# INFLUENCE OF TRAFFIC FLOW PARAMETERS ON THE DELAY DURATION AT SIGNALIZED INTERSECTIONS

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***Resume***

In this study is examined the influence of traffic flow parameters on delay duration at signalized intersections of urban multi-lane streets. The findings show that traffic composition strongly affects delays at low volumes, while its influence decreases as total volume grows. These results highlight the need to account for traffic composition, not only volume, when optimizing the signal timing and managing flows. The novelty of the study lies in modelling delay as a joint function of traffic volume and traffic flow composition, where the share of passenger cars is varied independently, rather than through the generalized passenger car unit-based growth, enabling a more accurate assessment of delay formation under heterogeneous traffic conditions.

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## 1 Introduction

Every year, a constant increase in the number of vehicles can be seen on the streets and roads of settlements. In return, that leads to several negative phenomena, such as traffic delays [1], increased environmental pollution [2], noise pollution [3], etc. Among all the above-mentioned consequences of motorization, the most significant impact is a sharp increase in traffic volume, which leads to traffic congestion. That can be explained by the fact that although the number of vehicles on streets and roads is increasing, the capacity of transportation routes usually remains unchanged. One of the reasons for this challenge is that reconstructing an existing roadway, or creating a new one, incurs significant financial costs. However, intersections are often the bottlenecks in the road network.

In compliance with the aforementioned, the existing indicators of traffic flows were measured and the traffic characteristics at signalized intersections on city streets were analyzed. These data were the input information for creating simulation models of traffic flows in the PTV VISSIM microsimulation environment (PTV - Planung Transport Verkehr). This approach enables the analysis of the dynamics of changes in traffic flows and traffic delays. In addition, the relevance of this approach lies in reducing the probability of erroneous engineering solutions in traffic management and predicting the behavior of traffic flows at signalized road network facilities.

The aim of this research was to identify the patterns of composition and intensity's influence on the duration of traffic delay at regulated intersections, providing an input for the management and setup of adaptive traffic signal control systems. In this case, the proven methods of traffic simulation at controlled city street intersections were used. Such modern approaches enable the identification of patterns in traffic delays within the dynamics of traffic flows, allowing for the intelligent control of traffic lights at intersections. Finding optimal solutions by analyzing existing intersection parameters and traffic flow characteristics is essential. The following main tasks needed to be accomplished to achieve this goal:

- to analyze the performance of a standard four-leg signalized intersections of city streets and determine the existing indicators of traffic flow on them;
- to create models of street intersections and calibrate them to the existing traffic conditions;
- to simulate traffic and determine the duration of traffic delays based on the results;
- to analyze the data and identify patterns of change

in the duration of traffic delays based on the characteristics of transport flows.

The next section of this article includes literature review with recent publications, which are related to traffic optimization. The research methodology is described in “Materials and methods” section. In the section “Main results”, presented are most important graphs and dependencies obtained during the survey. The sections with discussion and conclusions are given at the end of the paper.

## 2 Literature review

Delays at signalized intersections can occur due to several reasons. One of them is stopping of vehicles, which is directly caused by the operation of traffic lights.

These also include delays caused by the control process (Figure 1), particularly during the vehicle's acceleration and deceleration in the traffic light object area and its direct idle time [4-5].

The diagram in Figure 1 is rather generalized. This is because, depending on the dynamic characteristics of vehicles, the processes of braking and acceleration can be carried out to varying extents.

Webster's delay model can also be used to mathematically describe the duration of vehicle delays at signalized intersections. It involves considering the following quantities [6-7]: cycle length, effective green time, arrival flow rate, saturation flow, and exit capacity. However, as the composition of the traffic flow changes, the impact of a particular indicator may change. For example, the effective duration of a green signal for a traffic flow consisting of passenger cars will differ from that of slow-moving vehicles. It is primarily due to their starting delays after the permissive signal is turned on. In particular, the authors of [8] found a difference in the processes of car queue accumulation before the stop line and its dissipation, depending on the composition of the traffic flow. For example, as the share of trucks and buses in the queue grows, it leads to longer intervals in the movement of vehicles at the beginning of the permissive signal. At the same time, the authors noted that the dissipation process also depends on the directions in which the traffic is allowed to move simultaneously.

The Highway Capacity Manual is an important document that reflects transport processes in automotive transport and recommendations for traffic management. The manual also displays acceleration-deceleration delay patterns [9]. At the same time, the average values of the speed, acceleration, and deceleration are considered. It should be noted that the values of these indicators will be strongly related to the types of vehicles and their technical parameters. Thus, it is not enough to determine the duration of the delay based on average values. It is also essential to consider the composition of the traffic flow. Its distribution will change to varying degrees, both the initial delays of cars and the dispersion of the vehicles` queue during the traffic signal cycle.

Adaptive control systems can also be used to reduce the impact of traffic lights on traffic delays [6, 10]. They can consider the characteristics of traffic flows and various changes in movement conditions, including seasonal and short-term [11]. At the same time, adaptive traffic signal control systems can operate based on pre-created sustainable behavioral algorithms [12], as well as using approaches that involve the use of machine learning [13], fuzzy logic [14], deep reinforcement learning [15], multi-agent broad reinforcement learning [16], meta-heuristic search algorithms [17], etc. All of the above-mentioned traffic signal control options are designed to improve the traffic flow, reduce delays, and

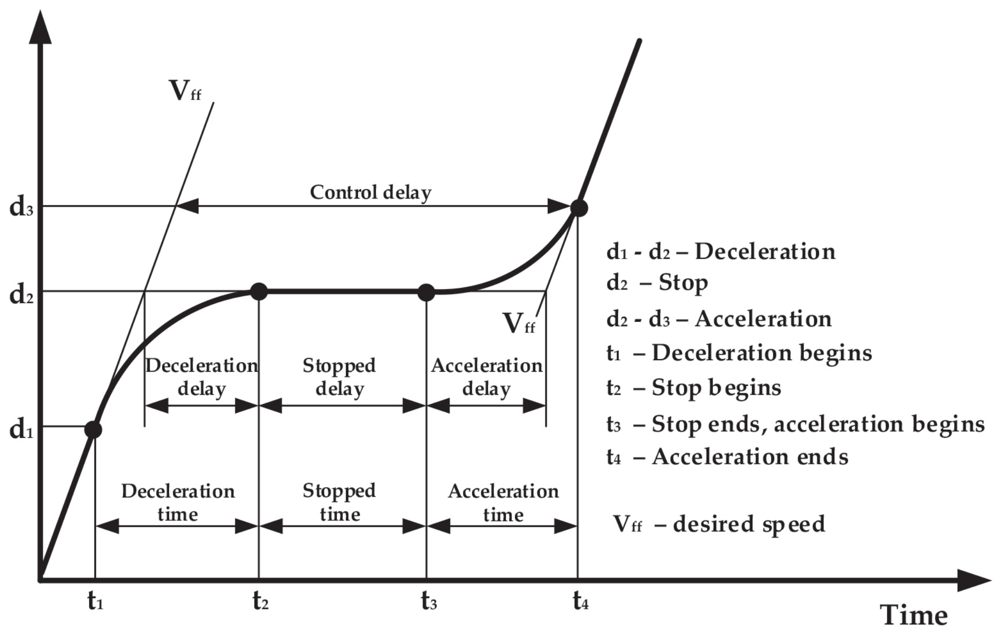



***Figure 1*** *The formation of traffic delays at signalized intersections [4]*

minimize congestion on the road network. However, each of the above cases requires input information and the training or adjustment of the system and traffic signal control algorithms. Therefore, an important task is conducting the field studies directly on the road network and obtaining initial traffic delay patterns and their causes.

It is equally important to note that today, numerous tools are available for analyzing traffic management design solutions. First, it is possible to use specialized software for simulation modelling. Simulation models enable the reproduction of complex transport processes under conditions as close as possible to the real-world ones. In its turn, it helps to determine the effectiveness of design solutions at the stage of their development. These tools contribute to an objective assessment of the road network's capacity and its elements [18], analysis of road safety and identification of accident sites [19], identification of areas for further development, and prioritization of public transport [20], among other applications. Additionally, the use of simulation tools enables the comparison of alternative traffic management options with the overall reconstruction costs of the study object and its associated facilities [21]. It should also be noted that the issue of using the simulation modelling tools is particularly relevant in the context of a dynamic increase in traffic volume and the need to make informed management decisions.

Thus, summarizing the above information, today, various scientific dependencies and models can reflect the formation of transport delays and allow for their measurement. However, they often consider generalized traffic flow indicators, including the calibrated passenger car equivalent. In contrast, the proposed model suggests considering the composition of the traffic flow, in particular, due to the passenger cars' share in the flow. In addition, a wide range of hardware and software solutions are available to adapt the operation of traffic signal control systems to traffic conditions and flow characteristics. However, the effective implementation of such solutions requires a deep understanding of the patterns of change in the traffic flow parameters, depending on the volume, composition of traffic, and traffic conditions at the intersection. Therefore, in any case, the primary task will continue to be field research and identification of patterns to make initial adjustments to the regulatory tools. Additionally, simulation modelling tools can currently be utilized to obtain initial data for machine learning and the adaptation of traffic signal activation programs by controllers, thereby achieving the aforementioned goals.

To summarize the state-of-the art from the presented research it should be noted that research devoted to assessing traffic queues, among methods of optimization and traffic light settings, should also focus on the causes of these delays. Therefore, studying the composition of traffic flow as one of the causes of increased congestion at the signalised intersections is a relevant task at this time.

## 3 Materials and methods

Delays in traffic flow at intersections lead to a decrease in the efficiency of the transportation network and a decline in road safety. Modelling the traffic flows at intersections of varying complexity helps to optimize traffic on streets and roads, reduce congestion, and increase the capacity of transport infrastructure [22]. Improving urban infrastructure (by building new roads or junctions) and analyzing the growth of motorization levels using simulation modelling helps to predict how the traffic flows would behave under different traffic conditions and intersection operations [23]. For the successful design of new transport systems or the modernization of existing ones, evaluating their performance in advance, under different traffic flow parameters, is crucial.

To clarify up the research methodology, there is step-by step survey chart, presented on Figure 2, dividing this work for two stages: research and analytics.

First, field data on traffic volume, composition and signal timings are collected at two standard four-leg signalised intersections, followed by a detailed characterisation of their lane geometry and phase structure. based on

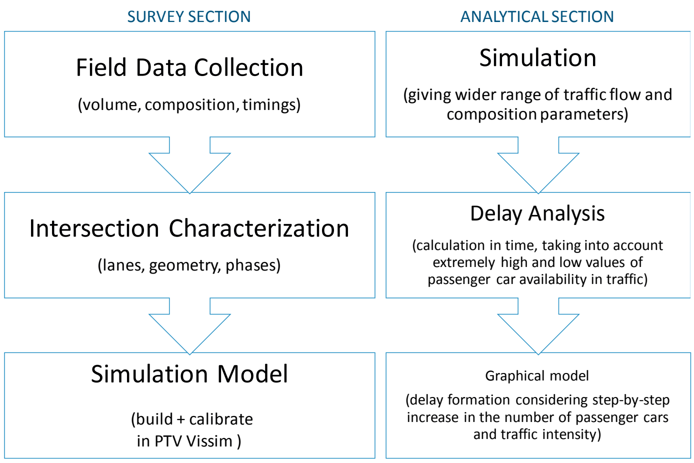



***Figure 2*** *Step-by-step methodology chart*

that, the calibrated microsimulation models are built in PTV VISSIM to reproduce the existing conditions. In the analytical section, those models are used to run a series of simulation experiments in which traffic flow parameters are systematically varied and the resulting delays are evaluated and summarised in graphical form.

The key novelty of the method lies in the analytical stage: instead of increasing only the total traffic volume, expressed in generalized passenger car units, the simulations independently vary both the traffic volume and the share of passenger cars in the flow, while keeping the presence of heavy vehicles and buses explicit. This allows the model to capture how changes in traffic composition, not just total intensity, influence the delay formation at signalised intersections and to identify the critical regimes associated with heterogeneous flows.

The challenge of improving the traffic flow at such standard four-leg signalized intersections lies in considering traffic from all directions. This requires a careful approach to the distribution of time duration between phases within

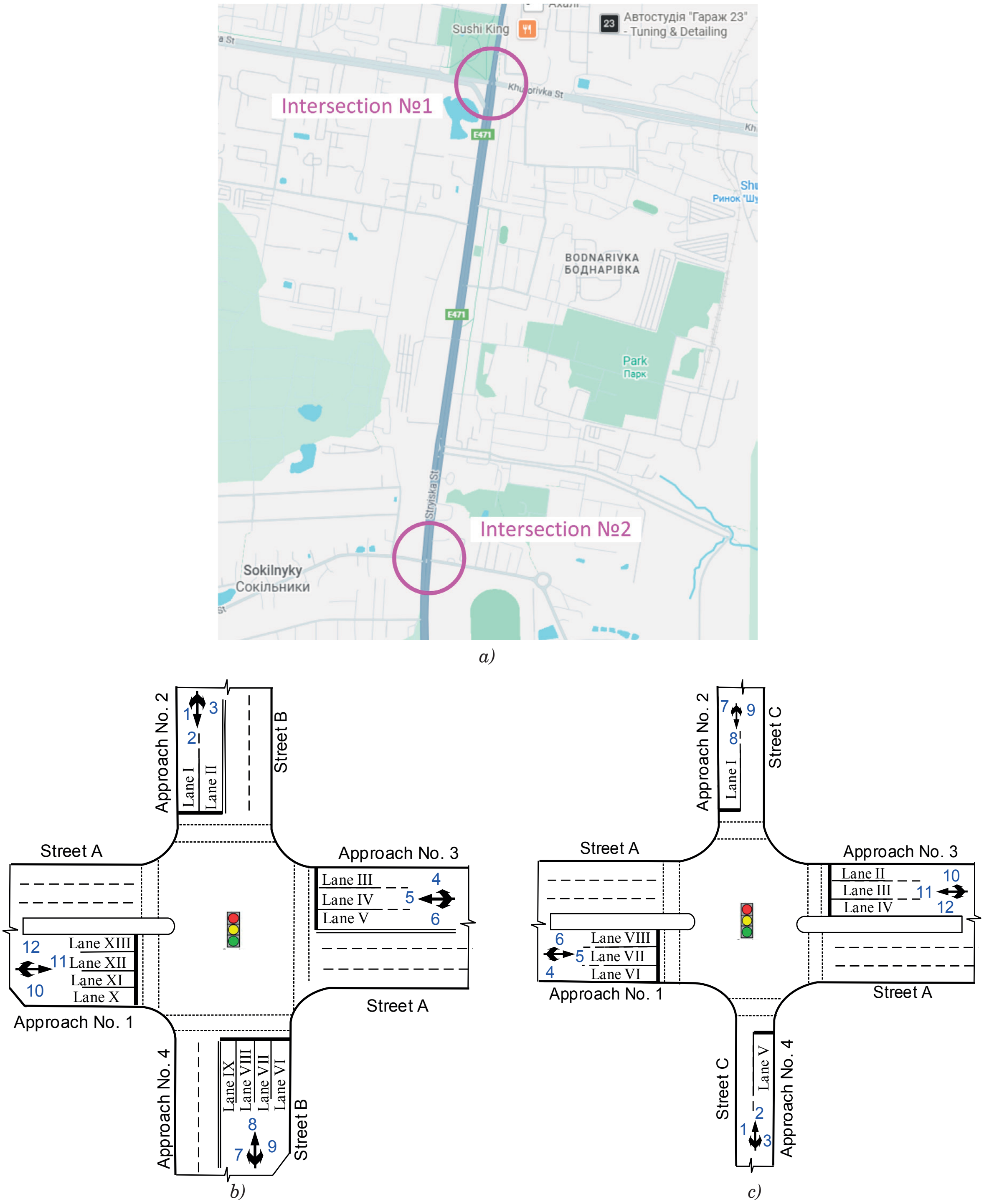
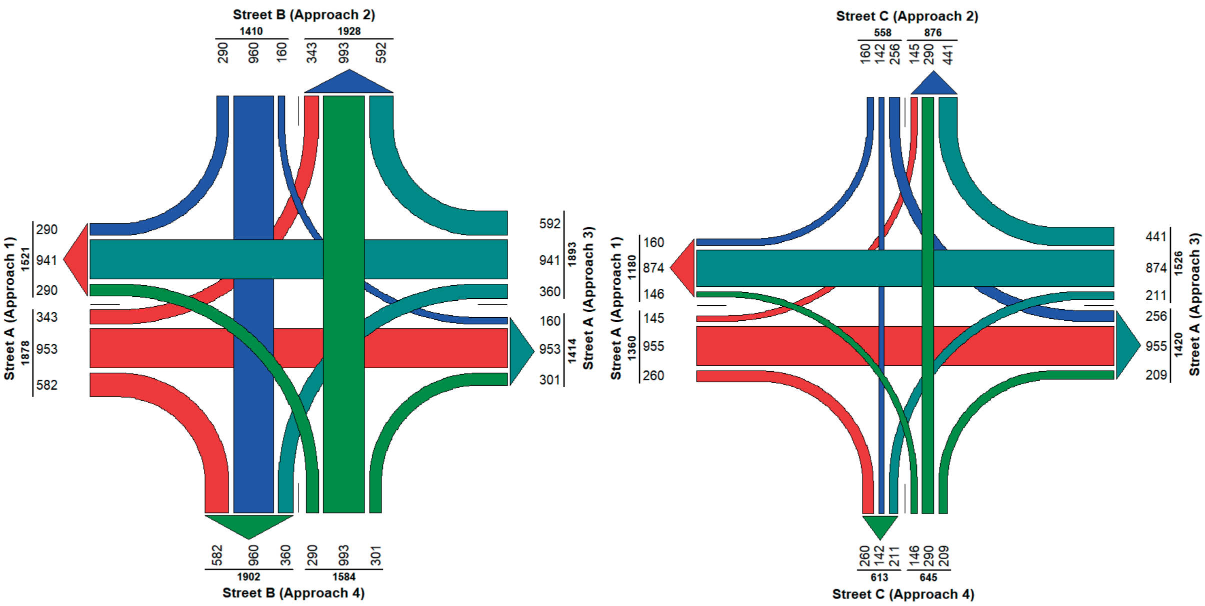



***Figure 3*** *Scheme of the two studied signalized intersections of urban arterial multi-lane streets: (a) Locations of intersections (b) Intersection of streets No. 1 (Streets A and B); (c) Intersection of streets No. 2 (Streets A and C)*

the control cycle. In conditions of high urban traffic, it is crucial to ensure a balance between safety, capacity, and minimization of traffic delays. Traffic control in three or more phases at an intersection requires a more flexible formation of the control cycle, including the conflictology of flows, the configuration of the intersection, and the main parameters of traffic flows. This complicates the development of measures to improve traffic management at standard four-leg signalized intersections, but allows for an increase in the efficiency of intersections in urban traffic conditions. Therefore, there is a close relationship between the traffic flow indicators and the effective operation of signalized intersections. For a comprehensive study of the peculiarities of signalized intersection functioning, a series of studies on existing traffic flow indicators at the standard four-leg signalized intersections on city streets is proposed. In particular, the first stage of the research involved analyzing the permitted traffic directions and planning parameters of two standard four-leg signalized intersections (Figure 3) located on the same urban arterial street section (Street A).

The planning characteristics of the studied signalized intersections are analyzed (Figure 3a), with particular emphasis on the geometric parameters of the traffic lanes at each approach. They both share the common characteristics that the main road at the two signalized intersections is Street A, the arterial Street, and, in general, the fact that both intersections form city streets that intersect at 90 degrees. In addition, it was found that at intersection No. 1 (Figure 3b) each approach features a multi-lane roadway with a lane width of 3.75 m, allowing for all possible maneuvers. Additionally, approach 1 (Street A) features a 3.5-meter-wide separation lane. It is also important to note that Street B, which also forms this intersection, is a major arterial street of general city significance. At intersection No. 2 (Figure 3c), there are three lanes in each direction in the main direction, with a width of 3.75 m, and a 3 m wide separation lane. The roadway surface on all approaches to the intersections is characterized by flatness and satisfactory technical condition. Street A here has the same arterial significance, as on previous intersection. Minor streets (streets B and C) have a lane width of 3.75 m. These streets belong to local significance, which corresponds to both their geometric parameters and traffic volume. In addition, the sufficient width of the lanes on these streets allows for the combination of turning and straight traffic flows from one lane during the control phases. There are no transverse and longitudinal roadway slopes on minor streets.

The next stage of the study involved investigating the parameters of traffic flows at two adjacent signalized intersections. The study of traffic flow parameters was carried out using the field method, manually counting the intensity and composition of the traffic flow. The short-term (15 min) measurements were made during the peak traffic periods on every hour from Tuesday to Thursday. Peak periods in the city under study (Lviv, Ukraine) are considered to be the morning hours from 8:00 to 9:30. It should also be noted, that intensity measurements were taken in dry and warm weather (in May 2025). A comparative analysis of the traffic flow`s composition and intensity was conducted based on the obtained data. In addition, it was established whether there were any random discrepancies in the measurements, including calculating the weighted average percentage of different types of vehicles. The results of the study on traffic volumes for each approach and by traffic direction are shown in Figure 4. In this scheme, the estimated traffic volume for each approach is the maximum intensity observed during the busiest hour of all days of the study.




*a)* *b)*

***Figure 4** Cartogram of traffic volume by directions at intersection No. 1 (a) and intersection No. 2 (b)*

*__Table 1__ Percentage distribution of traffic flows by direction on the approaches to the studied signalized intersections*

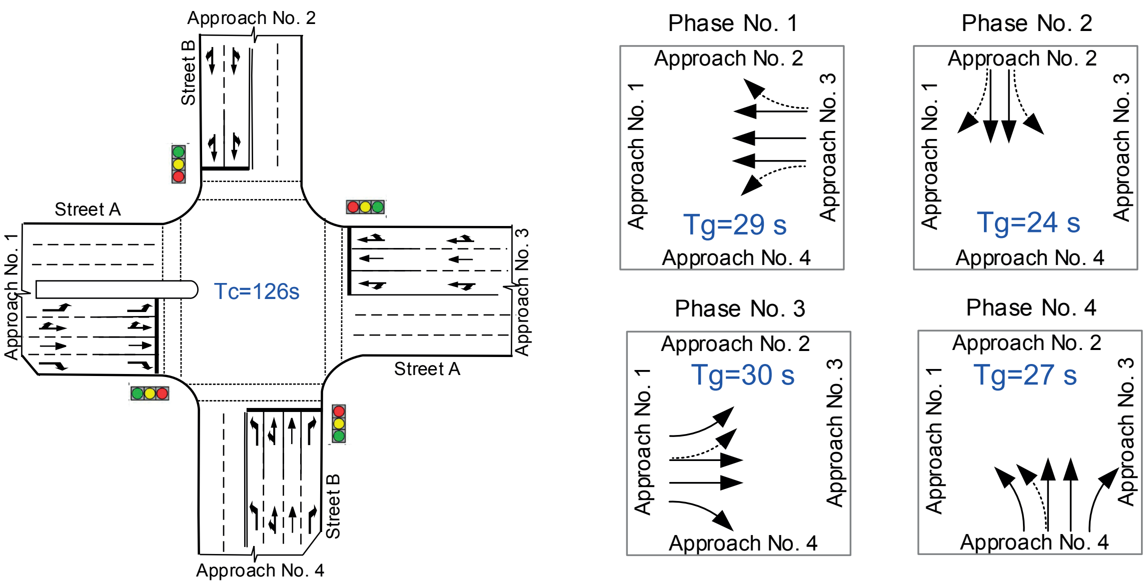
| Type of vehicle maneuver from the approach | Approach No. 1 | Approach No. 2 | Approach No. 3 | Approach No. 4 |
|---|---|---|---|---|
| | Intersection No. 1 | | | |
| Right-turn | 31% | 21% | 31% | 18% |
| Straight | 51% | 68% | 50% | 63% |
| Left-turn | 18% | 11% | 19% | 19% |
| | Intersection No. 2 | | | |
| Right-turn | 19% | 29% | 29% | 23% |
| Straight | 70% | 25% | 57% | 45% |
| Left-turn | 11% | 46% | 14% | 32% |

According to the above data, it was found that the highest values were recorded in the direction of the main road (Street A). Additionally, the direct driving vehicles (whose share ranges from 25% to 70%, depending on the approach) dominate the traffic flow. In turn, the share of right-turn flows varies from 11% to 46%, depending on the approach and direction of travel. Detailed information about the distribution of vehicles by traffic direction at the studied intersections is provided in Table 1.

It should be noted that on the main direction of the intersections (Street A), the largest share of vehicles moves straight ahead, and the smallest share of traffic flow is attributed to the left-turning maneuvers. In addition, it should be noted that the distribution of traffic flows by type of maneuver differs between different approaches to the same intersection and between intersections themselves. It indicates the various configurations and purposes of city streets, as well as the points of attraction near each intersection. According to the current law, the speed limit for settlements in all directions and at intersections is 50 km/h. Within the intersection, during the field studies, traffic speeds were observed that did not exceed the established standards, and sometimes were lower and ranged from 25-40 km/h. Different traffic flows and the automatic speeding cameras at these study intersections explain this speed.

At the studied intersections, there is also significant heterogeneity in traffic flows, which varies depending on the growth of total traffic volume on the approaches and different periods of the day. According to the results of field studies, it was found that passenger cars predominate in traffic flows, and public transport has the smallest share.

According to the results of field studies, it was found that the passenger cars predominate at all approaches to signalized intersections. The largest share is observed on Main Street A, where the highest traffic volume was recorded. It should also be noted that the studied intersections are located in urban areas, so the freight transport here is primarily represented by vehicles of small and medium capacity (2-5 tons) used to supply goods and deliver products within the settlement. Additionally, it is worth noting that at intersection No.




*a)* *b)*

*__Figure 5__ Permitted directions of traffic flow by lanes at intersection No. 1 (a) and the phase sequence of vehicles (b)*

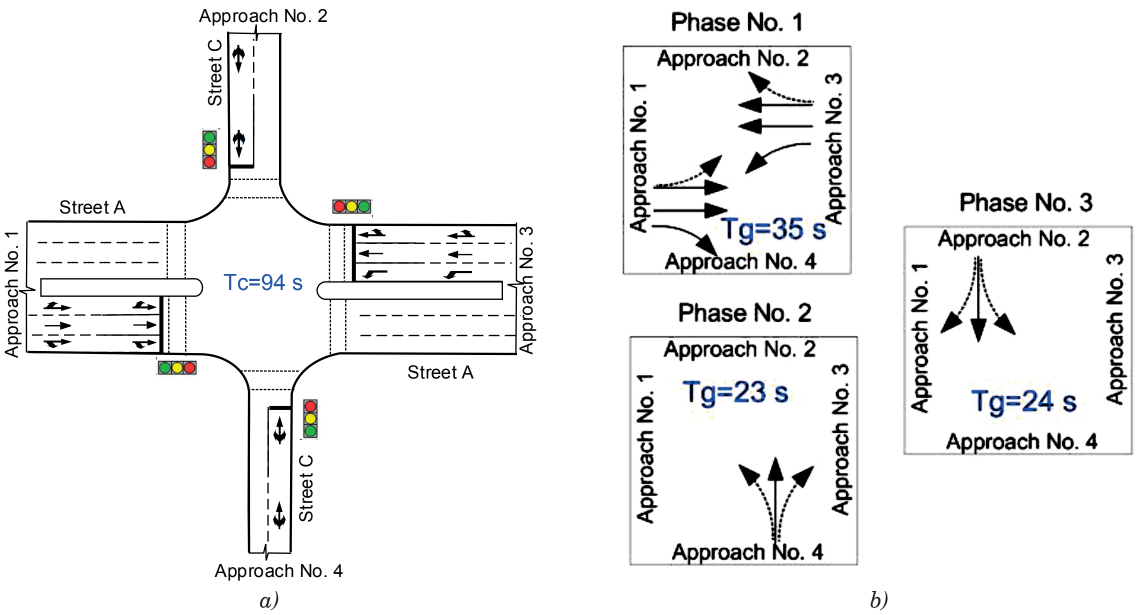



***Figure 6*** *Permitted directions of traffic flow by lanes at intersection No. 2 (a) and the phase sequence of vehicles (b)*

1, the public transportation is represented by medium-sized buses and trolleybuses, whereas at intersection No. 2, it is only represented by buses. Therefore, due to the absence of trolleybus traffic within the intersection No. 2, the share of public transport there is only 8%.

Based on the results of field studies, the parameters of the traffic signal operation modes were also determined. The phase sequence at intersection 1 consists of four phases, as shown graphically in Figure 5. The total duration of the traffic light cycle at this intersection is 126 seconds.

At the intersection of Streets No. 1 and No. 2, there is a low volume of pedestrian traffic that does not conflict with the traffic flow. At the same time, their movement occurs in each phase, but they were not taken into consideration. It is also worth noting that the intersection has good traffic conditions, with a minimal longitudinal slope of the roadway.

At intersection No. 2, the traffic light cycle time is 94 seconds. The phase sequence of traffic flows at the intersection consists of three control phases, which are graphically shown in Figure 6.

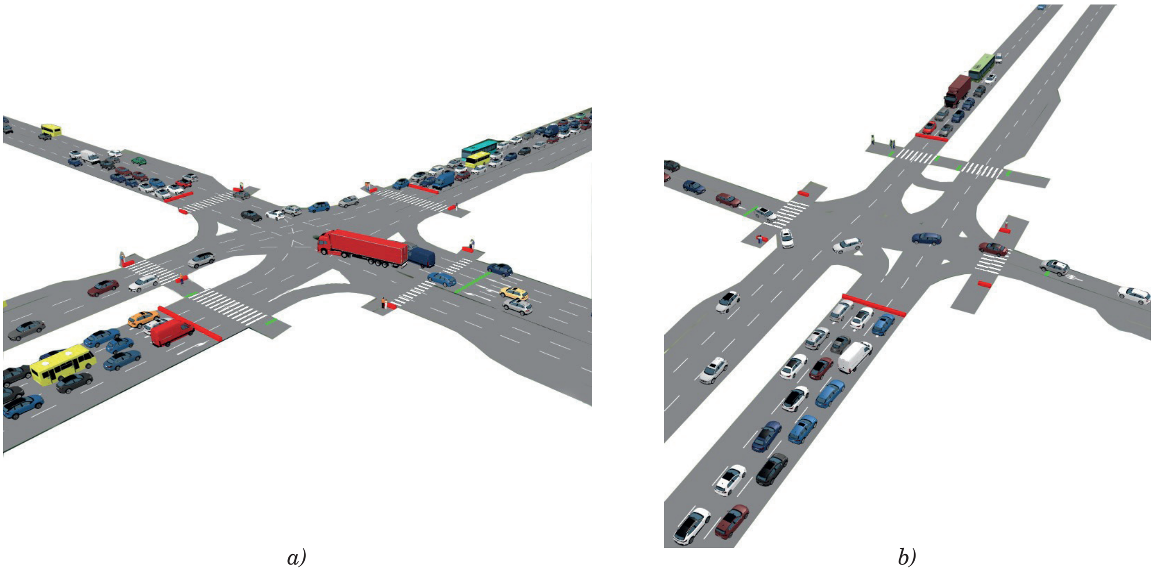
At each of the studied intersections, the duration of the yellow signal is 4 seconds. Both study objects are the standard four-leg signalized intersections with a significant control cycle of over 80 seconds. Their common characteristics is that the main direction of traffic passes along a city arterial street. It has three or more lanes on each approach, which allows for the distribution of traffic flows in separate directions. At the intersections, the traffic organization is realized using the multi-phase traffic signalization (three or more phases of regulation), considering the most congested directions of the intersection. As for the main difference between these intersections, unlike intersection No. 1, intersection No. 2 has combined turning and straight traffic on approaches No. 2 and No. 4 (on secondary streets) in one lane.

The field studies have shown that the heterogeneity of traffic flow at signalized intersections of city streets affects the duration of traffic delays. This phenomenon is prevalent during the peak periods, when traffic volume increases significantly. In addition, this phenomenon depends on the composition of the traffic flow, as different types of cars have distinct dynamic characteristics and, therefore, require varying times to maneuver and pass through the intersection. In turn, that affects the capacity and overall functioning of signalized intersections.

Based on the obtained numerical parameters and characteristics of traffic flows, the simulation models of street intersection functioning were created in the PTV VISSIM software environment. It should be noted that the design and operation of the traffic model of a signalized intersection in PTV VISSIM were based on its characteristics and structural components:

- planning characteristics of streets on the approaches to the intersection (number of lanes, their width, permitted directions);
- peculiarities of the operation of the system's controlled intersections and traffic signal control in general (number of control phases and their duration, total duration of the traffic light cycle);
- parameters of traffic flows (traffic volume, composition of the traffic flow, and its distribution by directions).

Considering the above, models of the studied intersections' functioning were created in the PTV VISSIM environment (Figure 7). This approach enables the collection of necessary data through the simulation and identification of dependencies between changes in traffic delay.



a) b)

***Figure 7*** *Created simulation models of the functioning of intersection No. 1 (a) and No. 2 (b) in the PTV VISSIM software environment*

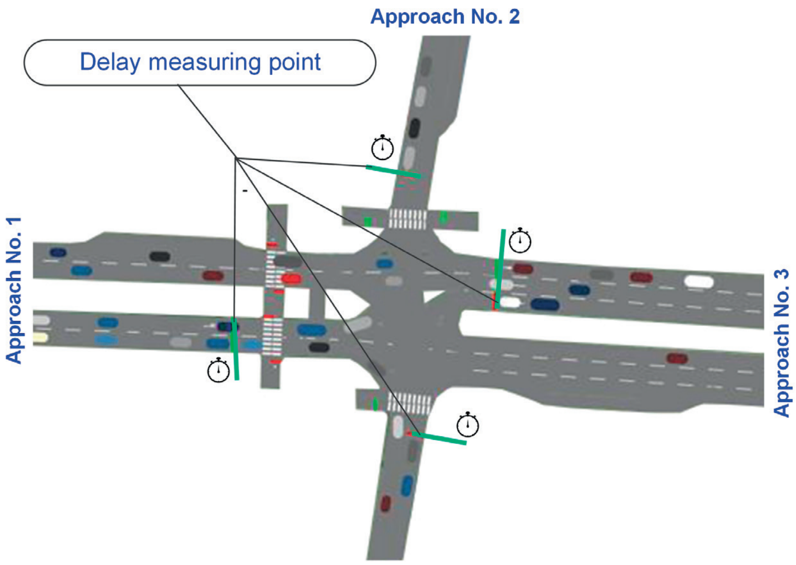



***Figure 8*** *An example of the placement of traffic delay counters at a signalized intersection*

Considering the accuracy of the forecast, the basic models of the standard four-leg signalized intersections under study are calibrated to reflect the existing traffic conditions. During calibration, the process of setting up the planning characteristics of the intersection and the initial parameters of the traffic flow in the specialized PTV VISSIM software environment is performed. The model of the intersection, with its initial parameters, is tested and verified for compliance with real data.

Given these inputs, it is planned to install counters at signalized intersections to record the duration of vehicle delays on all approaches to intersections (Figure 8). It is also necessary to model the traffic at the intersection under different scenarios of changes in traffic volumes, taking into account the different shares of passenger vehicles in the flow.

During the study of the operation of controlled intersections under different modelling scenarios, the traffic intensity at the intersection varied from 100 to 2800 vehicles per hour. This is due to the need to evaluate the efficiency of the regulated intersection. This range allows to model the intersection operation when traffic is moving. At a traffic volume of more than 2800 vehicles per hour on one of the approaches, a traffic jam occurs in the intersection area, and there is practically no movement. This leads to significant queues, and the traffic flow loses its dynamism. Under such conditions, further modelling becomes impossible, the intersection overloads, and cannot be reproduced adequately.

As noted earlier, the selected objects are typical intersections of arterial streets with controlled traffic and streets of district significance, where traffic control

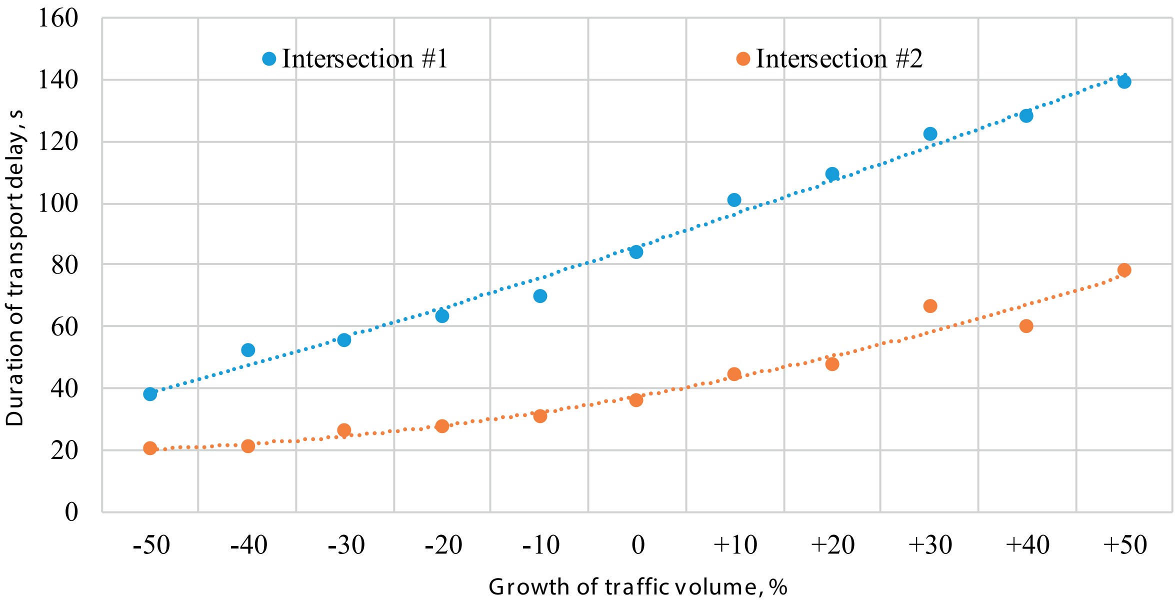



***Figure 9*** *Changes in the duration of traffic delays based on the traffic volume growth at controlled intersections*

***Table 2*** *Statistical indicators of transport delay depending on the increase in traffic intensity*

| Indicator | Intersection #1 | Intersection #2 |
|---|---|---|
| Arithmetic Mean, s | 85.5 | 42.3 |
| Median, s | 85.0 | 42.0 |
| Mode, s | 85.0 | 42.0 |
| Variance | 1093.2 | 345.8 |
| Standard Deviation | 33.07 | 18.59 |
| Range, s | 101.0 | 57.0 |
| Skewness Coefficient | 0.12 | 0.08 |

is implemented in three to four phases. Therefore, an important task is to identify the limit value of traffic volume at the intersection and the share of cars in the flow, at which the total traffic delay will be the smallest. It should also be noted that in this case, determining the total traffic delay duration for the entire signalized intersection would be the sum of the delays at each of its approaches.

## 4 The main results

In the basic intersection model, traffic flows consist of cars, trucks, and public transport. The intersection operation model incorporates the parameters of the roadway and traffic flow characteristics obtained during the field studies. In addition, the settings of the traffic light control system corresponded to the existing characteristics (the duration of the traffic light cycle was 126 seconds for intersection No. 1 and 94 seconds for intersection No. 2). The modelling involved changing the composition of the traffic flow by increasing or decreasing the share of cars. Additionally, there was a change in traffic volume (Figure 9). Creating such conditions gives an insight into the close relationship between the traffic flow indicators and the overall duration of traffic delays at signalized intersections.

The statistical analysis of the traffic flow parameters at intersections took into account the dynamic character of traffic composition changes and their impact on traffic delay. Therefore, normalization of the sample, data filtering, and calculation of the main statistical characteristics (Table 2) were performed during the processing of these parameters. After that, the correlation and regression analysis were used to determine the dependencies between the transport delay and the composition and volume of traffic flow.

For intersections, the arithmetic mean, median, and mode have almost the same value, indicating a symmetrical distribution of values around the center. The variation characteristics show a significant variance and standard deviation, indicating a wide range of delay fluctuations with a low skewness ratio.

The graph shows that as the traffic volume decreases from +50% to -50% (moving left to right along the X-axis), the average delay at Intersection #1 rises from approximately 40-45 s to nearly 150 s, indicating a strong sensitivity to reduced capacity and increased load

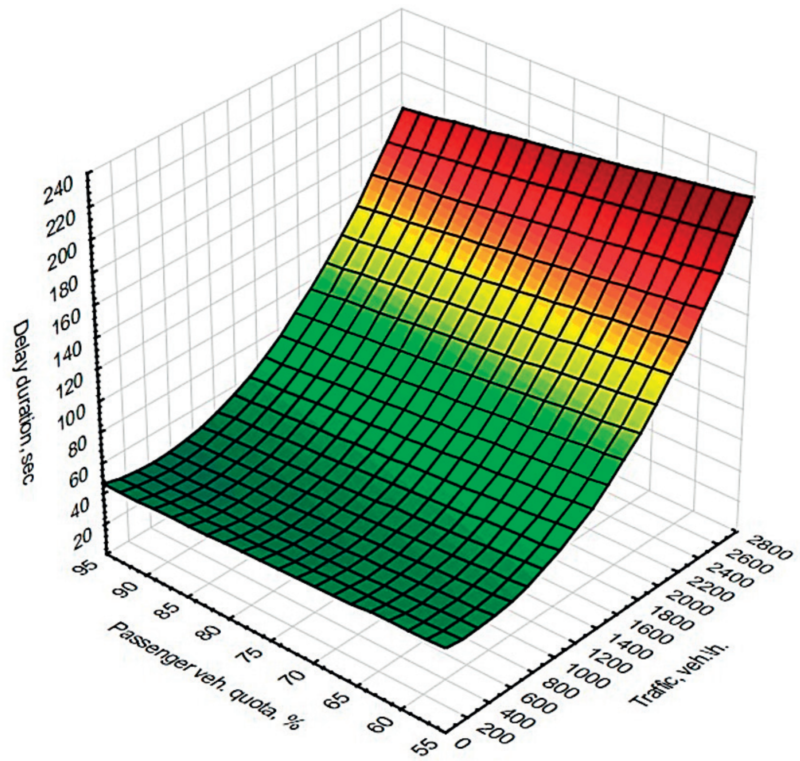



***Figure 10*** *Graphical dependence of the change in the total duration of traffic delay at a signalized standard four-leg signalized intersection, considering the traffic volume and the share of passenger cars in the traffic flow*

on the approaches. For Intersection #2, the delay grows more moderately - from about 20-22 s at +50% volume to roughly 75-80 s at -50% - demonstrating a more stable response to volume fluctuations. Overall, Intersection #1 experiences an increase of more than 100 s across the examined range, while Intersection #2 increase is about 55-60 s, confirming that the first intersection is significantly more affected by adverse changes in volume conditions.

Statistical analysis of the data obtained during the simulation indicates that, under existing traffic conditions at signalized intersections, the average delay duration at the entire intersection increases even with a slight increase in traffic volume. This, in turn, directly affects the intersection's capacity and, as a result, the overall delay for all the road users. The results differ somewhat for the two intersections because the planning characteristics of the secondary roads (Street B and Street C) are distinct. However, it was found that, in general, the dynamics of the growth of the share of passenger cars in the flow on all approaches to the intersection help to reduce the total delay at the intersection.

Additionally, it is worth noting that the composition of the traffic flow significantly impacts the duration of traffic delays on the approaches to the intersection. For example, as the number of slow-moving vehicles approaching the intersection from all directions increases, the probability of queuing increases.

There is a rather long traffic light cycle at the two signalized intersections. It allows determining the delay duration in more detail, considering the share of different types of vehicles and their interaction at urban signalized intersections. In addition, the operation of intersections with increased traffic volume was simulated to obtain an accurate and realistic estimate of the delay duration. This approach enables the prediction of moments when the intersection will operate in congestion mode, resulting in a significant increase in traffic delays.

Under the existing control cycle, minor congestion was observed on the secondary directions of the intersection. In turn, the most considerable delays were formed on the approaches No. 1 and No. 3 from Street A (both intersections). Therefore, the total delay at the intersection was taken into account. The simulation involved creating different loads under multiple options for changing the share of passenger cars in the traffic flow and their overall volume. The change in traffic delay, when the permissive signal was turned on, was evaluated over 10 simulation cycles. Based on the obtained values and the application of mathematical analysis tools, a graphical relationship between the traffic delay, traffic volume, and the proportion of cars in the traffic flow was established (Figure 10).

Figure 10 illustrates a three-dimensional geometric surface that displays the area of critical traffic volumes and various scenarios of fluctuations in the share of passenger cars in the flow, allowing for the visualization of changes in traffic delay at signalized intersections.

## 5 Discussion

The lowest average traffic delays are observed at traffic volumes of no more than 1500 vehicles per hour and a share of passenger cars in the traffic flow of more than 85%. Under such conditions, the signalized intersection is potentially efficient, as it has the lowest total traffic delay. In turn, a significant accumulation of traffic delays is observed on the main road, with a traffic volume exceeding 2000 vehicles per hour and a share of passenger cars of less than 80%. In the traffic volume range of 1600-2000 vehicles per hour on the approach to the intersection, even with a share of passenger cars of less than 90%, a significant increase in the duration of traffic delays was observed. These results are explained by the simulation conditions, under which forward and turning flows move from one lane of the road in one phase of traffic light control. Thus, the increase in the traffic delay duration at high traffic volumes on the same approaches to the intersection (in terms of the number of lanes and permitted maneuvers) is significantly affected by the share of cars in the flow. Such a delay is typical for complex signalized intersections of city streets, where the traffic light cycle has a significant duration and the phase sequence consists of three or more phases. Therefore, the data visualization demonstrates a clear functional relationship between the traffic delay and traffic volume, considering its share of passenger vehicles.

Taking into account the increase in traffic volume and the share of passenger cars in the flow, a general mathematical dependence of the delay duration was developed based on the traffic modelling under various scenarios of changes in traffic flow parameters ($T_d$):

$$T_d = 0.00003 \cdot N^2 - 0.4\mu + 50, \tag{1}$$

where $N$ - traffic volume at the intersection; $\mu$ - share of passenger cars in traffic flow, %.

Reducing the traffic delays at an intersection can be achieved by changing the homogeneity of traffic flow in the lanes. Generally, the most significant delays occur on approaches where there is a substantial difference in the composition of the traffic flow and the dynamic characteristics of the vehicles. At the same time, the traffic safety and capacity of a signalized intersection depend on the parameters of the traffic management scheme. Additionally, the study results demonstrate a clear relationship between the duration of traffic delay and both traffic volume and the proportion of passenger cars in the traffic flow. It is of great importance for planning and optimizing traffic signaling, as well as improving traffic management.

Based on the model of changes in traffic delay as a function of traffic flow parameters (volume and composition), algorithms can be developed for the operation of traffic signal control systems. This would enable the consideration of predicted traffic delay values during traffic management. The proposed model, in contrast to the existing ones, focuses on the composition of the traffic flow and its intensity at a standard four-leg signalized intersection when determining the traffic delay. This scientific method allows to enable the adaptive traffic control, which helps to reduce the accumulation of vehicle queues on the approaches to the intersection and lowers the probability of traffic jams.

Traffic modelling, considering the growth in traffic volumes, enables the prediction of moments when the intersection will start operating in saturation or overload mode. Such conditions can lead to a significant increase in traffic delays. Additionally, the approach to modelling various traffic flow parameters at the intersection enables the estimation of traffic delays before the intersection without altering the duration of the traffic light phases. It is especially relevant for intersections where all the traffic from one approach moves in one phase. In addition, this approach not only allows for determining the current values of traffic delays but also for predicting their change, as the volume capacity ratio on city streets and roads increases.

Simulation of options for adjusting the share of passenger cars in the traffic flow at a signalized intersection revealed that the best results in terms of minimizing the total traffic delay are achieved with a homogeneous traffic flow. According to the results, the duration of the delay at the intersection increases significantly when the traffic volume on the approach exceeds 800 vehicles per hour and the share of passenger vehicles is less than 70%. This increase was especially noticeable if traffic was moving simultaneously from one lane. It highlights the need to regulate the entry of freight transport, clearly zoning lanes by direction of traffic, and allocating lanes for public transportation. It will reduce conflicts between vehicle types and ensure uniform and smooth traffic flow.

The correlations obtained between delay, traffic intensity, and traffic flow composition can be directly used as input parameters or training data for adaptive traffic light control systems based on machine learning. Since the simulation covers a wide range of traffic intensity and passenger car share, these results provide a structured dataset that helps algorithms learn how heterogeneous flows affect delay formation. Integrating delay predictions that account for flow composition into the real-time optimization will allow controllers to proactively adjust green light times, especially in conditions where small changes in vehicle composition cause disproportionate increases in delays. Thus, the proposed model supports the development of more accurate, predictable, and reliable adaptive traffic signal control strategies.

Future research may extend this approach by incorporating pedestrian flows, examining the effects of public transport prioritization, and analyzing coordination strategies between adjacent signalized intersections, all of which may further influence delay formation and overall network performance.

## 6 Conclusions

1. The study of planning features, phase sequence, and traffic flow parameters by direction was conducted at the signalized intersections. It was found that the highest traffic volumes were recorded on approaches No. 1 and No. 3 of the main direction of Street A. The straightforward traffic flows predominate at intersections, and there is a significant share of trucks, which averages 20%. At signalized intersections, each phase is designed to accommodate the flows of a particular approach or direction of the main road.
2. As a part of the study, a simulation of signalized intersections was developed to determine the traffic delays at them. The application of the basic model enabled the analysis of changes in traffic delays resulting from variations in traffic flow indicators. The analysis of the modelling results shows that the most significant increase in traffic delay, over 10 consecutive simulation cycles, is observed on the main road approaches. In particular, the traffic delay on such approaches within the modelling period ranges from 50 to 240 seconds. Additionally, it was found that at the current traffic volume level, the traffic flow structure also significantly affects traffic delay.
3. In the PTV VISSIM software environment, a study was conducted to investigate the impact of traffic flow parameters on traffic delay indicators at a signalized intersection. As a result of the modelling, the average values of traffic delays were determined, which varied with the growth of traffic volume and fluctuations in the composition of the traffic flow. The analysis of scenarios in which the share of passenger cars changed with a constant duration of traffic signal phases revealed a clear link between the traffic flow parameters and delays. In particular, the average traffic delay did not change significantly when the traffic volume was up to 1,600 vehicles per hour and the share of passenger cars was up to 70%. However, at traffic volumes exceeding 1,800 vehicles per approach, even a slight decrease in the share of passenger cars (below 60% of the total flow) resulted in a significant increase in both the average and maximum values of traffic delay for the entire intersection. The results demonstrate a high sensitivity of the duration of delays to the structure of the traffic flow, particularly the share of passenger cars, which should be considered when optimizing the traffic control modes and traffic management at complex intersections where flows separate into more than three phases of control.
4. Based on the developed simulation model, clear graphical and mathematical dependencies were obtained linking delay duration with both traffic volume and the share of passenger cars in the flow. The 3D delay surface shows that for mid-range volumes of 1,200-1,500 veh/h, increasing the passenger-car share from 55% to 90% reduces the total intersection delay by approximately 20-35 seconds, demonstrating the strong influence of flow homogeneity even before reaching saturation. At higher intensities above 2,200 veh/h, the model indicates that each additional 5% decrease in passenger-car share can add 10-15 seconds to overall delay, even when the total volume is kept constant. These numerical patterns confirm that delay growth is not only a function of intensity but strongly depends on structural changes in the traffic stream as well, reinforcing the need to incorporate flow composition into optimisation of traffic control strategies and into the development of adaptive or machine-learning-based signal control systems.

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## Conflicts of interest

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

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