International Journal of Mathematical, Engineering and Management Sciences
Vol. 11, No. 4, 1663-1679, 2026
https://doi.org/10.33889/IJMEMS.2026.11.4.068

Modelling of the Process of Vehicle Queue Formation at Controlled Intersections

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(Received on December 23, 2025; Revised on March 21, 2026 & May 22, 2026; Accepted on June 18, 2026)

Abstract
Traffic congestion is one of the most significant and still unsolved problems of modern cities. Turning traffic flows further aggravate this problem. Channelizing vehicle traffic generally has a significant impact on road traffic. Complete reconstruction of road network sections to channelize traffic flows is not a flawless traffic management option. A relatively cheap way to channelize traffic is construction of turn lanes. Such lanes are characterized by a relatively shorter length compared to a full lane for motor vehicles. In order to achieve effective channelization of traffic flows, the turning traffic queue should be stored within the turning lane. This will reduce the influence of the turning traffic flow on the overall process of vehicle movement at the intersection. The aim of the presented research is to obtain a mathematical model describing the formation of motor vehicle queues approaching urban controlled intersections in turning directions. In the course of the study, the authors developed a hypothesis that the formation of vehicle queue length can be described by a two-factor linear additive model. Experimental studies, which were planned and conducted at more than 20 controlled intersections in different cities of the Russian Federation, confirmed the hypothesis. Ultimately, the authors of the study proposed a mathematical model that can be used to design new or adjust existing traffic light cycles at controlled intersections in cities.

Keywords- Turn-storage lane, Traffic management, Controlled intersections, Channelization of traffic flows, Road network.

1. Introduction

The interaction of traffic and pedestrian flows within urban transport networks is a complex process. To a large extent, urban design depends on the applied methods of transport services for the population (Petrova et al., 2020; Yang et al., 2012; Zakharov et al., 2018).

The strategy of transport services for the population based on stimulating the satisfaction of the population's need to travel by individual cars forms an urban space that adapts to extensive car usage (Noy & Givoni, 2018; Shepelev et al., 2020). As a result, pedestrian traffic and public transport are poorly developed. The road network is actively expanding, primarily due to construction of roads.

One of the main advantages of using individual cars is the possibility to travel at any time, as well as actual door-to-door travel. However, the mass use of cars exclusively within large urban transport systems is an unacceptable solution to the issue of transport services for the population. The continuous growth of the city road network leads to further stimulation of the growth of motorization level (Morozov et al., 2022; Petrov & Petrova, 2020; Zhankaziev, 2017). The situation becomes even more complicated in cities with historically established dense urban development. As the road network expands, it requires more and more investments in its maintenance (repair, keeping the road surface clean, treatment with anti-icing agents, etc.).

The most rational solution is balanced urban development, which implies that different modes of transport are available to the public (Diao, 2019; Wang et al., 2020). There is no such type of transport that can single-handedly meet all the needs of the city within acceptable costs.

Almost every modern city faces the problem of traffic congestion. Traffic congestion indicates the inefficiency of traffic organization (Deryabin, 2022; Karmanov et al., 2018; Nallathambi & Principe, 2020; Olayode et al., 2020; Stasi et al., 2022). The road network capacity is determined by its lower capacity sections. One of such sections are controlled intersections. (Han et al., 2021; Nadrian et al., 2022; Song et al., 2022). To minimize the impact of traffic congestion, it is important to identify the hidden capacity resources of the road network. Therefore, this study aims at solving the scientific and practical problem of improving traffic management efficiency at urban controlled intersections. In this matter, it makes sense to pay the greatest attention to the movement of traffic flows in turning directions. For this purpose, we need to develop a mathematical apparatus describing the formation of traffic queues when moving in turning directions. Thus, the aim of this study is to develop a mathematical model describing the formation of traffic queues at urban controlled intersections in turning directions.

Ultimately, the authors developed a two-factor linear additive model describing the formation of queue lengths. Unlike existing solutions, the proposed model is based on the influence of the residual queue and road surface slipperiness on changes in the length of the developing queue.

2. Analyzing the State of the Issue

For many years, the world has maintained an active rate of motorization (Wei et al., 2020; Zhang et al., 2022). When the capacity of the road network is inadequate, traffic congestion happens. Creating a balanced transport system is an urgent problem for the administrative, engineering and scientific communities.

A common method of traffic organization is separation of vehicles and pedestrians in space. This method involves directing flows along the most optimal trajectories thereby increasing traffic capacity and safety. However, large-scale transformation of intersections in order to increase the level of channelization of traffic and pedestrian flows is not always a rational variant of traffic organization (Chen & Jia, 2021; Visan et al., 2022).

On each approach to an intersection, at least three lanes should be provided. This allows for a convenient distribution of traffic flows by directions (Hu et al., 2022; Ouallane et al., 2022; Zhang & Su, 2021). As a rule, the intensity of turning traffic flows is not more than one third of the total flow (Li & Lasenby, 2023). It is more rational to direct turning traffic flows to lanes of shorter length.

The analysis of earlier studies shows that for many years scientists have been considering the issues of traffic flow channelization and specifically the convenience of traffic flow distribution at an intersection with three lanes (Azcuy et al., 2021; Batishcheva & Ganichev, 2018; Giuffrè et al., 2018; Grote et al., 2021;

Lécureux & Kaddoura, 2021; Madaan & Sharma, 2022; Navarro-Ligero & Valenzuela-Montes, 2022; Pérez-Acebo et al., 2021; Ramirez-Polo et al., 2022; Roy et al., 2017; Sala & Soriguera, 2021; Zhuang et al., 2020). The use of left-turn lanes helps to increase road safety.

For the considered method of channelization, the authors propose the definition of a turn-storage lane. From the authors' point of view, this term is defined as an additional lane in the immediate vicinity of the intersection, allocated structurally or by road markings and intended for movement of traffic flows in turning directions (**Figure 1**).

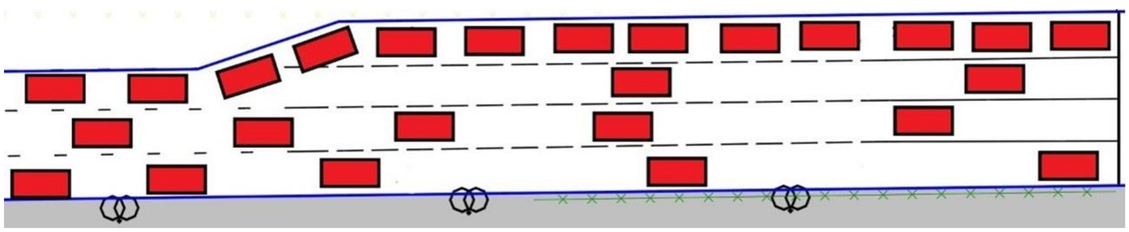

Figure 1. Enlarged scheme of traffic flows at an intersection with a turn-storage lane.

Figure 1 shows that the length of the turn-storage lane plays a key role in channelization of the turning flow. This parameter needs to be determined due to the following reasons:
- A turn-storage lane of short length will not lead to the desired level of channelization of turning flows;
- Excessive length leads to cost overruns (including urban space).

One way or the other, current methodologies that are designed to size the length of turn-storage lanes are related to the estimation of vehicle queues (Chacoma et al., 2021; Enjalbert et al., 2020; Krylatov et al., 2020; Liu et al., 2021). Unfortunately, these methodologies do not fully take into account the influence of residual vehicle queues and pavement conditions.

Precipitation and changes in ambient temperatures significantly impact vehicle movement by altering the traction characteristics of the road surface. As road surface slipperiness increases, the dynamic clearance of vehicles changes, ultimately reducing the number of vehicles served per traffic signal cycle. Reduced throughput at controlled intersections contributes to longer queues.

When throughput at a controlled urban intersection is reduced, vehicle delays increase. When implementing traffic management improvements, it is essential to strive to reduce vehicle delays.

The key result of the analysis of earlier works can be considered the following conclusion: to determine the optimal length of the turn-storage lane, the length of the forming vehicle queue should be taken into account. This indicator has an impact on the process of vehicle channelization. This paper will study its influence on the process given the residual vehicle queue and the condition of the road surface.

Unlike existing solutions, the proposed model is based on the patterns of influence of the residual vehicle queue and the slipperiness of the road surface on changes in the length of the forming vehicle queue.

3. Methods and Materials

The authors have identified the primary focus of their research as ensuring accessibility to the urban transportation network by reducing traffic delays through improved traffic management based on channelizing traffic flows at controlled intersections. To this end, they propose developing a mathematical model describing the formation of vehicle queues in turning directions at controlled intersections.

The methodological basis of the study is a systems approach. Systems analysis and synthesis were chosen as more specific methods within the framework of this approach. Based on the methodology, a preliminary selection of factors was made influencing the system under study and the processes taking place in it. To do this, the results of earlier studies were considered and studied. Further, the authors divided the list of factors into the following categories (**Figure 2**): vehicle delays that arise due to the need to rearrange cars to bypass the turning traffic queue; vehicle delays due to the operation of traffic lights on the road network; vehicle delays that arise due to other factors.

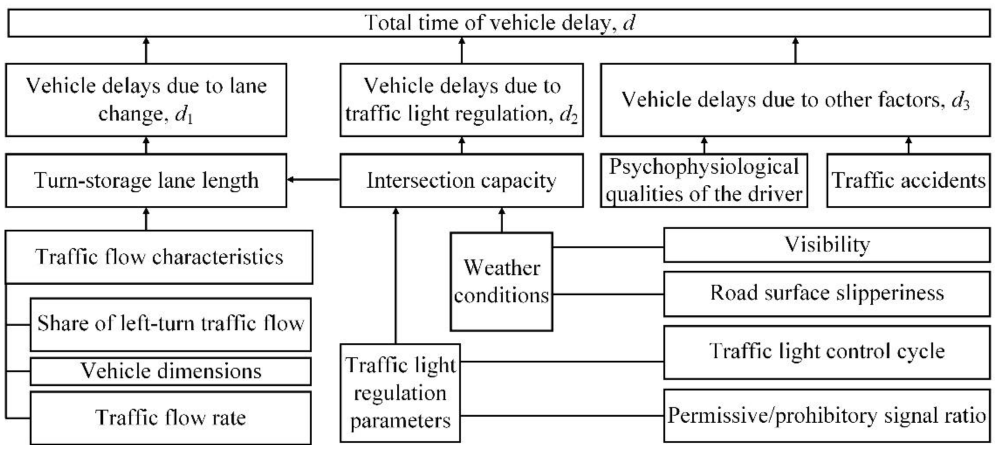

Figure 2. Result of the preliminary selection of factors and structuring of the system under study.

The first category of vehicle delays is directly related to the need to bypass a left-turn traffic queue. Such queues occur due to waiting for an opportunity to make a left turn (Bharadwaj et al., 2018). Vehicles in such a queue occupy the lane for vehicles travelling in the forward direction thereby reducing the efficiency of road traffic. Delays in this category tend to zero when the influence of left-turning traffic flow is reduced.

The second category of vehicle delays is a constant for controlled intersections. In the traffic light control process, delays occur mainly due to traffic signal prohibitions and time losses during the traffic light control cycle.

The third category includes accidental delays caused by driver's individual qualities, traffic accidents on the urban transport network, etc. In the study, the indicator of driver's individual qualities is taken as an average value. The data obtained in the presence of road accidents and road construction works, which in one way or another could interfere with the movement of traffic flows, were excluded in order to improve the purity of experimental research.

The paper considers left-turn directions as reducing traffic capacity and safety at urban intersections the most.

In order to reduce the impact of left-turn traffic queue on vehicle movement, it is necessary to organize channelization at intersections. The left-turn traffic queue should be accommodated within the turn-storage lane. This eliminates the occurrence of additional traffic delays. These delays are due to the need to realign vehicles bypassing the turn queue. Taking into account the previously considered factors, the boundaries are valid for the system:

$$\begin{cases} d_1 \geq 0 \\ d_2 = t_{proh} + t_L \\ d_3 \geq 0 \end{cases} \tag{1}$$

where, d – total cumulative time of average vehicle delay, s; d_1 – delays including factors of the first category, s; d_2 – delays including factors of the second category, s; t_{proh} – duration of the prohibiting traffic signal in the regulation cycle, s; t_L – lost time in the total duration of the traffic light cycle, s; d_3 – delays including factors of the third category, s.

Thus, the target function of the study is as follows:

$$d = d_1 + d_2 + d_3 \rightarrow \min \tag{2}$$

In practice, the length of the vehicle queue is calculated by the following mathematical expression (He et al., 2019):

$$Q = Q_1 + Q_2 \tag{3}$$

where, Q – vehicle queue length, vehicles; Q_1 – first component of vehicle queue formation, vehicles; Q_2 – second component of vehicle queue formation, vehicles.

Expressions (4)-(6) are based on the formulas for calculating delays given in the "Highway Capacity Manual." This practical guide has a scientific basis and is used in road traffic practice in many countries worldwide. The variable Q_1 in formula (3) represents the uniform arrival of vehicles to the controlled intersection:

$$Q_1 = \frac{\frac{N_{turn} \cdot C}{3600} \cdot \left(1 - \frac{g}{C}\right)}{1 - \left[\min(1, X_{lane}) \frac{g}{C}\right]} \tag{4}$$

where, N_{turn} – vehicle traffic flow rate in the turning direction, vehicles/hour; C – total duration of the traffic light control cycle, s; g – duration of the signal permitting the movement of vehicles, s; X_{lane} – level of lane utilization by vehicles.

In turn, Q_2 in formula (3) should be considered in terms of random arrival of vehicles:

$$Q_2 = 0,25 C_{lane} T \left[(X_{lane} - 1) + \sqrt{(X_{lane} - 1)^2 + \frac{8 k_r X_{lane}}{C_{lane} T}} \right] \tag{5}$$

where, C_{lane} – lane capacity of vehicle traffic, vehicles/hour; T – measurement period, hour; k_r – reduction factor.

In formula (4) it is possible to temporarily replace the right side of the mathematical expression by a new coefficient:

$$F = \frac{\left(1 - \frac{g}{C}\right)}{1 - \left[\min(1, X)\frac{g}{C}\right]} \tag{6}$$

Consequently, formula (4) is transformed to the following form:

$$Q_1 = \frac{N_{turn} \cdot C}{3600} \cdot F \tag{7}$$

Analyzing the left side of formula (7), we can see that it represents the average number of cars per one cycle of traffic light regulation. We need the value of the constant in the denominator is necessary to further convert the result of the original value to its hourly equivalent. Thus, formula (7) takes the form:

$$Q_1 = \frac{N_{turn}}{n_C} \cdot F \tag{8}$$

where, n_C – number of traffic light control cycles in the time period under study.

It is also possible to represent the traffic flow rate per turning direction as two additive components:

$$N_{turn} = N_{Ctl} + N_{res} \tag{9}$$

where, N_{Ctl} – the total number of vehicles passing through the controlled intersection under study without stopping during the allotted time of the traffic light signal allowing traffic, vehicles/hour; N_{res} – the number of vehicles that have to pass with a stop due to the end of the permissive signal, vehicles/hour.

To assess the formation of a vehicle queue in the left-turn direction, we propose to use the residual queue length as a factor describing the interaction between traffic signal control and traffic flow rate. The need to consider the residual queue length was first described in the works of American scientist D. Drew, who characterized the formation of a vehicle queue as a measure of traffic inefficiency (Drew, 1968).

Taking into account formula (9), formula (8) can be represented as follows:

$$Q_1 = \frac{N_{res}}{n_C} \cdot F + \frac{N_{Ctl}}{n_C} \cdot F \tag{10}$$

As a result, formula (3) takes the form:

$$Q = \frac{N_{res}}{n_C} \cdot F + \frac{N_{Ctll}}{n_C} \cdot F + Q_2 \tag{11}$$

The average residual queue can be represented as:

$$Q_{res.\,queue} = \frac{N_{res}}{n_C} \tag{12}$$

If we divide the traffic flow rate according to formula (9), we can formulate an assumption about the existence of the basic (minimum) value of the vehicle queue length. The basic value of the vehicle queue length is the minimum value that can be serviced during a traffic light control cycle without creating additional delays, which is formed from vehicles passing without stopping. This value can be represented as:

$$Q_0 = \frac{N_{Ctl}}{n_C} \cdot F + Q_2 \tag{13}$$

Formulas (12) and (13) allow us to transform formula (11), as a result it will take the following form:

$$Q = Q_0 + F \cdot Q_{res.\ queue} \tag{14}$$

Q_0 and F can be considered as constants within a single isolated controlled intersection. Thus, the formation of vehicle queue length depends on the residual queue. This dependence can be described by a linear model of the form:

$$Q = b + a \cdot Q_{res.\ queue} \tag{15}$$

In addition, the authors believe that the length of the forming queue is affected by the condition of the road surface due to precipitation combined with changes in ambient air temperature. First of all, it is expressed in reduced traction qualities of the road surface, increased resistance to movement, deterioration of orientation conditions on the terrain and other similar phenomena and processes (Muñoz-Villamizar et al., 2020). Winter is the most challenging period for vehicle traffic. During the winter, the vehicle's dynamic dimensions change significantly (Choi & Ewing, 2021). This process is most clearly described by the microscopic model of Tanaka:

$$d_V = L_{car} + c_1 V + c_2 V^2 \tag{16}$$

where, d_V – dynamic vehicle dimensions, m; V – average vehicle speed, m/s; c_1 – mean value of the driver's reaction time to road traffic events, s; c_2 – value of the braking distance proportionality factor, s^2/m; L_{car} – value of the average vehicle length in the traffic flow, m.

The signalized intersections under study are typically part of the public transport network. In most developed countries, high-quality road surfaces are maintained through roadway maintenance for passenger transportation in cities. Therefore, the impact of roadway maintenance is not considered in this study.

It is proposed to determine the capacity of a controlled intersection using the following formula:

$$P_s = 3600 \cdot \frac{t_e - t_\Delta}{t_L \cdot T_C} \tag{17}$$

where, P_s – number of vehicles passing through the controlled intersection in the direction of traffic under consideration, vehicles/hour; t_e – duration of permissive signal, s; t_L – average vehicle traffic interval, s; T_C – total duration of the traffic light control cycle, *s*.

The dynamic vehicle dimension in model (16) is expressed in meters, and in model (17) in seconds, therefore, let us define t_L as

$$t_L = \frac{d_V}{V} \tag{18}$$

Using formulas (16)-(18), a study was conducted to examine the impact of road surface slipperiness on lane capacity, depending on weather conditions. The change in lane capacity at a controlled intersection was assessed under wet and icy road surface conditions relative to the capacity under dry road surface conditions. Based on the models, a coefficient was derived that takes into account road surface conditions:

$$K_{sur} = \frac{P_{av.\,sur}}{P_{av.\,dry\,sur}} \tag{19}$$

where, K_{sur} – road surface condition coefficient; $P_{av.\,sur}$ – value of lane capacity in case of wet or icy road surface, vehicles/cycle; $P_{av.\,dry\,sur}$ – capacity value under basic conditions (dry pavement), vehicles/cycle.

Road surface slipperiness occurs when wet or icy precipitation is present on the road surface. In fact, while road surface slipperiness varies depending on weather and climate conditions. The formation of icy conditions requires the road surface to be wet. The reduction in capacity due to the impact of road surface condition can be expressed as:

$$W_s = 1 - K_{sur} \tag{20}$$

where, W_s – coefficient of reduction of lane capacity taking into account dynamic dimensions of vehicles.

Considering the formation of the base value of the vehicle queue, let us write down the following expression:

$$Q = Q_0 + P_{av.\,dry\,sur} \cdot W_s \tag{21}$$

Thus, a linear model represents the influence of road surface condition on the length of the forming vehicle queue:

$$Q = b + a \cdot W_s \tag{22}$$

For the subsequent formation of a two-factor mathematical model, we used the recommendations reflected in Santos-González et al. (2019) and Tian et al. (2021). The resulting patterns are linear, indicating the monotonicity of the function. Zeroing out the factors does not result in zero response. During transport service, under unsaturated conditions, $Q \rightarrow Q_0$. As demand for travel increases, the emerging vehicle queue grows. When the traffic flow rate per traffic light cycle corresponds to the number of vehicles passing per traffic light cycle, the queue does not grow. Increasing the load on the controlled intersection leads to an increase in the output parameter. As a result of theoretical research, the working hypothesis is formulated, which is as follows: the process of formation of vehicle queue length under the influence of residual vehicle queue and road surface condition is described by a two-factor linear additive model on the main effects:

$$Q = Q_0 + F \cdot Q_{res.\,queue} + P_{av.\,dry\,sur} \cdot W_s \tag{23}$$

In order to confirm or refute the theoretical statements, experimental research must be planned and carried out. Experimentation includes the following steps:
1) identifying intersections that are suitable for the purposes of the study;
2) obtaining information about the intersections on their geometric parameters, traffic light control modes, traffic flow rate, etc.;
3) identifying patterns and parameters of the proposed mathematical models and checking their adequacy.

4. Results

Intersections with the following parameters were selected for the experiments:
1) the study examines urban intersections, so they must be located within city limits;

2) the intersections are controlled by traffic lights;
3) there are at least two lanes for vehicle traffic in one direction, with the leftmost lane dedicated to left-turn traffic;
4) left-turn traffic either moves during a separate traffic light phase, or flows with through traffic without intersecting with oncoming traffic during the traffic light phase.

The data collection process involved observing the intersections during peak traffic periods. Photo and video recordings were taken for one hour during a pre-designated time period. The process of photographing and video recording the required intersection was based on cameras installed at the controlled urban intersections, the live feed from which is publicly available online. The resulting data was then processed, including queue lengths and intersection capacity calculations, and recorded in the appropriate forms.

For the purpose of the study, urban controlled intersections in the Russian Federation were selected on the condition of mandatory presence of left-turn traffic flows. Data collection was carried out in the period of generally accepted peak hours. Based on the results of the selection, data was collected for more than 20 controlled intersections in different cities of the Russian Federation: Yekaterinburg, Chelyabinsk, Ufa, Tyumen, Vologda, Pskov, Kamensk-Uralsky.

Taking into account the limitations and assumptions introduced at the previous stage of the study, data collection was performed under the following conditions:
1) No conflict with oncoming traffic flow when the traffic flow is moving in the left-turn direction;
2) Initial experimental data collection is performed in conditions of saturated traffic flow, i.e. close to the saturation flow values;
3) Absence of road accidents and road construction works that may hinder the movement of vehicles on the road network.

The cumulative sample of input data is presented in **Figure 3**.

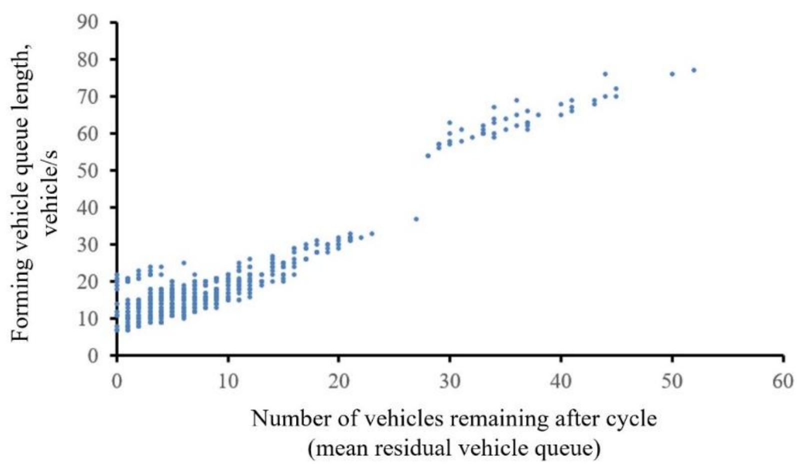

Figure 3. Results of initial data collection for experimental studies.

The sample size was 494 values. Preliminary data were divided according to the criterion of loading factor (**Table 1**).

Table 1. Results of distribution of initial measurements by load factor.

No.	Load factor X	Number of measurements
1	X>1	206
2	X<1	288

The results of processing of the initial experimental data showed that the values of the residual vehicle queue are stochastic and generally obey the exponential law of distribution of the random variable (**Figure 4**).

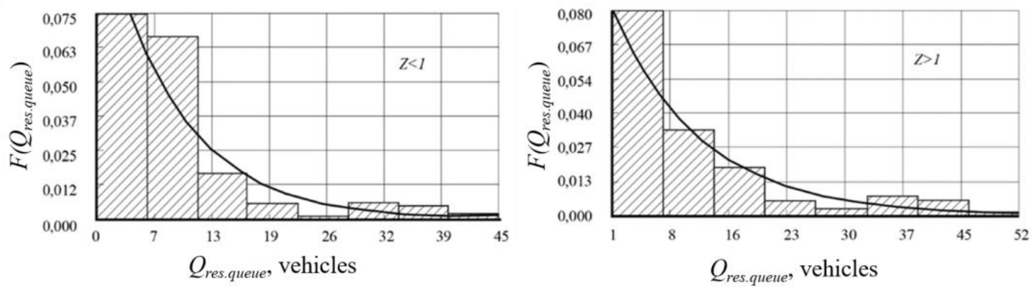

Figure 4. Histograms and their corresponding distribution curves of the residual vehicle queue random variable values.

The method of least squares was used to establish the existence of dependence between the variables under study (**Figure 5**).

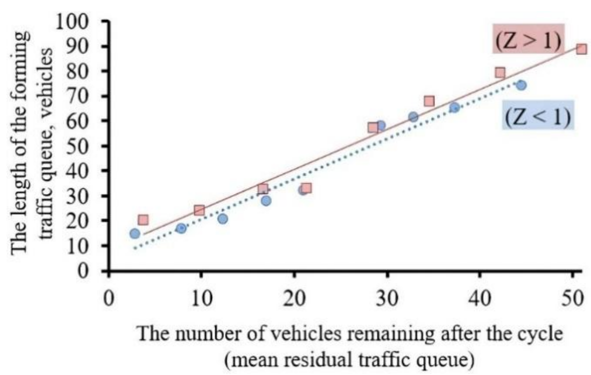

Figure 5. Length of the forming vehicle queue depending on the load factor of the turning direction of traffic.

Numerical values of parameters and statistical characteristics were determined for the obtained mathematical models (**Table 2**).

Table 2. Results of determination of statistical characteristics and numerical values of parameters of the model (15).

No.	Load factor	Parameters of the model		Correlation factor r	Determination coefficient R^2	Student's t-test. $t_{tabulated\ value}$	Student's t-test, $t_{true\ value}$	Fisher's dispersion ratio, F	Fisher's criterion, $F_{0.90}$
		a	b						
1	X > 1	1.58	8.58	0.98	0.96	1.63	15.34	25.85	5.99
2	X < 1	1.63	4.38	0.98	0.96	1.39	13.47	28.02	5.59

Figure 6 shows the graphical representation of model (22). The analysis of the obtained results showed the following. Deterioration of the traction characteristics of the road surface increases the dynamic range of car movement. Eventually, the capacity of the controlled intersection decreases. As a result, the length of the formed traffic queue also increases (**Figure 6**).

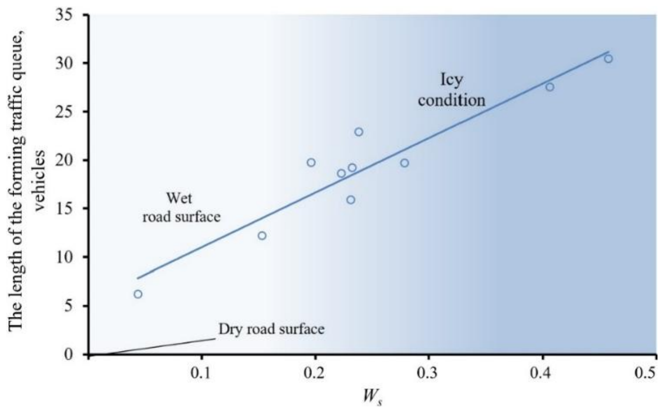

Figure 6. Change in the length of the forming vehicle queue under the influence of the road surface condition.

Numerical values of parameters and statistical characteristics were also determined for the mathematical model (22) (**Table 3**).

Table 3. Results of determination of statistical characteristics and numerical values of parameters of the model (22).

Parameters of the model		Correlation factor r	Determination coefficient R^2	Student's t-test, $t_{tabulated\ value}$	Student's t-test, $t_{true\ value}$	Fisher dispersion ratio, F	Fisher's criterion, $F_{0.90}$
a	b						
56.33	5.39	0.94	0.9	3.02	8.55	9.15	5.32

The surface is presented in **Figure 7**. This is the graphical representation of the combined influence of the considered factors on the length of the forming vehicle queue.

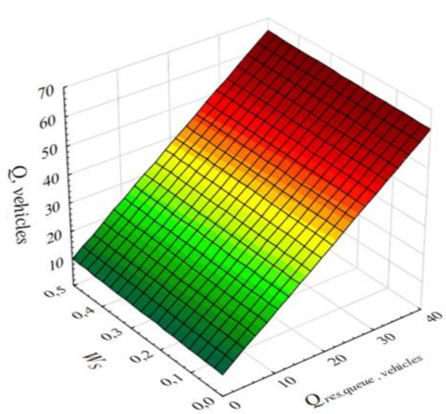

Figure 7. Combined influence of factors on the length of the forming vehicle queue.

Table 4 presents numerical values of statistical characteristics and parameters of the two-factor mathematical model.

Table 4. Numerical values of statistical characteristics and parameters of the two-factor mathematical model (23).

Parameters of the model			Correlation factor r	Determination coefficient R^2	Student's t-test, $t_{tabulated\ value}$	Student's t-test, $t_{true\ value}$	Fisher dispersion ratio, F	Fisher's criterion, $F_{0.90}$
a	b	c						
1.37	4.81	7.71	0.91	0.95	8.86	19.87	18.04	3.27

Thus, the results of experimental studies confirmed the previously developed theoretical provisions. The numerical value of the coefficient of determination in all cases was more than 0.82. The excess of the obtained Student's t-criteria confirms the significance of correlations. The excess of Fisher's criterion F relative to the tabulated value indicates the adequacy of the developed mathematical models in all cases.

5. Discussion

Traffic congestion remains an unsolved problem for many modern cities in the Russian Federation and all over the world. Studies of road traffic processes explain the existence of this problem by the high level of motorization. Also, the formation of traffic congestion depends on the nature of applied methods of transport service of the city population.

The use of turn-storage lanes can serve as one of the ways, if not to solve the whole problem, then at least to reduce its negative consequences. In some cases, it is possible to increase the carriageway of the road to three lanes, to allow vehicles in the middle lane to turn left. In the future, middle lanes can be converted for public transport by introducing BRT systems or rail transport systems.

Channelizing traffic flows has a significant impact on the capacity of the road network and road safety. The total number of conflict situations is reduced, which leads to a decrease in the psychophysiological load on drivers.

Mathematical models obtained as a result of the research have practical application in regions with humid climate and harsh operating conditions. In regions with minimal precipitation, the influence of the climatic component of the obtained Equation (23) will be insignificant.

Also, it should be noted that the presented results of the study are valid only under a number of limitations and assumptions, which are outlined at the beginning of Section 3 of this article. The authors recognize that the limitations and assumptions significantly narrow the scope of possible application of the study results. However, the limitations and assumptions are quite valid for many modern cities. For example, in the central part of the city the traffic flows are almost always saturated and intensive at least during daylight hours. For the same reason, the movement of traffic flow in the left-turn direction is carried out in a separate phase of traffic light regulation and has no conflict with oncoming traffic. Of course, the authors also understand that the occurrence of any traffic accidents (accidents, incidents, repair works, etc.) will have a significant negative impact on the capacity of the road network. However, since the formation of traffic queues in turning traffic directions is an incompletely studied process, the authors decided to exclude this largely stochastic factor. In the future, all the introduced restrictions and assumptions will put things in perspective for new research.

The resulting mathematical models can be directly used to adjust the traffic signal cycle depending on the methods used to channelize traffic flows at the intersection. The length of the existing turn-storage lane may not correspond to the length of the forming vehicle queue. To achieve this, it is necessary to adjust the traffic signal cycle based on traffic demand and the current length of the turn-storage lane. However, there are also situations in which it is impossible to find the ratio of traffic flow, turn-storage lane length, and traffic signal cycle that accommodates the forming vehicle queue in the turn-storage lane while maintaining an adequate traffic signal cycle in terms of time distribution for other traffic directions at the controlled intersection. Therefore, in such cases, it is necessary to select the required turn-storage lane length for the current or future conditions. This typically occurs during the development of measures to improve traffic management on urban transport networks.

Ultimately, the following practical applications of the research findings can be identified:
1) adjusting the traffic light control cycle to account for the current organization of the traffic flow channelizing process;
2) improving the traffic flow channelizing process at an urban controlled intersection by changing the length of the turning-storage lane.

Separating through traffic from left-turn traffic by using a turn-storage lane reduces the likelihood of turning vehicles blocking the through lane, improving traffic safety and overall intersection capacity. The economic benefit of this method is reduced fuel consumption due to reduced vehicle delays at the intersection. Reducing fuel consumption has a positive impact on the environment by reducing emissions of harmful substances such as CO, CH, NO_x, SO_2.

6. Conclusion

Based on expressions (1)-(22), mathematical modeling of the processes under study was performed. The result of the modeling is expression (23). The following conclusions present the most significant results of the study.
1) The parameters of traffic flows and the state of the road surface, which changes due to climatic conditions, play a significant role in the formation of traffic congestion.
2) Linear mathematical models describe the length of the forming vehicle queue depending on the above-mentioned indicators. The residual vehicle queue indicator obeys the exponential law of distribution of a random variable.
3) In the process of composing the multifactor mathematical model it is established that a two-factor mathematical model of linear type describes the process of formation of vehicle queue depending on the considered indicators.
4) The economic impact of implementing the study results could include a reduction in fuel consumption by vehicles idling at intersections. Preliminary calculations and analytical assessments have shown that adjusting traffic signal to account for the length of turn-storage lanes can reduce traffic delays by an average of 35%. Given the average fuel cost of one liter of AI-95 gasoline in the Russian Federation is 0.80 USD, the estimated economic impact of implementing the system for each controlled intersection over the course of a single weekday could reach 72 USD.
5) The purpose of further research is to expand the possibilities of the methodology of application of turn-storage lanes by improving the mathematical models obtained in the study; to work out the issue of right-turn flows, and to take into account the influence of factors that constitute the area of limitation within the framework of the presented work.

Ultimately, the authors developed a fundamentally new mathematical model describing the formation of a vehicle queue. Unlike existing solutions, the proposed model is the first to take into account the influence of the remaining queue of vehicles and the slipperiness of the road surface on the change in the length of the developing queue.

Conflicts of Interest
The authors confirm that there is no conflict of interest to declare for this publication.

Acknowledgments
The article was prepared within the framework of the implementation of the Russian Science Foundation (RSF) grant project № 25-29-01020 «Investigation of the possibilities of optimizing the functioning of urban transport systems using artificial intelligence», 2026-2027.

AI Disclosure
The author(s) declare that no assistance is taken from generative AI to write this article.

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