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DETERMINATION OF THE IMPACT OF TRAFFIC DELAYS AT SIGNALIZED INTERSECTIONS ON THE TRAVEL TIME OF A FIRE ENGINE TO THE PLACE OF A CALL

The paper outlines the problem of the influence of various factors, in particular traffic delays at signalized intersections, on the movement of a fire engine to the place of a call. The object of research is the process of queue formation of vehicles at a signalized intersection, which leads to delays of a fire engine during its response. The conditions for queue formation at signalized intersections were identified, under which the queue may reach its maximum value or remain in a continuous growth mode. Thus, prerequisites for further research were established, and the maximum traffic flow intensity of 1000 passenger car units was selected. Using simulation modeling in the PTV Vissim environment, a model of a signalized intersection with a two-lane approach was developed. This model enables simulation of intersection crossing by varying traffic flow intensity, signal cycle length, and the proportion of green time within each cycle. Experimental studies of the maximum queue length were conducted using the full factorial experiment method. A relationship was obtained to determine the maximum queue length at a signalized intersection as a function of traffic flow intensity, signal cycle length, and the proportion of green time in each cycle. The magnitude of the influence of each identified parameter on queue formation at the intersection was analyzed separately. It was established that increasing the proportion of the green signal from 0.20 to 0.50 reduces the queue length by approximately 35–40%. An increase in traffic intensity from 200 to 1000 passenger car units per hour leads to an approximately fourfold increase in queue length. The obtained relationships can be further used in the development of new or the improvement of existing models for determining optimal response routes of emergency vehicles to the place of a call, taking into account possible delays at signalized intersections.

Keywords: *signalized intersection, travel route, traffic delay, fire, travel time, fire engine.*

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1. Introduction

It is known that one of the key factors in effective fire extinguishing is the fastest possible arrival of fire and rescue units to the place of a call. This issue is also relevant for other operational services, where speed of action and arrival to the place of a call are important. The relevance of the outlined issue is also confirmed by the results of the study [1], which emphasizes the critical importance of the time of arrival of special vehicles to the place of a call. Vehicles of such services enjoy a number of advantages when driving on the city's street and road network. Of course, other road users are obliged to give priority to such vehicles. However, in practice, the effects on special vehicles in the "road conditions – traffic flows" system are often noticeable. A heavy-duty fire tanker will not always be able to bypass a traffic jam, unlike smaller vehicles (for example, a light-type special emergency rescue vehicle, etc.). Therefore, when choosing the optimal route for special vehicles to the place of a call, it is worth considering such a factor as a potential delay at a controlled intersection. It is here that a queue of vehicles in the traffic flow can form, waiting for the traffic light signal and the opportunity to continue moving.

The issues of minimizing travel time and optimizing routes for special vehicles are addressed in one way or another in a number of scientific publications. In [2] it is shown that even a slight delay in the arrival of a fire truck can cause a significant increase in the burning area. Here, a graph model for choosing the optimal route to the place of call is proposed. At the same time, such a model is static in nature and does not take into account the real parameters of traffic flows and the structure of the street and road network, which limits its practical application in modern urban traffic conditions. In addition to increasing the burning area, the speed of arrival at the place of a call will also contribute to increasing the efficiency of evacuation, which can be ensured by fire and rescue workers [3].

An adaptive graph approach to routing evacuation flows is proposed in [4]. It involves dynamic change of traffic directions on sections of the street and road network in order to reduce the total evacuation time. The methodology is based on iterative analysis of the network state and reconfiguration of traffic directions depending on the current load.

In [5], the issue of ensuring the accessibility of fire and rescue units to historical wooden sacral buildings in rural areas of eastern Slovakia was investigated. The main attention is focused on the analysis of the condition of access roads, the availability and parameters of sites for the deployment of fire equipment, as well as the time of arrival of fire units to cultural heritage sites.

The movement of special vehicles on main sections of the street and road network is considered in [6]. It is devoted to the development of a strategy for preliminary lane clearing to give priority to emergency vehicles through cooperative interaction with connected vehicles.

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In [7], an approach for dynamic route design of special vehicles is proposed, which takes into account intraday fluctuations in travel time on the street and road network. This approach combines a model of dynamic traffic flow distribution and the problem of dynamic vehicle routing, linking them through short-term forecasting of travel time on network sections.

An autonomous traffic control system for priority passage of special vehicles at controlled intersections is considered in [8]. The key feature of the outlined approach is the dynamic use of the side lane for temporary redistribution of traffic flows and algorithmic prioritization of special vehicles depending on the type and criticality of the call, as well as the distance to the place of a call.

Work [9] provides the reader with a systematic review of forecasting methods used in emergency management systems, including natural and anthropogenic disasters. Here, the authors classify approaches based on statistical methods, machine learning models, artificial intelligence, and simulations. They also summarize their application to predict the occurrence of emergency events and the need for resources, and highlight the main limitations and directions for future research in this area. In [10], the issue of rapid response to emergencies is considered in the context of optimizing the placement of relevant units, as well as routing to ensure the delivery of necessary resources in the event of an emergency under limited time windows and spatial constraints. In [11], an overview of modern approaches to the management of isolated intersections in the context of the use of connected and automated vehicles is provided. Attention is focused on two key areas: traffic trajectory planning and joint management of intersections and vehicles. A comprehensive review of the issue of optimizing traffic routes and priority in traffic for special vehicles is given in the publication [1]. In [12], intelligent traffic management at intersections using connected and automated vehicles is considered to increase throughput and reduce vehicle delays.

In [13], a two-level routing system is proposed to facilitate the rapid passage of special vehicles through the street and road network. Here, the upper level provides global route planning taking into account road conditions and delays, and the lower level adapts local decisions at intersections to minimize travel time. This, in turn, allows for cooperative decision-making between the general network and local traffic light objects, thus reducing delays and increasing the efficiency of the process of following special vehicles to the place of a call.

Traffic light object management to optimize the passage of intersections by special vehicles is considered in [14]. Here, in particular, the queue length management algorithm is considered to ensure that excessive queues at the intersection will not impede the prompt pursuit of special vehicles.

The analysis shows that many solutions for optimizing the duration of the pursuit of special vehicles involve the use of a number of additional traffic control systems, the use of road controllers and traffic detectors, etc. Such approaches require additional implementation, a number of technical components and software. The analysis shows that the issue of interaction of special vehicles in the "road conditions – traffic flows" system in the context of identifying possible causes of potential delays of such vehicles when passing controlled intersections still remains relevant.

The object of research is the process of formation of a queue of vehicles at a controlled intersection, which leads to a delay of a fire truck in the process of its pursuit to the place of a call.

Therefore, *the aim of research* is to reveal the features of the formation of a queue of vehicles at controlled intersections and their impact on potential delays of a fire truck.

To achieve the outlined aim, the following objectives were set:
– to determine the conditions for the formation of a queue of vehicles at controlled intersections;
– to perform experimental studies of the queue length at a controlled intersection using a simulation model built in the PTV Vissim environment;
– to obtain an experimental dependence for determining the maximum queue length at a controlled intersection, on the basis of which to analyze the influence of factors on the formation of a queue of vehicles.

2. Materials and Methods

When conducting research, simulation modeling was used in the PTV Vissim environment (PTV Group, Germany). The methodology combined the construction of a micromodel of a controlled intersection, the performance of a full factorial experiment and statistical processing of the results obtained with the construction of a regression model.

It was assumed that the maximum length of the queue of vehicles at a controlled intersection significantly depends on the duration of the traffic light regulation cycle, the proportion of the permitting signal and the intensity of the traffic flow. And the corresponding dependence can be adequately described by a regression model obtained on the basis of a full factorial experiment.

A simulation model of a controlled intersection with an approach to it in two lanes was built. The model made it possible to vary the following factors:
– intensity of the traffic flow;
– duration of the traffic light regulation cycle;
– proportion of the permitting signal in each of such cycles for a certain phase of traffic.

During the research, the following assumptions were made:
– traffic light objects at the intersection operate in the "hard regulation" mode;
– stochastic nature of traffic flows and behavioral factors of drivers in the context of the simulation model;
– road accidents, emergency situations and blocking of the intersection from other directions are not taken into account;
– there are no technical means to provide priority passage for special vehicles;
– traffic flow intensity is reduced to aggregate units;
– the effects of pedestrian phases are not taken into account.

Planning and implementation of experimental studies were carried out using the method of a complete orthogonal factorial experiment of type 23 with repetitions at each point. The levels of change of factors were taken within the following limits: traffic flow intensity from 200 to 1000 pass. units/h; duration of the traffic light regulation cycle from 60 to 120 s; the fraction of the permitting signal is from 0.2 to 0.5.

At each point, 5 studies were performed according to the experimental plan in order to take into account the stochastic nature of the traffic flow and ensure the statistical reliability of the results. The natural values of the factors were converted into dimensionless coded variables. For further construction of the power model, logarithmic transformation of variables was used. The coefficients of the regression model were determined by the least squares method. The significance of the coefficients was checked using the Student test. The homogeneity of the variances of the experimental data was assessed using the Cochrane test. The adequacy of the obtained model was checked using the Fisher test at a confidence level of 0.95.

The processing of the obtained results and the construction of graphical dependencies were performed using standard means of numerical data processing.

3. Results and Discussion

3.1. Determining the conditions for the formation of a queue of vehicles at controlled intersections

The route of a fire engine in urban conditions, in particular in large and significant cities, was considered. It is obvious that in most cases, while driving to the place of a call, such a vehicle will interact with other road users in the system "road conditions – traffic flows". Such interaction can have a significant impact on the time of arrival of such a vehicle to the place of a call. Among other factors, there may be an impact of traffic delays at a controlled intersection, where a queue of vehicles of the traffic flow can form, waiting for the traffic light signal and the opportunity to continue driving.

This problem is exacerbated in sections of the street and road network, where the entrance to the intersection has one or two lanes of traffic, which, in turn, due to limited space sometimes makes it impossible to create a so-called "corridor" for special vehicles. Therefore, first of all, in the context of this problem, it is possible to consider the dynamics of queue accumulation at such intersections.

It is known that one of the key factors characterizing the traffic flow is the intensity of the traffic flow N. Let's consider this factor in the context of units reduced to a passenger car N_{pass}, since the composition of the traffic flow can vary. Also, in addition to the traffic intensity, controlled intersections are characterized by the total duration of the traffic light regulation cycle T and the number of phases in it. Under ideal conditions, the queue of vehicles will accumulate depending on the share of the permitting signal λ in each of such cycles for a certain phase of traffic.

The queue size Q_{k+1} in a certain period of time at a certain entrance to the intersection can be described by the dependence

$$Q_{k+1} = Q_k + P_{add} - A_p, \quad (1)$$

where Q_k – the queue size of vehicles, passenger car units, (pass. units) at the beginning of the k-th cycle of traffic light regulation; P_{add} – the number of vehicles (pass. units) that arrived during the k-th cycle of traffic light regulation; A_p – the number of vehicles (pass. units) that passed the intersection during the k-th cycle of traffic light regulation.

If

$$A_p \geq P_{add}, \quad (2)$$

then the size of the queue at the intersection will not grow. If the condition

$$A_p < P_{add}, \quad (3)$$

then with each cycle the queue at a constant or increasing traffic intensity N will grow.

Since the analytical determination of the length of the queue at the intersection will not allow taking into account the stochastic nature of traffic flows and behavioral factors of drivers, it is advisable to use simulation modeling for such studies.

3.2. Experimental studies of the queue length at a controlled intersection

To carry out the research, let's use simulation models obtained in the PTV Vissim environment. For this purpose, a model of a controlled intersection with a two-lane approach to the intersection was built. It allows for simulation modeling of intersections by changing the traffic flow intensity N, the duration of the traffic light regulation cycle T, and the proportion of the permitting signal λ in each of these cycles for a certain phase of traffic.

Experimental studies of the maximum queue length Q were performed based on the full factorial experiment method 23. The aim was to establish the influence on Q of the traffic flow intensity N, the duration of the traffic light regulation cycle T, and the proportion of the permitting signal λ in each of these cycles for a certain phase of traffic.

The levels of change of factors were taken within the following limits:

1. The duration of the traffic light regulation cycle T is from 60 to 120 s. This range is most often found in practice.
2. The share of the permitting signal λ from 0.2 to 0.5. Such values are inherent in existing traffic light regulation cycle diagrams in a strict mode.
3. Traffic flow intensity N from 200 to 1000 pass. units/h. The traffic flow intensity was immediately taken in units reduced to a passenger car, which allows to implement the resulting simulation model. Also, previous experiments made it possible to establish that at $N \leq 1000$ pass. units/h, condition (2) is met, which will allow to obtain an adequate model.

Fig. 1 shows a fragment of the window for setting the cycle of regulation of traffic light objects of the studied simulation model of a controlled intersection (with the studied approach to the intersection in two lanes).

The specified factors were encoded by converting natural quantities into dimensionless ones. This information, as well as the levels of factor changes, are given in Table 1.

Based on Table 1, a planning and results matrix of the full factorial experiment 23 was constructed, which indicates the results of experimental studies. Each experiment was performed 5 times to obtain more accurate results.

The results of the experimental studies are given in Table 2.

The values obtained in Table 2 indicate that the discrepancy in the results of the studies of the queue length Q in cycles is due to the realism of the simulation model. Otherwise, all values for each experiment would be the same.

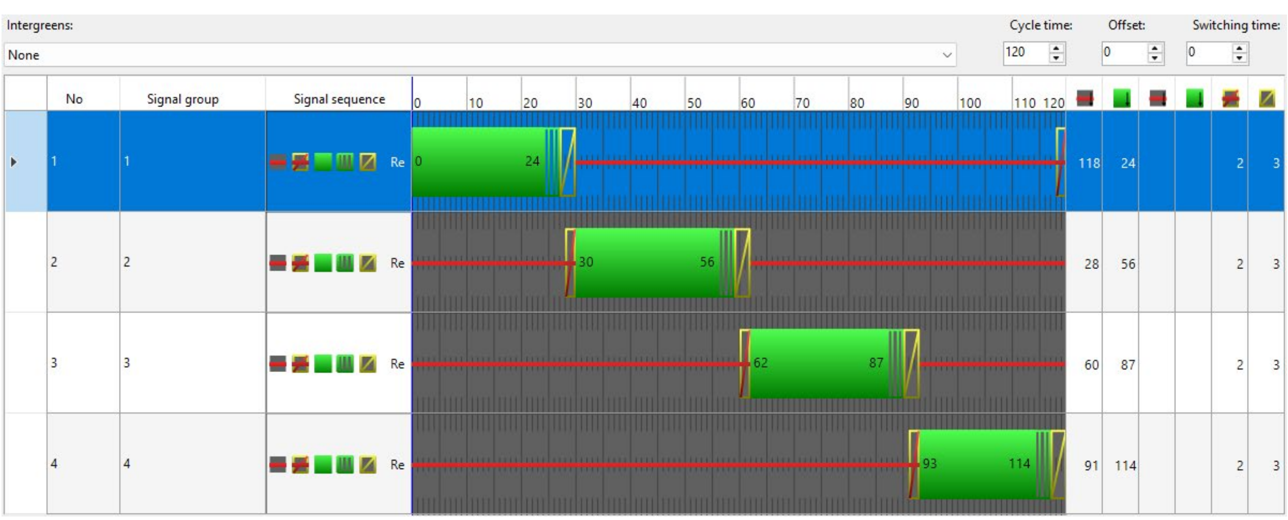

Fig. 1. Fragment of the traffic light adjustment cycle settings window for an intersection modeled in the PTV Vissim environment, where T = 120 s, and λ = 0.2

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Table 1

Levels of factor changes

Factor level		Cycle duration, T, s		Part of the enabling signal, λ		Intensity, N_{pass}, pass. units	
Name	Coded value	X_1	$\ln X_1$	X_2	$\ln X_2$	X_3	$\ln X_3$
Top	+1	120	4.7874	0.5	–0.6931	1000	6.9077
Main	0	90	4.4998	0.35	–1.0498	600	6.3969
Low	–1	60	4.0943	0.2	–1.6094	200	5.2983

Table 2

Experimental study of the maximum queue length for a lane when approaching a controlled intersection with two lanes

Series No.	Cycle duration, T, s		Part of the enabling signal, λ		Intensity, N_{pass}, pass. units		Results of research on the queue length Q in cycles (1–5), pass. units					Q_{av}, pass. units
	Code	Value	Code	Value	Code	Value	1	2	3	4	5	
1	–1	60	–1	0.2	+1	1000	8	9	6	10	7	8.0
2	+1	120	–1	0.2	+1	1000	19	16	17	14	16	16.4
3	–1	60	+1	0.5	+1	1000	6	5	2	5	3	4.2
4	+1	120	+1	0.5	+1	1000	10	12	11	8	9	10.0
5	–1	60	–1	0.2	–1	200	1	1	3	1	3	1.8
6	+1	120	–1	0.2	–1	200	3	4	5	3	2	3.4
7	–1	60	+1	0.5	–1	200	1	1	2	1	1	1.2
8	+1	120	+1	0.5	–1	200	2	2	5	3	1	2.6

3.3. Construction of a regression model and analysis of the influence of factors on the queue length

The dependence in the code variables with the introduction of terms that take into account the interaction of factors for the experiment of class 2^3 will have the form

$$Y = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_{12}X_1X_2 + b_{13}X_1X_3 + b_{23}X_2X_3 + b_{123}X_1X_2X_3, \quad (4)$$

where b_0, b_1, b_2, b_3, b_{12}, b_{13}, b_{23}, b_{123} – the coefficients of the regression equation.

It was assumed that $\ln X_1 = \xi_1$, $\ln X_2 = \xi_2$, $\ln X_3 = \xi_3$. Then, according to the results of mathematical processing of the results of the full factorial experiment based on Table 1 and Table 2, the model (4) took the form

$$Q = 5.95 + 2.15\xi_1 - 1.45\xi_2 + 3.70\xi_3 - 0.35\xi_1\xi_2 + 1.40\xi_1\xi_3 - 1.10\xi_2\xi_3 - 0.30\xi_1\xi_2\xi_3. \quad (5)$$

Taking into account Table 1, as well as performing mathematical transformations, a model was obtained for natural variables for determining the maximum queue length for a lane when approaching a controlled intersection with two lanes

$$Q = 9.93 \cdot 10^{-5} T^{1.080} \lambda^{-0.495} N^{0.880}. \quad (6)$$

After analyzing the model (6), the response surfaces of the influence of factors on the maximum queue length Q for a two-lane approach to a controlled intersection were obtained, when condition (2) is met. In this case, the constant values of the factors were taken in accordance with the basic level according to Table 1.

The obtained response surfaces allow for a more detailed analysis of the level of influence of factors on the queue formation process when approaching a controlled intersection.

Fig. 2 shows the graphical dependence of the maximum queue length on the values of T and λ.

Having analyzed the graphical dependence shown in Fig. 2, it can be concluded that at N = 600 pass. units/h the length of the vehicle queue increases significantly with increasing T and decreases with increasing λ. When T increases by two times, the length of the vehicle queue will increase by more than two times, which indicates the influence of continuous waiting time on the formation of the queue. At the same time, increasing λ from 0.20 to 0.50 allows to reduce Q by approximately 35–40%, but this decrease is not enough to fully compensate for the negative impact of long cycles. Thus, at a fixed N, it is T that is the determining factor in the accumulation of the transport queue, while an increase in the share of the green signal plays an auxiliary, but limited compensatory role.

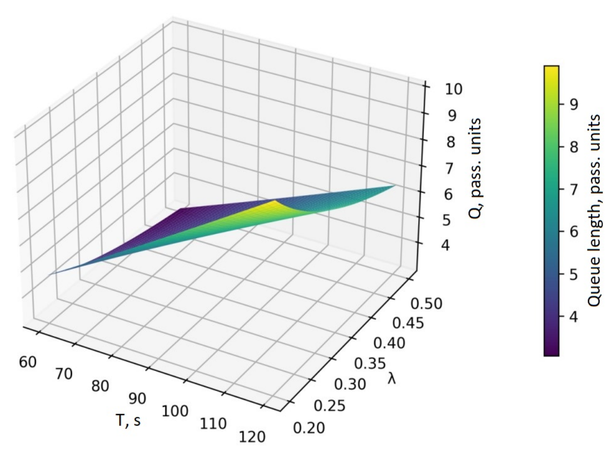

Fig. 2. Dependence of Q on the values of T and λ at N = 600 pass. units/h

Fig. 3 shows the influence of T and N on the maximum queue length.

Based on Fig. 3, it is possible to conclude that at λ = 0.35 the value of Q increases both with increasing N and with increasing T. Moreover, the most dramatic increase is observed with simultaneously high values of both factors. An increase in the value of N from 200 to 1000 pass. units/h (5 times) leads to an increase in Q approximately 4 times, i. e. N is the key factor in queue formation in this graph. Here, as in the previous graph, it is possible to see that with an increase in T by 2 times, the length of the queue of vehicles will increase by more than two times. Therefore, it is possible to see that at larger values of N, an increase in T can increase the risk of forming a significant queue in front of a controlled intersection.

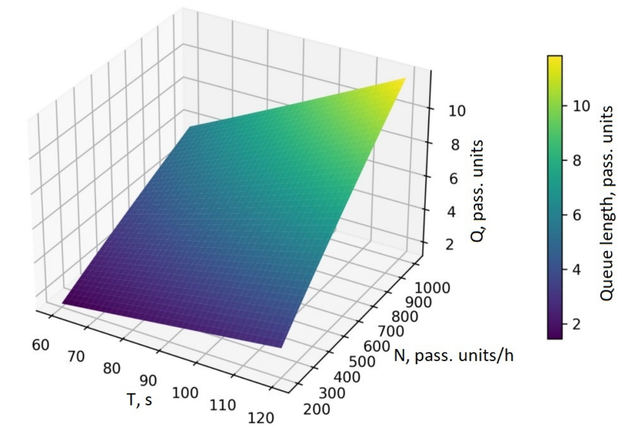

Fig. 3. Dependence of Q on the values of T and N at $\lambda = 0.35$

Fig. 4 shows the dependence of Q on the values of N and λ at $T = 90$ s, where it is possible to see that the efficiency of increasing λ significantly depends on N. For relatively small values of N (about 200–300 pass. units/h), increasing λ from 0.20 to 0.50 allows to reduce Q by approximately 40%, which indicates the presence of significant capacity reserves. However, when N reaches a value of 800–1000 pass. units/h, the decrease in Q due to increasing λ does not exceed 15–20%, i. e. the compensatory effect of the green signal is significantly weakened.

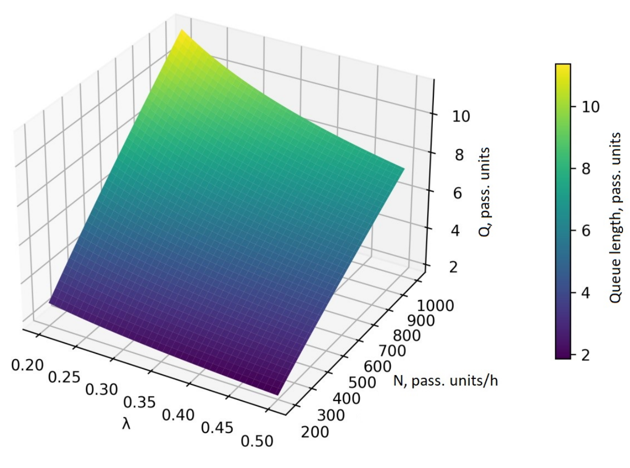

Fig. 4. Dependence of Q on the values of N and λ at $T = 90$ s

The queue formed by vehicles in front of a controlled intersection will have a direct impact on the duration of the special vehicles' journey to the place of a call. Because even if there is a priority in traffic, such vehicles will be forced to either spend additional time waiting for the creation of a "corridor", or, in the absence of such an opportunity, move as an element of a possible queue in narrow places of the street and road network. In this context, the length of the queue can be considered as an integral indicator of the potential delay of a fire truck, which allows to link the obtained dependencies with the actual time of its movement in the conditions of the city street and road network.

Known approaches to optimizing the duration of the journey of special vehicles involve the use of a number of additional traffic control systems, the use of road controllers and transport detectors, etc. Some approaches are static in nature [2]. At the same time, the proposed model allows to directly evaluate the change in the queue length when varying the parameters of traffic light regulation. This, in turn, expands the possibilities of practical application of the results for the analysis of traffic conditions of fire engines and other special vehicles.

3.4. Research limitations and directions of its development

In conditions of martial law, periodic restrictions in the operation of transport infrastructure elements, in particular traffic light facilities, often occur due to emergency power outages. In this regard, the work considers the basic mode of operation of controlled intersections provided that technical means of road traffic management are in good working order. The results obtained can be used for analysis and planning of traffic under the conditions of restoration of the regular mode of operation of such means.

The obtained dependencies can be further used in the development of new or improvement of existing models [2, 15] for determining the optimal routes of special vehicles to the place of a call, taking into account possible delays at controlled intersections. Promising directions of research in the outlined area in the future may be obtaining similar models using the methodology disclosed here. This will be relevant for different intersection configurations, taking into account the direction of traffic along the lanes and the number of these lanes, the influence of pedestrian crossings, as well as the accumulation of queues at unregulated intersections. Of interest to researchers should be the issue of revealing the features of the formation of a "corridor" in the queue modeled in this article in front of a two-lane intersection, etc.

4. Conclusions

1. The condition for the formation and accumulation of a queue of vehicles at a controlled intersection is outlined. It is shown that if the traffic intensity exceeds the capacity of the control phase, the queue accumulates with each subsequent cycle. The choice of a traffic intensity range of up to 1000 pass. units/h is justified to ensure correct simulation modeling.

2. Based on the simulation model of a controlled intersection built in the PTV Vissim environment, experimental studies were performed using the full factorial experiment method 2^3. The dependence for determining the maximum queue length for a controlled intersection on the traffic flow intensity, the duration of the traffic light control cycle, and the share of the permitting signal in each of such cycles was obtained.

3. The magnitude of the influence of each of the outlined parameters on the formation of a queue at the intersection was analyzed separately. It was found that when T increases by two times, the length of the vehicle queue will increase by more than two times, which indicates the influence of continuous waiting time on queue formation. At the same time, increasing λ from 0.20 to 0.50 allows to reduce Q by approximately 35–40%, but this decrease is not enough to fully compensate for the negative impact of long cycles. Increasing the value of N from 200 to 1000 pass. units/h (by 5 times) leads to an increase in Q by approximately 4 times, i. e. N acts as a key factor in queue formation at $\lambda = 0.35$. For relatively small values of N (about 200–300 pass. units/h), increasing λ from 0.20 to 0.50 allows to reduce Q by approximately 40%, which indicates the presence of significant capacity reserves. The obtained dependencies can be further used in the development of new or improvement of existing models for determining the optimal routes of special vehicles to the place of a call, taking into account possible delays at controlled intersections.

Conflict of interest

The author declares that he has no conflict of interest regarding this research, including financial, personal, authorship or other, which could affect the research and its results presented in this article.

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Data availability

The manuscript has no related data.

Use of artificial intelligence

The author confirms that he did not use artificial intelligence technologies when creating the presented work.

Authors' contributions

Ivan Pasnak: Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review and editing, Visualization.

References

1. Hao, Z., Wang, Y., Yang, X. (2024). Every Second Counts: A Comprehensive Review of Route Optimization and Priority Control for Urban Emergency Vehicles. *Sustainability, 16 (7),* 2917. https://doi.org/10.3390/su16072917
2. Pasnak, I., Renkas, A. (2020). Optimization of the duration of emergency vehicle movement to the place of fire. *Transport Problems, 15 (4, Part 1),* 117–124. https://doi.org/10.21307/tp-2020-053
3. Hulida, E., Pasnak, I., Koval, O., Tryhuba, A. (2019). Determination of the Critical Time of Fire in the Building and Ensure Successful Evacuation of People. *Periodica Polytechnica Civil Engineering,* 63 *(1),* 308–316. https://doi.org/10.3311/ppci.12760
4. Behrooz, H., Ilbeigi, M. (2025). Adaptive emergency evacuation routing: a graph-based approach. *International Journal of Transportation Science and Technology, 20,* 178–192. https://doi.org/10.1016/j.ijtst.2024.11.010
5. Huliak, M., Marková, I. (2026). Analysis of access roads, boarding areas and arrival times of firefighting units to selected heritage wooden buildings. *Transportation Research Procedia, 93,* 1006–1012. https://doi.org/10.1016/j.trpro.2025.12.035
6. Wu, J., Kulcsár, B., Ahn, S., Qu, X. (2020). Emergency vehicle lane pre-clearing: From microscopic cooperation to routing decision making. *Transportation Research Part B: Methodological, 141,* 223–239. https://doi.org/10.1016/j.trb.2020.09.011
7. Musolino, G., Polimeni, A., Rindone, C., Vitetta, A. (2013). Travel Time Forecasting and Dynamic Routes Design for Emergency Vehicles. *Procedia – Social and Behavioral Sciences, 87,* 193–202. https://doi.org/10.1016/j.sbspro.2013.10.603
8. Humayun, M., Almufareh, M. F., Jhanjhi, N. Z. (2022). Autonomous Traffic System for Emergency Vehicles. *Electronics, 11 (4),* 510. https://doi.org/10.3390/electronics11040510
9. Huang, D., Wang, S., Liu, Z. (2021). A systematic review of prediction methods for emergency management. *International Journal of Disaster Risk Reduction, 62,* 102412. https://doi.org/10.1016/j.ijdrr.2021.102412
10. Wang, W., Wu, S., Wang, S., Zhen, L., Qu, X. (2021). Emergency facility location problems in logistics: Status and perspectives. *Transportation Research Part E: Logistics and Transportation Review, 154,* 102465. https://doi.org/10.1016/j.tre.2021.102465
11. Wu, J., Qu, X. (2022). Intersection control with connected and automated vehicles: a review. *Journal of Intelligent and Connected Vehicles, 5 (3),* 260–269. https://doi.org/10.1108/jicv-06-2022-0023
12. Li, Z., Wang, Q., Wang, J., He, Z. (2024). A Flexible Cooperative MARL Method for Efficient Passage of an Emergency CAV in Mixed Traffic. *IEEE Transactions on Intelligent Transportation Systems, 25 (8),* 8898–8912. https://doi.org/10.1109/tits.2024.3411487
13. Nahofti Kohneh, J., Murray-Tuite, P. (2025). Two-Level Routing Framework to Facilitate the Movement of Emergency Response Vehicles in a Transportation Network. *Transportation Research Record: Journal of the Transportation Research Board, 2679 (11),* 1143–1170. https://doi.org/10.1177/03611981251351873
14. Chen, Y., Wang, J., Lo, S., Sung, W. (2024). An emergency vehicle traffic signal preemption system considering queue spillbacks along routes and negative impacts on non-priority traffic. *IET Intelligent Transport Systems, 18 (8),* 1385–1395. Portico. https://doi.org/10.1049/itr2.12518
15. Pasnak, I., Prydatko, O., Gavrilyk, A. (2016). Development of algorithms for efficient management of fire rescue units. *Eastern-European Journal of Enterprise Technologies, 3 (3 (81)),* 22–28. https://doi.org/10.15587/1729-4061.2016.71604

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