on a street with 2, 3, 4, and 5 traffic lanes using a micromodel created in the PTV VISSIM program. The constructed in PTV VISSIM model was used the Weidemann 99 psychophysiological model of following the leader (car-following model), built in by default, which simulates, in a microscopic format, the behavior of a driver when driving behind another car. It takes into account the personal characteristics of the driver (aggressiveness, attentiveness), the distance between cars, the reaction to the deceleration/acceleration of the leader, the relative speed.

During the simulation experiments, the speeds of buses and other vehicles were determined before and after the introduction of a bus lane. First, regression equations were obtained for the dependence of the speed on the intensity of vehicle traffic and the frequency of bus traffic when buses move in the general flow on a street with 2, 3, 4 and 5 traffic lanes. Then, the regression dependencies of the flow speed on the intensity of the traffic flow, as well as the dependence of the speed of buses on the frequency of bus arrivals after the introduction of the bus lane were determined.

Based on the speed value, determined using the regression dependencies, a method for determining the total time losses of road users on roads with different numbers of traffic lanes (2, 3, 4 and 5) is proposed. The condition for the effectiveness of introducing a bus lane for considered period (hour) based on the values of time losses is adopted. The proposed method was tested on a two-lane road based on the values of traffic flow intensity, the number of bus passengers and the frequency of bus arrivals taken from real road conditions.

The proposed model does not impose restrictions on use for city streets with more than five lanes. The consideration of the effectiveness of using bus lanes on streets with a maximum of 5 lanes is related to local road conditions (specifically for the city of Baku).

4 Requirements for the implementation of bus lanes on city streets

According to various methodologies, bus lanes are introduced primarily when the hourly frequency of buses is more than 30 bus/h and the traffic intensity is more than 1000-1200 veh/h. In addition, it is considered appropriate to use the bus lanes when the speed is less than 15 km/h. Lane allocation should prioritize buses, even if private vehicles predominate, as long as

Table 1 *Recommended solutions for organizing the bus lanes taking into account the frequency of bus arrivals and the number of passengers*

Treatment	Minimum one-way peak-hour volume		Related land use and transportation factors
	bus	passanger	
Bus streets or malls	80-100	3200-4000	Commercially oriented frontage
CBD curb bus lanes, main streets	50-80	2000-3200	Commercially oriented frontage
Curb bus lanes, normal flow	30-40	1200-1600	At least 2 lanes available for other traffic in same direction
Merdian bus lanes	60-90	2400-3600	At least 2 lanes available for other traffic in same direction; ability to separate vehicular turn conflicts from buses
Contraflow bus lanes, short segments	20-30	800-1200	Allow buses to proceed on normal route, turn around or bypass comgestion on bridge aproach
Contraflow bus lanes, extended	40-60	1600-2400	At least 2 lanes available for other traffic in opposite direction/ Signal spacing greater than 150 m intervals

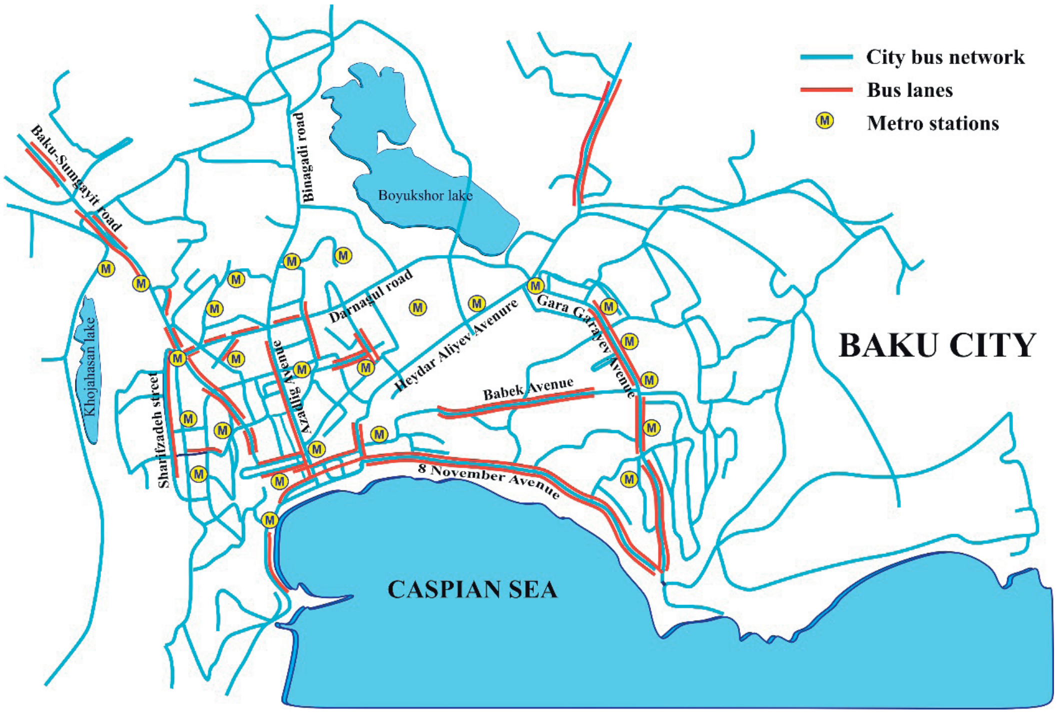


Figure 1 *Streets with dedicated bus lanes in the Baku city bus route network*

Table 2 *Number of bus lanes and number of routes passing through some streets in Baku*

Streets where bus lanes are used	Forward direction			Reverse direction		
	Total number of lanes	Number of bus lanes	Number of bus routes	Total number of lanes	Number of bus lanes	Number of bus routes
Gara Garayev ave.	3	1	27	3	1	26
Y.Safarov street	5	1	11	6	1	11
28 May street	4	1	10	0	0	0
A.M. Sharifzade street	4	1	8	4	0	5
Khoyski street	3	1	12	3	1	11
Tbilisi ave.	3	1	7	4	1	7
Moskow ave.	2	1	17	2	1	19
Sh.Badalbayli street	5	1	9	0	0	0
Rovshan Jafarov street	2	1	12	2	1	2

efficiency criteria are met. Priority to buses is justified if the bus ridership is higher than that of private cars (even if there are fewer cars). Furthermore, the city's goal is to optimize the transportation of people, not cars. The recommended solutions for the use of bus lanes depending on the frequency of buses and the number of passengers, presented in the TRB TCQSM report [1], are shown in Table 1.

As can be seen from Table 1, the creation of bus lanes is recommended in heavy traffic conditions, when the frequency of bus arrivals is 11-20 buses per hour and the flow intensity is 800-1500 vehicles per hour. Observations conducted on the Baku bus route network show that on many streets the frequency of bus arrivals often exceeds 80 vehicles per hour and the flow intensity is over 800 vehicles per hour, not only during the peak hours but also at normal times. Figure 1 shows the streets where the bus lanes have been created in Baku. The total number of traffic lanes on streets with bus lanes in Baku by direction is given in Table 2.

The flow indicators can vary over short periods, such as 10-15 minutes. However, obtaining data over a longer period, such as an hour, can improve reliability. For these experiments, the data from hourly measurements of traffic flow and bus speeds under real-world conditions were used, reflecting dynamic changes in traffic flow as bus intensity and frequency change. Taking measurements during the peak and off-peak hours and incorporating these indicators also improves reliability and ensures that dynamic variability is accounted for.

Table 2 shows the values of the number of lanes and the number of bus routes passing along some streets in the forward and reverse directions.

The road capacity for general traffic on the streets shown in Table 2 varies from 1,800 vehicles per hour to 6,400 vehicles per hour, depending on the number of lanes and traffic organization. Bus lanes are located on the right and are demarcated from the general traffic flow by a solid line. Parking near the sidewalk is prohibited.

Over the past 10-15 years, the traffic density in cities has increased as a result of a sharp increase in the number of private car owners, and serious traffic jams have begun to be observed in all the cities with a population of over 1 million people. Observations show that on all the streets where the bus lanes are created, traffic jams occur during the peak hours, and the speed of the traffic flow decreases. To prevent conflicts with other traffic participants, when allocating lanes for buses on narrow city streets, a solution can be time-based lanes, shared or alternating lanes, the use of reverse traffic, priority of buses at traffic lights, point allocation of lanes, creating space for the lane. It is advisable to check the effectiveness of creation of bus lanes based on the total time losses of all the road users. A test based on the total time lost by all the road users, when creating bus lanes, initially requires determining the speeds of buses and vehicles on streets with different number of lanes for given conditions.

5 Assessment of the impact of vehicle traffic intensity and bus arrival frequency on flow speed

The following relationship exists between the main parameters of the transport flow [27]:

$$N = kv, \qquad (1)$$

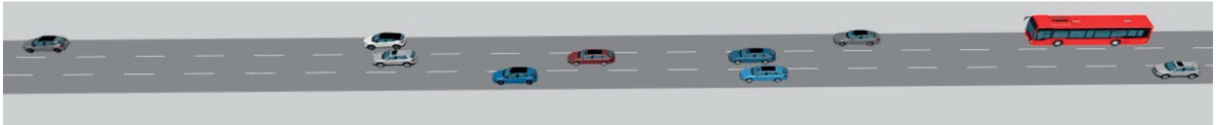
where:
N is the traffic flow intensity, veh/hour;
k is the traffic flow density, veh/km,
v is the average flow speed, km/h.

As can be seen from the formula, there is a mathematical relationship between the speed of movement and the intensity of vehicles. Traffic density can change under the influence of various factors. At the same time, the speed of the flow can be affected by the composition of flow, the width of the lanes, permitted maneuvers, methods of traffic control and other factors. In addition, when introducing, the bus lanes, the number of lanes used by the general traffic flow decreases, the density of vehicles increases, and the speed of the traffic flow decreases. Therefore, when creating the bus lanes on each section of the street and on the street as a whole, the effect of the frequency of bus arrivals and the intensity of the traffic flow on the speed of movement should be studied, based on the actual values of the indicators.

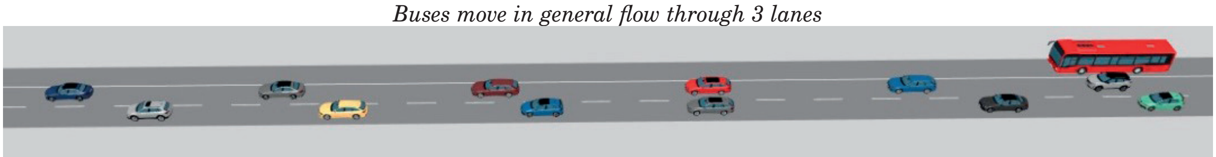
As already mentioned, based on the classical approach, the conditions for the use of bus lanes are determined by certain maximum values of traffic speed, bus arrival frequency and traffic flow intensity. Even if all these conditions were met, in real conditions, problems, such as an increase in the overall time loss of road users, may arise when using the bus lanes. A dedicated lane reduces overall delay time if the lane is used by many buses and passengers. A dedicated lane shifts delays if buses arrive infrequently, the capacity of the remaining lanes is not taken into account, and there are no alternative routes for passenger vehicles. Therefore, it is important to test the situation that will arise when using the bus lanes under the given conditions using simulation modelling. The TRB TCQSM report also notes that before making a decision on allocating lanes for the bus traffic, it is advisable to conduct simulation experiments based on parameters corresponding to current road conditions [1]. Such programs as SUMO, Aimsun, PARAMICS [28-30] are used to simulate traffic on streets and roads. In the models created to test the effectiveness of bus lanes on a street section using PTV VISSIM, it is possible to take into account the values of the quantities (number and size of lanes, speed limit, bus arrival frequency, traffic intensity of vehicles, etc.).

In the simulation model, created in PTV VISSIM to analyze the speed of buses and other vehicles in the flow, before and after the introduction of a special lane for buses, the lane width was taken to be 3.5 meters, and the permitted speed was taken to be 50 km/h in accordance with real traffic conditions based on observations made on the streets of Baku. The situation that may arise when introducing the bus lanes was simulated by entering the obtained traffic parameters and behavior models of vehicles and buses. The length of the measured street section was taken to be 800 meters. Measurements were carried out when the bus arrival frequency changed from 80 to 240 buses per hour, and the traffic intensity of the flow from 800 to 2400 vehicles per hour. Figure 2 shows the exemplary images of the resulting situation as a result of simulation tests, when buses move in the general flow and through a bus lane on a 3-lane road.

Based on the results of simulation tests of a bus traffic in the general flow and on the bus lane, the obtained values of the indicators were processed. As a result of numerous measurements carried out using the created micromodel, it was found that the frequency of bus traffic and the hourly traffic intensity of other vehicles, when moving in the general flow on a street with a different number of traffic lanes, are completely independent of each other. Thus, there is no correlation between the frequency of bus traffic and the traffic intensity of the flow. Therefore, it is possible to consider the regression dependence of the influence of these parameters on the speed of movement. The correlation coefficients of the dependence of the traffic flow speed on the intensity of vehicles and the frequency of bus arrivals when buses move in the general flow are given in Table 3, for different numbers of traffic lanes.



Buses move in general flow through 3 lanes



Buses move through bus lane in a street with 3 lanes

Figure 2 *3D visualization example of the model before and after the introduction of bus lanes in PTV VISSIM for a 3-lane road*

Table 3 *Correlation coefficients of the dependence of the speed of movement in the general flow on the intensity of movement and the frequency of arrival of buses*

Number of lanes	Correlation coefficients of the dependence of the speed of movement in the general flow on:	
	Bus arrival frequency	Intencity of vehicles
2	-0.32049738	-0.805978864
3	-0.1824384	-0.793671492
4	-0.14571551	-0.741598638
5	-0.27796198	-0.647205939

Table 4 *Parameters of the dependence of the speed of movement on the frequency of bus arrivals and the intensity of car traffic on 2, 3, 4 and 5 lane roads when buses move in the general flow*

Lanes	R^2		Coefficients	Standard deviation	t-statistics	P-value	Significance F
		Y intersection	64.391605	1.274799	50.51118	$2.39 \cdot 10^{-61}$	
2	0.752	Veh. intensity	-0.003124	0.000549	-5.68757	$2.15 \cdot 10^{-7}$	$2.3 \cdot 10^{-24}$
		Bus arrival freq.	-0.078561	0.005493	-14.3030	$1.66 \cdot 10^{-23}$	
		Y intersection	62.93425	1.296197	48.55301	$4.75 \cdot 10^{-60}$	
3	0.663	Veh. intensity	-0.00155	0.000559	-2.77636	0.006897	$3.69 \cdot 10^{-19}$
		Bus arrival freq.	-0.06746	0.005585	-12.0785	$1.53 \cdot 10^{-19}$	
		Y intersection	61.0832	1.295880	47.13647	$4.44 \cdot 10^{-59}$	
4	0.613	Veh. intensity	-0.00110	0.000558	-1.96529	0.005294	$4.55 \cdot 10^{-15}$
		Bus arrival freq.	-0.055846	0.005584	-10.0021	$1.25 \cdot 10^{-15}$	
		Y intersection	59.23299	0.994523	59.55918	$8.64 \cdot 10^{-67}$	
5	0.576	Veh. intensity	-0.001482	0.000428	-3.45842	0.00088	$2.46 \cdot 10^{-12}$
		Bus arrival freq.	-0.034506	0.004285	-8.05256	$7.44 \cdot 10^{-61}$	

Table 4 shows the parameters of the regression dependence of the speed on the frequency of bus arrivals and the intensity of vehicle traffic when buses move in the general flow on 2, 3, 4 and 5 lane roads.

As can be seen from Table 4, with an increase in the number of traffic lanes, the influence of the frequency of bus arrivals and the intensity of vehicles on the speed of movement decrease. Analysis of the parameters of movement of vehicles passing through the bus stop zone, carried out using the simulation experiments, also shows that with an increase in the number of lanes, the impact of bus maneuvers at the stop on the loss of flow time decreases sharply [31].

According to Table 4, the regression equation, describing the dependence of the speed of movement of vehicles in the general flow on the intensity of movement of vehicles and the frequency of arrival of buses on a street with a two-lane road, will have the following form:

$$v_{flow} = 64.39 - 0.003N_{veh} - 0.079N_{bus}\,, \tag{2}$$

where:

N_{veh} is intensity of vehicles, veh/h;

N_{bus} is frequency of bus arrivals, bus/h.

Since in this case only the buses use the bus lane, the speed in this case is affected by the frequency of bus arrivals. Furthermore, the obtained R^2 value shows that the speed of buses in the dedicated lane is fairly well described by the proposed model.

Based on the values from Table 4, it is possible to similarly create the regression equations describing the dependence of the speed of movement of vehicles in the general flow on the frequency of arrival of buses and the intensity of movement of other vehicles for a street with 3, 4 and 5 traffic lanes.

As a result of creating a dedicated lane for buses, the number of lanes used by the general flow will decrease. For instance, when creating a dedicated lane on a two-lane road, one lane will remain for vehicle traffic and the speed of movement will depend only on the intensity of vehicle traffic.

During the simulation experiment it was found that when the buses move along a dedicated lane, for an increase in the frequency of movement from 80 to 240 bus/h the speed of buses decreases from 53.8 km/h to 36.7 km/h. The speed of buses along the dedicated lane does not decrease significantly until the frequency of arrival of buses reaches 180 bus/h, but then decreases sharply.

Based on the results of statistical analysis, the dependence of the speed of buses on the dedicated lane on the frequency of buses will be determined by the regression equation:

$$v_{bus} = -0.0013N_{bus}^2 + 0.3058N_{bus} + 37.066, \quad R^2 = 0.9139 \tag{3}$$

When the bus lanes are introduced, the traffic flow speed may decrease due to increased density. The frequency of bus arrivals in this case does not affect the average flow speed.

After the introduction of a bus lane, the impact of traffic volume on the speed of the remaining lanes must also be considered. Table 5 shows the regression equations describing the dependence of traffic speed on vehicle intensity for different numbers of traffic lanes. The regression equations in the Table 5 account for the dependence of traffic speed on the traffic volume after the bus lane is used (after reducing the number of lanes by one unit).

As can be seen from Table 5, it is possible, with sufficient accuracy to describe, the dependence of speed on the traffic intensity of vehicles on 2, 3, 4 and 5-lane roads after the implementation of a bus lane. With an increase in the number of lanes, vehicle time loss decreases comparatively. Furthermore, as can be seen from the values of the constant terms in the regression equations, the impact of traffic volume on speed decreases.

6 Checking the effectiveness of bus lane implementation due to lost time

The key performance indicators for public transport passengers using a bus lane include a reduction in average travel time, average delays on the lane, increased bus speeds, and an increase in the proportion of passengers served on time. For the entire transport system, these include the total time lost by all the users and the lane's throughput capacity for people and vehicles. The total time lost can be quantified by calculating the difference in travel time compared to the baseline scenario (without the lane). This takes into account the number of vehicles and passengers by mode, as well as the change in travel time.

Using the time lost as the sole criterion ignores effects such as reduced emissions, increased public transport reliability, and safety. However, it is clear that the creation of a bus lane improves safety by reducing conflicts between vehicles and increases reliability by increasing delivery speed. Furthermore, by regulating and coordinating the operation of buses operating on different routes, the dedicated lane can significantly reduce passenger time lost [32].

Using the obtained dependencies, the efficiency of introducing a bus lane is evaluated based on a comparison of the time losses of vehicles and bus passengers during the period under consideration. A bus lane will be efficient if the total time losses of vehicles and passengers before introducing the bus lane are greater than the total time losses after introducing the bus lane:

$$\sum T_{tl.bbl} > \sum T_{tl.abl} . \tag{4}$$

The time losses of all the vehicles and passengers before introducing the bus lane, during the period under consideration, are determined as follows:

Table 5 *Description of the dependence of the speed of movement of vehicles on the traffic intensity corresponding to different numbers of lanes after the introduction of bus lanes*

Number of lanes	Regression equations	R^2
2	$v_{veh} = -3 \cdot 10^{-6}N_{veh}^2 + 0.0069N_{veh} + 48.143$	$R^2 = 0.9648$
3	$v_{veh} = -2 \cdot 10^{-7}N_{veh}^2 + 0.002N_{veh} + 52.362$	$R^2 = 0.9643$
4	$v_{veh} = 9 \cdot 10^{-9}N_{veh}^2 + 0.0002N_{veh} + 52.648$	$R^2 = 0.9152$
5	$v_{veh} = 3 \cdot 10^{-7}N_{veh}^2 + 0.0015N_{veh} + 54.108$	$R^2 = 0.973$

$$\sum T_{tl.bbl} = \frac{l(N_{pass} + N_{veh})}{v_{flow}}, \quad (5)$$

where:

l is length of the section under consideration, km;

N_{pass} is a number of passengers passing through the section under consideration in one hour.

The value N_{pass} can be defined as $N_{pass} = N_{bus} \cdot D_{bus}$, where D_{bus} is the average number of passengers carried on one bus. It is also possible to obtain accurate information on the number of passengers carried per hour from the transport companies or directly from buses by direct observation.

The total time losses of all the road users after the creation of a bus lane are determined as:

$$\sum T_{tl.abl} = \sum T_{plt.abl} + \sum T_{vlt.abl}, \quad (6)$$

where:

$\sum T_{plt.abl}$ is total passangers loss time after implementation of bus lane, hour;

$\sum T_{vlt.abl}$ total vehicless loss time after implementation of bus lane, hour.

$$\sum T_{plt.abl} = \frac{lN_{pass}}{v_{bus.abl}}, \quad (7)$$

$$\sum T_{vlt.abl} = \frac{lN_{veh}}{v_{veh.abl}}. \quad (8)$$

Thus, the implementation of a bus lane on the road is advisable when the time loss values, calculated using Equations (5) and (6), satisfy the condition in Equation (4). If this condition was met throughout the day (for all hours of operation of buses), then the use of an exclusive bus line is required. Otherwise, the effectiveness of implementation other types of bus lanes should be checked.

7 Discussion

Now is checked the expediency of implementation a bus lane for a given section of a two-lane road for considered period (hour). According to Equations (2) and (5), the total time loss of all the road users, on a given section of a two-lane road before the bus lane implementation, is determined as:

$$\sum T_{tl.bbl} = \frac{l(N_{pass} + N_{veh})}{64.39 - 0.003N_{veh} - 0.079N_{bus}}. \quad (9)$$

According to Equations (3) and (7), the time loss of passengers on a given section of a two-lane road, after the bus lane implementation, is determined as:

$$\sum T_{plt.abl} = \frac{lN}{-0.0013N_{bus}^2 + 0.3058N_{bus} + 37.066}. \quad (10)$$

According to data in Table 5 and Equation (8) the time loss of vehicle users on a given section of a two-lane road, after the bus lane implementation, is determined as:

$$\sum T_{vlt.abl} = \frac{lN_{veh}}{-3 \cdot 10^{-6}N_{veh}^2 + 0.0069N_{veh} + 48.143}. \quad (11)$$

Thus, the total time losses of all the road users after the creation of a bus lane will be:

$$\sum T_{tl.abl} = \frac{lN_{pass}}{-0.0013N_{bus}^2 + 0.3058N_{bus} + 37.066} + \frac{lN_{veh}}{-3 \cdot 10^{-6}N_{veh}^2 + 0.0069N_{veh} + 48.143}. \quad (12)$$

For example, let the number of passengers transported by buses on a given section of a two-lane road be 2000 pass/h, the intensity of vehicle traffic - 1800 veh/h, the frequency of buses - 90 buses per hour, then, based on Equations (9) and (12), one obtains:

$$\sum T_{tl.bbl} = 58.6\,h; \ \sum T_{tl.abl} = 57.909\,h. \quad (13)$$

In this case, the traffic density according to the obtained speed values and according to Equation (1), before using the dedicated lane for one traffic lane will be $k = 26veh/km$, and after using the dedicated lane for one traffic lane of the general flow $k = 35veh/km$.

If the condition in Equation (4) was satisfied for the case under consideration, during all the periods of the day, the use of an exclusive bus lane is appropriate. If the condition in Equation (4), was not satisfied, it is then logical to conduct a check for each hour separately and determine the appropriateness of introducing a specific type of bus lane. Since the off-peak hours reduce the traffic density and the flow becomes free, it does not particularly affect delays for buses moving in the flow. More precisely, it is possible, for example, to determine hours, which allow the movement of other vehicles on the bus lane during these hours (temporary bus lane). For comparison to the last example, if the number of passengers transported by buses on a given section of a two-lane road was 1350 pass/h, the intensity of vehicle traffic - 1200 veh/h, and the frequency of buses - 60 buses per hour, based on Equations (9) and (12) one gets:

$$\sum T_{tl.bbl} = 36.4\,h; \ \sum T_{tl.abl} = 39.7\,h. \quad (14)$$

In this case the traffic density before the application of a dedicated lane for one traffic lane would be $k = 12veh/km$, and after the application of a dedicated lane for one traffic lane of the general flow $k = 22veh/km$.

Similarly, the effectiveness of introducing a bus lane on a road with a large number of traffic lanes can be checked. Moreover, it is possible to check the expediency of bus lane implementation permitted for the movement of taxis or vehicles with 2-3 passengers, then the values of the traffic intensity of these vehicles should be taken into account in Equation (6) separately.

The formulas take into account the variability of traffic flow. However, in the event of unexpected disruptions, other approaches can be used, such as risk management methods.

8 Conclusion

Reducing the travel time is one of the main goals in organizing traffic in cities. Assessing the traffic efficiency, based on individual vehicle delays does not yield the desired results. Depending on the current state of the traffic flow, individual vehicle delays can fluctuate significantly, so it is important to assess the overall delay. Therefore, when introducing the bus lanes in the section under consideration, it is also advisable to check whether the overall time losses for all the road users are reduced.

Simulation experiments can be used to estimate the speed of vehicles on a given section for the given road conditions. Statistical processing of the results of simulation experiments in the PTV VISSIM program shows that the dependence of the speed of buses and other vehicles on the intensity of the traffic flow and the frequency of bus arrivals is well described by regression equations. Based on the speed of movement obtained by the regression models, it is possible to calculate the time losses of vehicles and buses (and therefore passengers).

The proposed methodology for determining the feasibility of using dedicated bus lanes, based on a comparison of the total time lost by all the road users for bus travel in the general traffic flow and in a dedicated bus lane, can be applied for each hour of the day, taking into account the dynamic changes in traffic flow and the frequency of bus arrivals under given conditions (lane width, speed limit, street section length, stop placement, etc.).

Taking into account the intensity of other vehicles allowed to use the bus lane, the proposed methodology can be used to test the effectiveness of other forms of bus lane implementation.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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