MODELING THE FORMATION OF A VEHICLE QUEUE AT URBAN SIGNAL-CONTROLLED INTERSECTIONS

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Viacheslav V. Morozov,
Tyumen Industrial University, Tyumen, Russia,
morozov1990_72@mail.ru

Georgy N. Morozov,
Sverdlovsk region, Baikalovo village, Russia,
morgn11@yandex.ru

Vladimir D. Shepelev,
South Ural State University (National Research University), Chelyabinsk,, Russia, **shepelevvd@susu.ru**

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The study addresses the problems of urban transport systems, their structure, and integrated development. The object of this study is the formation of traffic queues within the urban street and road network, and the subject is the patterns of changes in the length of traffic queues formed at signal-controlled intersections in left-hand directions. The purpose of the study is to develop a mathematical model for the formation of a traffic queue depending on the traffic capacity of urban signal-controlled intersections and weather and climate conditions. The methodological framework of the study is systems approach, including systems analysis and synthesis; mathematical statistics; mathematical and simulation modeling; correlation, regression analysis; experimental planning theory. The study revealed that traffic management is a significant element of the urban transport system in modern cities. The sustainable operation of the urban transport system directly depends on the efficiency of traffic management. A method for optimizing traffic at signal-controlled intersections is the use of turn storage lanes. Simulation modeling using PTV Vissim software demonstrated that the introduction of turn storage lanes helps to increase the traffic capacity of signal-controlled intersections and reduce traffic delays. However, the unjustified extension of these lanes does not significantly increase the traffic capacity. Analytical studies allowed framing a linear, two-factor, additive mathematical model that describes changes in the length of the transport queue at signal-controlled intersections. Unlike existing models, the new model takes into account the influence of the residual transport queue and road slipperiness. Experimental studies were carried out at more than 20 signsl-controlled intersections in Russian cities to collect a sample size of 759 measurements. The analysis of the obtained data showed that there is an effect of joint interaction between the residual transport queue and the road surface slipperiness, which influences the length of the forming transport queue.

Information about authors:

Viacheslav V. Morozov, *Tyumen Industrial University, Associate Professor of the Department of Transport and Technological Systems, Candidate of Engineering Sciences, Tyumen, Russia, ORCID: 0000-0001-6840-1247*

Georgy N. Morozov, *LLC Rokada, category I engineer, Candidate of Engineering Sciences, Sverdlovsk region, Baikalovo village, Russia*

Vladimir D. Shepelev, *South Ural State University (National Research University), Associate Professor of the Department of Vehicles and Automobile Service, Candidate of Engineering Sciences, Associate Professor, Chelyabinsk, Russia, ORCID: 0000-0002-1143-2031*

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Introduction

A modern city is a complex and diverse system that consists of many different elements, including the urban transport system, which is essential for the unimpaired functioning of the city. Urban appearance directly depends on the methods of transport public services [1-3].

The increase in motorization and stimulating the use of private cars contributes to the formation of an urban space with a large number of multi-level junctions, wide roadways, overpasses, and other similar structures. The key advantage of using a private car is the ability to move around the city at any time of the day. However, the use of this transport service system constitutes risks that pedestrian traffic and the development of public transport will be stopped. Global experience shows that an increase in transport supply increases transport demand. The unreasonable and active growth of the street and road network leads to an increase in the number of private vehicles [4-7].

Cities with dense historical development face difficulties in adapting to active motorization conditions and vehicle storage. In practice, the courtyard area of old districts is not designed to accommodate many cars. In limited space conditions, vehicles arriving in the city center encounter difficulties in parking, which additionally loads the street and road network. Besides, randomly parked cars reduce the traffic capacity of the street and road network, create emergency situations, and have a negative impact on the urban ecology.

An alternative approach to transport services and road traffic organization is a set of methods and techniques focused on the development of pedestrian and public transport. The main goal of this strategy is to ensure appropriate conditions for pedestrian and bicycle traffic, as well as the development of public transport. Some measures are aimed at limiting the use of private cars: the introduction of additional taxes, paid parking, and paid entry into the city center. This approach requires much less capital investment in the development and subsequent maintenance of the road network.

The most efficient strategy for the development of the transport system is to find a compromise involving a balance between different modes of transportation, which allows setting up an integrated multimodal transport system [8, 9]. The practice of road traffic organization shows that in reality there is no single mode of transport able to satisfy all the human needs for transportation. An effective transport system should offer transportation services combing both individual and mass modes of transportation.

Modern cities face traffic congestion of varying degrees, which indicates ineffective traffic organization [10]. The traffic capacity of the road network is determined by the capacity of its individual components, such as space intervals, signal-controlled intersections, and artificial structures. Road sections with limited traffic capacity, including signal-controlled intersections, have a particularly significant impact [11-14]. Elements of the road network are often used at urban signal-controlled intersections to channel traffic flows. A turn storage lane is one of them [15-18].

This study considers the use of turn storage lanes to optimize left-turn traffic flows. The improvement of traffic organization at urban signal-controlled intersections using turn storage lanes reduces traffic delays and minimizes the number of vehicle changes in the flow. Such lane-changes are also associated with bypassing the forming traffic queues in left-turn directions. Therefore, the resources of a signal-controlled intersection with turn storage lanes can be used most efficiently through the understanding of the most effective use of the turn storage lane length relative to the traffic light control cycle and the traffic capacity of the signal-controlled intersection.

To this end, the purpose of the study is to develop a mathematical model describing the formation of a traffic queue depending on the traffic capacity of urban signal-controlled intersections and weather and climate conditions.

The object of this study is the formation of traffic queues within the urban street and road network, and the subject is the patterns of changes in the length of traffic queues that occur at signal-controlled intersections in left-turn directions.

The methodological framework of the study is the systems approach, including systems analysis and synthesis; mathematical statistics; mathematical and simulation modeling; correlation, regression analysis; experimental design theory.

Analytical studies

Simulation modeling was carried out using the PTV Vissim software suite to assess the effect of introducing a turn storage lane at urban signal-controlled intersections.

The simulation model reflecting the key features of the transport system elements enables to analyze the impact of various traffic organization methods without interfering with the real process, as well as to obtain extensive data and assess both the current and expected traffic situation [19-21]. Figure 1 shows the implemented simulation model.

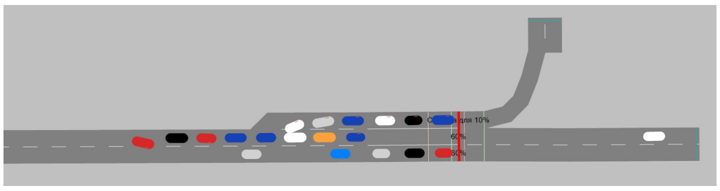

Fig. 1. Simulation model of the street and road network section

The implemented simulation model includes a turn storage lane and two lanes for the forward movement of vehicles. The model parameters are presented in Table 1.

Table 1

Simulation model parameters

Parameter	Value
Duration of the traffic light regulation cycle, sec	180
Forward traffic flow, vehicles/hour	900
Duration of the traffic light signal permitting the forward traffic flow, sec	40
Left-turn traffic flow, vehicles/hour	300

We assessed two operation variants of a signal-controlled intersection with different durations of the traffic light go signal for the left-turn direction: 20 and 25 seconds, respectively.

Traffic parameters were determined for each variant with a gradual increase in the length of the turn storage lane (Table 2).

Table 2

Vehicle delays depending on the length of the turn storage lane

Length of the turn storage lane, vehicles	Traffic delay during the go traffic light signal, sec/vehicles	
	20 seconds	25 seconds
0	405.06	404.84
11	270.77	224.07
12	188.36	148.33
15	125.94	95.28
18	120.93	68.38
23	117.12	65.54
24	113.85	61.43
26	106.03	66.16
32	105.62	64.99
36	106.26	62.51
39	103.94	64.52
41	101.98	63.49

Figure 2 graphically represents the numerical values of the simulation results.

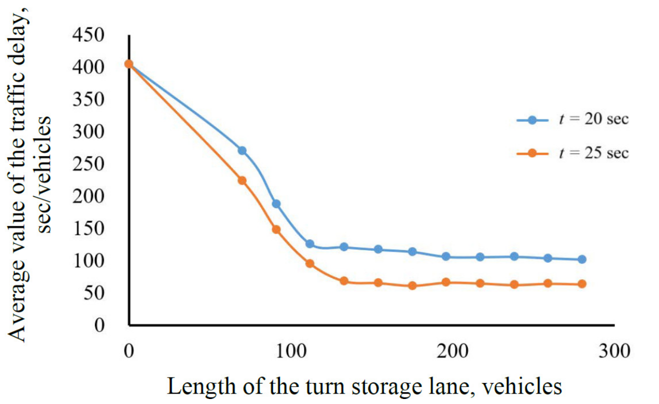

Fig. 2. Estimation of changes in traffic delays at different lengths of traffic queues and durations of the go traffic light signal

The analysis of the simulation modeling results shows that channeling the movement of vehicles at a signal-controlled intersection using a turn storage lane helps to reduce traffic delays. A further increase in the length of the turn storage lane does not change significantly the considered indicator of road traffic organization efficiency. Optical traffic capacity can be achieved if the time of the traffic light signal permitting movement for the left-turn flow is comparable to the length of the turn storage lane.

Besides, the turning traffic queue formed during the stop traffic light signal should be located in the turn storage lane. A process built in this way reduces the likelihood of an event when the traffic flow going forward needs to maneuver around the formed traffic queue or wait until the queue in the left-turn direction decreases, thereby freeing up the traffic lane.

The authors obtained linear models describing the length of the forming traffic queue depending on the residual traffic queue (1) and the road surface slipperiness (3) [15-18]:

$$Q = Q_0 + F \cdot Q_{res.\ queue}, \quad (1)$$

where $Q_{res.\ queue}$ is the average residual queue, vehicles; Q_0 is the length of the traffic queue, which is the number of vehicles that can pass during the traffic light regulation cycle; F is the coefficient reflecting the influence of the traffic light regulation cycle (2).

$$F = \frac{\left(1-\frac{g}{C}\right)}{1-\left[\min(1,Z)\frac{g}{C}\right]}, \quad (2)$$

where C is the duration of the regulation cycle, s; g is the duration of the go traffic light signal, s; Z_n is the lane loading level.

$$Q = Q_0 + P_{av.\ dry\ sur} \cdot W_s, \quad (3)$$

where W_s is the slipperiness coefficient (4); $P_{av.\ dry\ sur}$ is the number of vehicles passing in the road section during the traffic light regulation cycle on dry road surfaces, vehicles/cycle.

$$W_s = 1 - \frac{P_{av.\ sur}}{P_{av.\ dry\ sur}}, \quad (4)$$

where $P_{av.\ sur}$ is the number of vehicles passing in the road section during the traffic light regulation cycle depending on the road surface slipperiness, vehicles/cycle.

At the first stage of framing the mathematical model, we chose the dependence type (multiplicative or additive). To this end, the following should be established [22]:

1. Whether the desired dependence is monotonic.

The desired dependence is monotonic because regularities (1) and (3) are linear.

2. The behavior of function Y at $X \to 0$ and $X \to \infty$.

If $Q_{res.\ queue}$ is equal to zero, the demand for movement does not exceed the number of requests processed by the traffic light signal in the left-turn direction. The forming transport queue Q does not exceed Q_0. When the traffic light signal operates in normal mode, $Q_{res.\ queue}$ cannot be more than the queue Q. That is, at $Q_{res.\ queue} = Q$, it turns out that during the cycle, no vehicle was able to cross the intersection. Such a traffic state at the intersection is exceptional and results from random events, such as, for example, road accidents. Under normal operating conditions of the traffic light signal, $Q_{res.\ queue} \to 0$ and, therefore, $Q(Q_{res.\ queue}) \to Q_0$.

The following expression is also true Q_0, $Q(W_s) \to Q_0$. The queue of vehicles grows with an increase in the road surface slipperiness. W_s at a dry road surface does not affect the traffic capacity and, therefore, is zero. In the warm season, when precipitation falls, the surface slipperiness increases briefly. However, over a certain period of time, the surface dries restoring its original characteristics. In winter, when icy conditions appear, roads are subjected to special treatment to reduce the roa surface slipperiness. Thus $W_s \to 0$.

3. Points of the factor space that obligatorily belong to the graphical display of the response function.

Let us take the coordinate space *XYZ*, where *X* is the variable of $Q_{res.\ queue}$, vehicles; *Y* is the variable of W_s; *Z* is the response function of *Q*, vehicles. The graph of the response function *Z* will be a certain surface, which should necessarily pass through point $(0;Y;Z)$ taking into account items 1 and 2 of this algorithm.

4. The influence of factors on the response function.

Above points 1–3 show that zeroing the factors does not zero the response *Q*. In case of unsaturated traffic flows within the urban street and road network $Q \to Q_0$.

The traffic queue grows with an increase in the intensity of the traffic flow and the road surface slipperiness. When the traffic demand corresponds to the traffic capacity of the signal-controlled intersection and the length of the turn storage lane, the time of traffic delays does not increase. Otherwise, the length of the traffic queue *Q* exceeds Q_0, which leads to the formation of a traffic jam.

The nature of the behavior of the response functions indicates that the multifactorial mathematical model should be configured based on the general form of the additive model. Therefore, it is assumed that the change in the length of the traffic queue under the influence of the residual traffic queue and the road surface slipperiness is described by a two-factor linear additive model based on the main effects:

$$Q = Q_0 + F \cdot Q_{res.\ queue} + P_{av.\ dry\ sur} \cdot W_s \qquad (4)$$

Experimental studies

A natural, passive experiment was carried out to confirm the formulated assumptions under the experimental studies. It consisted of the following stages:

1) establishing the necessary intersections to carry out experimental studies;

2) collecting and processing the initial information on the parameters of traffic light regulation, as well as the characteristics of traffic flows and the road surface slipperiness;

3) analyzing the obtained data, determining the parameters of the mathematical model, and assessing its adequacy.

The following restrictions, assumptions, and conditions were introduced for the correctness of the studies:

1) the turning traffic flows can move either in a separate traffic light regulation phase, or simultaneously with the direct preceding traffic flow without intersecting with oncoming flows within the same traffic light regulation phase;

2) data are collected under the conditions of high traffic flow density;

3) when collecting data within the studied street and road network section, traffic accidents and road works able to affect the traffic capacity should be completely excluded.

The necessary intersections meeting the stated conditions were selected to implement the experiment. The time for the experiment was set based on the traffic density of traffic flows, with most typical ‘rush hours’.

The data were collected from 2018 to 2024. Thus, the experiments were conducted at more than 20 intersections in Tyumen, Vologda, Chelyabinsk, Ufa and other Russian cities. As a result of the gross error check of the sample, the number of measurements was 759. Figure 3 presents the results of experimental data collection.

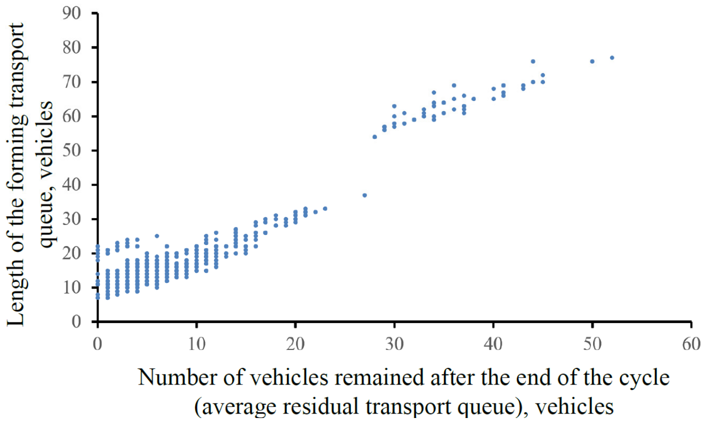

Fig. 3. Aggregate sample of experimental data

The initial data were processed using the STATISTICA 10 software suite, which resulted in the graphical image of the interaction of the residual traffic queue and the road surface slipperiness affecting the length of the forming traffic queue (Fig. 4).

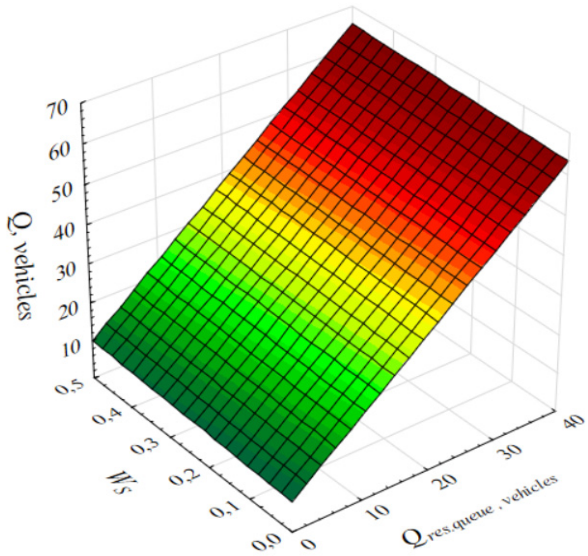

Fig. 4. The influence of the residual traffic queue and the road surface slipperiness on the length of the forming traffic queue

The experimental studies showed that the residual traffic queue has a significant effect on the length of the traffic queue formed when the traffic flow crosses a signal-controlled intersection in the left-turn direction. An increase in the residual traffic queue indicates worsening in road traffic organization and traffic jamming. The efficiency of road traffic organization decreases due to an increase in the intensity of traffic flows or a decrease in the traffic capacity of the street and road network section. It was also established that changes in the road surface slipperiness affect the traffic capacity of the signal-controlled intersection. Thus, the combined effect of the residual traffic queue and the road surface slipperiness is reflected in the change in the length of the forming traffic queue. An unfavorable manifestation of this effect may be linked with an increase in the traffic flow intensity and worsening of weather conditions that change the characteristics of the road surface, such as an increase in the level of slipperiness. Ultimately, the speed of vehicles decreases and traffic delays increase when crossing a signal-controlled intersection increase. These factors should be taken into to develop traffic management models aimed at minimizing transport losses when moving around the city and increasing the traffic capacity of signal-controlled intersections.

The experimental studies allowed defining the main parameters and statistical characteristics for the multifactorial mathematical model, as well as determining and analyzing their numerical values (Table 3).

Table 3

Parameters and statistical characteristics of the proposed mathematical model

Model parameters			Determination coefficient R_2	Table value of Student's criterion *t*	Calculated value of Student's criterion *t*	Calculated Fisher's criterion *F*	Table Fisher's criterion $F_{0.9}$
a, vehicles	*b*	*c*, vehicles/cycle					
1.4	4.8	7.7	0.9	8.85	19.88	18.03	3.27

The obtained statistical characteristics allowed concluding that the developed mathematical model is adequate and reliable. Ultimately, the experimental studies confirmed the proposed assumption about the mathematical model type.

The research findings revealed the significance of the influence of such factors as the residual traffic queue and the road surface slipperiness on the formation of a traffic queue in turn storage lanes when the traffic flow moves in the left-turn direction, which provides a basis for the further improvement of urban traffic management methods.

Conclusion

The studies revealed new dependencies aimed at improving traffic accessibility within the urban transport network. This improvement can be achieved by reducing transport delays, which is ensured by optimizing road traffic through traffic flow channeling at urban signal-controlled intersections. The most significant conclusions include:

1. The study established that the organization of road traffic as one of the most significant elements of the transport system should be improved to maintain a variety of travel options along urban transport systems. One of such methods is the introduction of turn storage lanes at intersections.

2. Simulation modeling carried out in the PTV Vissim software suite established that an infinite increase in the length of the turn storage lane does not significantly increase the traffic capacity of the intersection and decrease the time of transport delays. To ensure the most efficient use of the traffic capacity of a signal-controlled intersection, the time of the traffic light signal permitting movement for the left-turn flow should comparable to the length of the turn storage lane.

3. The authors configured a multifactorial mathematical model describing the change in the traffic queue and developed a two-factorial linear additive mathematical model describing the formation of a traffic queue at a signal-controlled intersection in the left-turn direction.

4. The experimental studies included the collection of initial data at more than 20 signal-controlled intersections in different Russian cities. The sample size of the initial experimental data was 759 values. The experimental studies established that the combined effect of the residual traffic queue and the road surface slipperiness is manifested in changes in the length of the forming traffic queue.

5. The further prospect for research and improving the obtained results can be the refinement of the proposed mathematical model taking into account other possible factors and developing a methodology for the practical application of traffic flow channeling at urban signal-controlled intersections.

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МОДЕЛИРОВАНИЕ ПРОЦЕССА ФОРМИРОВАНИЯ АВТОТРАНСПОРТНОЙ ОЧЕРЕДИ НА ГОРОДСКИХ РЕГУЛИРУЕМЫХ ПЕРЕСЕЧЕНИЯХ

Морозов Вячеслав Валерьевич, *Тюменский индустриальный университет, г. Тюмень, Россия,* **morozov1990_72@mail.ru**

Морозов Георгий Николаевич, *ООО "Рокада", Свердловская обл., с. Байкалово, Россия,* **morgn11@yandex.ru**

Шепелёв Владимир Дмитриевич, *Южно-Уральский государственный университет (национальный исследовательский университет), г. Челябинск, Россия,* **shepelevvd@susu.ru**

Представленные результаты исследования получены в рамках выполнения проекта гранта РНФ № 23-79-01021 "Исследование процесса управления транспортными потоками в городах на основе нейросетевых технологий", 2023-2025 гг.

Аннотация

Исследование затрагивает проблемы транспортных систем городов, их структуру и вопросы комплексного развития. Объектом данного исследования является процесс формирования транспортных очередей на городской улично-дорожной сети, а предметом – закономерности изменений длины транспортных очередей, возникающих на регулируемых пересечениях в левопоротных направлениях. Цель исследования – разработка математической модели формирования транспортной очереди в зависимости от пропускной способности городских регулируемых пересечений и погодно-климатических условий. Методологической базой исследования являются: системный подход, включая системный анализ и синтез; математическая статистика; математическое, имитационное моделирование; корреляционный, регрессионный анализы; теория планирования эксперимента. В ходе проведения исследования установлено, что организация дорожного движения является значимым элементом городской транспортной системы современных городов. Устойчивое функционирование транспортной системы города напрямую зависит от эффективности организации дорожного движения. Одним из методов оптимизации дорожного движения на регулируемых перекрестках является использование поворотно-накопительных полос. Имитационное моделирование, проведённое с использованием программного обеспечения PTV Vissim, продемонстрировало, что внедрение поворотно-накопительных полос способствует увеличению пропускной способности регулируемых перекрёстков и снижению транспортных задержек. Однако неоправданное удлинение этих полос не приводит к значительному росту пропускной способности. В ходе аналитических исследований была создана линейная, двухфакторная, аддитивная математическая модель, которая описывает процесс изменения длины транспортной очереди на регулируемых перекрёстках. В отличие от уже существующих моделей, новая модель учитывает влияние остаточной транспортной очереди и скользкости дороги. Проведены экспериментальные исследования на более чем 20 регулируемых перекрёстках в городах Российской Федерации, в ходе которых собран объём выборки, составивший 759 измерений. Анализ полученных данных показал, что существует эффект совместного взаимодействия между остаточной транспортной очередью и скользкостью дорожного покрытия, оказывающий влияние на длину формирующейся транспортной очереди.

Ключевые слова: *канализирование транспортных потоков, поворотно-накопительная полоса, транспортная очередь, регулируемое пересечение, транспортная система города. имитационное моделирование, PTV Vissim*

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Информация об авторах:

Морозов Вячеслав Валерьевич, *Тюменский индустриальный университет, доцент кафедры транспортных и технологических систем, канд. техн. наук, г. Тюмень, Россия, ORCID: 0000-0001-6840-1247*

Морозов Георгий Николаевич, *ООО "Рокада", инженер I категории, канд. техн. наук, Свердловская обл., с. Байкалово, Россия*

Шепелёв Владимир Дмитриевич, *Южно-Уральский государственный университет (национальный исследовательский университет), доцент кафедры "Автомобили и автомобильный сервис", канд. техн. наук, доцент, г. Челябинск, Россия, ORCID: 0000-0002-1143-2031*