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ESTABLISHING PATTERNS OF CHANGE IN THE EFFICIENCY OF REGULATED INTERSECTION OPERATION CONSIDERING THE PERMITTED MOVEMENT DIRECTIONS

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The object of this study is a regulated intersection of city streets. The main task being solved is the reduction of queue lengths on approaches to such intersections by organizational measures. As a result of the research, patterns of change in queue lengths in front of the stop line were revealed, taking into consideration the specialization of traffic lanes and the distribution of traffic flows by directions. It was established that with an increase in the share of left-turning vehicles in the lane by 15 % and above, there is an increase in the length of the queue before the intersection from 45 to 80 m. The results indicate that when choosing a traffic pattern at the intersection, it is necessary to take into consideration not only the intensity of the flow itself but also the proportion of vehicles performing certain maneuvers (in this work, turning left is considered).

A feature of the results is that they are obtained using simulation tools. This research method has made it possible to derive the value of the length of the queue in front of the intersection, changing the load on the approach from 200 to 1000 vehicle/h and the share of left-turning vehicles from 5 to 15 %. In addition, using a simulation model, it was checked how the intersection functions under various traffic management schemes on it when the input parameters of traffic flows change.

The research results are recommended to be used in the development of traffic management schemes at regulated intersections. When determining the permitted directions of movement in the lanes, it is necessary to take into consideration the patterns of change in the length of queues before the intersection since under certain circumstances they may exceed critical values

Keywords: traffic flow, regulated intersection, simulation modeling, queue length, traffic safety

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1. Introduction

The rapid development of the pace of housing construction occurred precisely at the period of increasing the purchasing power of residents of urban spaces, which led to two problems in the field of transport planning of cities at once. The first is a natural increase in the number of personal vehicles (Vs) on the street-road network (SRN), which is explained by the growth of the share of the population that has the financial ability to purchase and maintain personal cars. This phenomenon affects the increase in the intensity of traffic flows (TF) on the network as a whole, and provokes a critical load on the main transport hubs of cities. Another, no less acute problem, is the change in the patterns of resettlement of urban residents since the territory of a city, which until recently was not used, or had another purpose, is now massively allocated for residential development. Thus, the urban transport infrastructure and the main conceptual routes of communication no longer correspond to the vectors of demand for movement. Separately, it can be noted that most large residential complexes are located along key main streets since this is a criterion for the attractiveness of real estate in the prospect of their acquisition. All this causes a critical load on the transport infrastructure, which is not designed for such traffic volumes.

At the same time, there were trends in the development of sustainable mobility, the principles of which provide for a reduction in the use of private transport for urban commute, as well as the popularization of public transport and alternative types of movement (bicycle, micro mobility, car sharing, etc.). At the same time, such trends imply a change in the philosophy of using the urban area, namely the creation of more public spaces and the compaction of the population due to new residential development. Under such conditions, the value of urban land increases significantly, which makes it impossible to implement infrastructure solutions aimed at changing the geometrical parameters of streets and intersections.

In large and significant cities, there are serious transport problems that are associated, on the one hand, with a decrease in spending on street infrastructure, and on the other hand, with the growth and compaction of the urban population. There are conditions under which the number of commuters and private transport increases while the infrastructure is not able to develop. A gap is created between the constant value of the capacity of streets and intersections and the increasing intensity of TFs. With the achievement of sustainable mobility goals, this gap will narrow, however, certain solutions are needed for the transition period. They will make it possible to quickly and comfortably move around in personal cars until the time when public transport and other types of movements will become a significant alternative. During this period, organizational decisions come to the fore, due to which it is possible to increase the reserves of capacity of SRN.

Improvements in the organization of traffic at the intersections of main streets are usually associated only with changes in permitted traffic directions, optimization of phase-by-phase traffic, the operation of traffic lights and channeling of traffic directions. These approaches provide an opportunity to partially increase the throughput of intersections without resorting to a radical change in their geometric parameters.

The design of traffic management schemes and the development of modes of operation of the traffic light alarm is based on input data, which include the study of the intensity, speed of movement, and composition of TFs. The heterogeneity of TFs on SRN, especially on approaches to intersections, negatively affects the efficiency of their work. Different in their parameters and dynamic characteristics, vehicles during maneuvering in the intersection zone reduce their throughput. This reduction largely depends on the permitted driving directions. In turn, this leads to a decrease in the speed of movement of TFs and traffic safety during the merging or separation maneuver.

The criterion for the effectiveness of the proposed changes in the organization of traffic at intersections is the loss of time, which is expressed by the amount of traffic delays (general and in directions), as well as the value of the lengths of queues before intersections. Among the means of designing and studying the effectiveness of traffic management schemes, it is worth highlighting simulation. It makes it possible to change the input parameters and derive the values of the criteria for the expediency of applying various traffic management schemes. In view of the above information, studies related to determining the effectiveness of the intersection in different specializations of traffic lanes are relevant. It is necessary to take into consideration the value of the intensity of TFs and the proportion of turning vehicles. This will allow us to find ways to improve traffic conditions at intersections, even only through organizational measures.

2. Literature review and problem statement

Transport delays are a forced stop or decrease in the speed of the vehicle compared to the possible values on the same section of the street or road. Long-term transport delays often lead to the formation of traffic congestion. They are a phenomenon of the immobility of TFs, which is formed on the basis of its maximum compaction. It occurs due to an increase in traffic intensity, which exceeds the capacity of a section of a street or road [1].

The phenomenon of vehicle traffic delays leads to a decrease in the efficiency indicators of the transport network and the proper level of road safety. It is impossible to completely eliminate them but with a clear understanding and study of problem areas, it is possible to minimize the loss of the main indicators of TFs. At the same time, traffic delays and congestion are often formed on the approaches to intersections. This is due to the fact that in such areas the ways of regulating traffic, the number of lanes for movement often change, conflict points are formed [2]. Thus, an important direction to improve the existing situation on SRN and, in particular, to reduce traffic delays at intersections is to increase traffic safety, increase capacity, ensure proper conditions for the movement of public transport and pedestrians, etc. [3]. However, it is obvious that it is very difficult to take into consideration all the factors at the same time, especially for cities with dense infrastructure.

It should be noted that the whole set of technical means and methods of traffic management should be a single system, which is aimed at improving the safety and ease of movement of all road users [3]. Thus, owing to the introduction of modern means of information technology in the field of traffic regulation and control, it is possible to increase the capacity of intersections, traffic safety, and reduce vehicle delays. In [4], adaptive regulation of traffic lights is the application of such technologies. However, the introduction of such systems is expensive and effective at low intensities of TFs.

As for traffic delays, their assessment at unregulated intersections can be carried out using microsimulation for all turning TFs. Work [5] reports the results of the study of vehicle traffic delay and queue length for turning flows at an X-shaped intersection. In this case, the PARAMICS software environment was used. It was established that at unregulated intersections with high intensity, turning maneuvers of cars are possible only if there are sufficient intervals in the traffic flow of the conflicting direction. However, at regulated intersections, with the appropriate setting of the regulatory phases, these TF conflicts can be avoided.

According to the results of research reported in work [6], it was found that vehicle traffic delays are an important parameter for assessing both the efficiency of work and the safety of intersections in general. This is due to the fact that even for vehicles that carry out the merger maneuver, there is a significant danger and it depends on the homogeneity of TF. At the same time, in urban environments, there are usually mixed flows of cars with different dynamic parameters, which will make it difficult to maneuver the vehicle at intersections.

At regulated intersections, turning vehicles often move in conjunction with forward-moving TFs. Thus, in places where movement in several directions from one lane is allowed, turning vehicles should give preference to forward-moving flows. Accordingly, while expecting the possibility of making a safe maneuver, they create obstacles to Vs, which are moving directly from the same lane. In addition, under urban traffic conditions, where pedestrians with TF are often allowed to move, queues of cars are created waiting for their maneuver. At the same time, the lane of traffic by which the vehicle is moving directly is completely blocked during the green signal of the traffic light. Thus, the authors of work [7], based on modeling, constructed a mathematical model that takes into consideration the probability of blocking lanes at intersections, which is caused by turning TFs. However, the stochastic nature of the arrival of TFs at regulated intersections leads to a complication of the relevant calculations. In addition, in practice, this is accompanied by significant delays, which are greater in value from the indicators obtained by standard deterministic models for estimating queues in front of the stop line. This leads to the fact that the delay associated with the accidental arrival of rolling stock at the intersection will be higher than the delay associated with uniform flow [8]. In turn, work [9] noted that the uneven arrival of the vehicle at a regulated intersection has a significant impact on the assessment of delays at the entire intersection. This is due to the fact that fluctuations in the arrival of TFs to the intersection leads to a significant dispersion in the distribution of delays on all its approaches. In addition, with a significant intensity of movement, especially during peak periods of the day, at the beginning of the control cycle there is often already a queue of vehicles that do not have time to pass the duration of the permitting signal. As a result, there is an accumulation of the queue of cars in anticipation of the permitting signal of the traffic light in the next adjustment cycle.

For a more detailed comparison of the change in the average delay at an adjustable intersection, it is advisable to conduct research on a fully saturated adjustment phase (for saturation degrees from 0.7 to 1.2). At the same time, it is necessary to calculate the transport delay for a long period (several control cycles). Thus, the analysis of the organization of traffic at a regulated intersection using simulation makes it possible to improve the planning parameters and make an objective assessment of the existing state of TF indicators. However, it will not give a clear answer regarding the traffic pattern at the intersection without further detailed analysis [10]. This is due to the fact that the cause of vehicle delays is the heterogeneity and unevenness of TFs. Therefore, taking into consideration the composition of TF in each lane of traffic at the intersection during research makes it possible to identify the effectiveness of the functioning of the regulated intersection and increase its capacity.

In accordance with the above, it can be argued that the duration of movement of rolling stock on city streets largely depends on the delays of vehicles at key intersections of SRN. The study of changes in traffic delays at regulated intersections will provide a comprehensive picture of the travel time at difficult intersections and the total duration of the vehicle's stay on the road. Taking into consideration the fact that the process of arrival of cars at the intersection is probabilistic in nature, the real delay at the intersection may differ from the expected one. Thus, in order to choose the optimal traffic management scheme and increase the efficiency of regulated intersections, it is advisable to carry out simulation modeling under different traffic conditions, TF parameters, and the duration of the traffic light cycle.

3. The aim and objectives of the study

The aim of this work is to determine the patterns of change in the efficiency of the functioning of a regulated intersection depending on the permitted directions of movement on it. This will make it possible to make informed decisions on the choice of permitted driving directions at regulated intersections.

To accomplish the aim, the following tasks have been set:

– to carry out field studies of the existing traffic conditions;

– to create and calibrate a simulation model of the street intersection;

– to determine changes in queue lengths taking into account the share of turning vehicles;

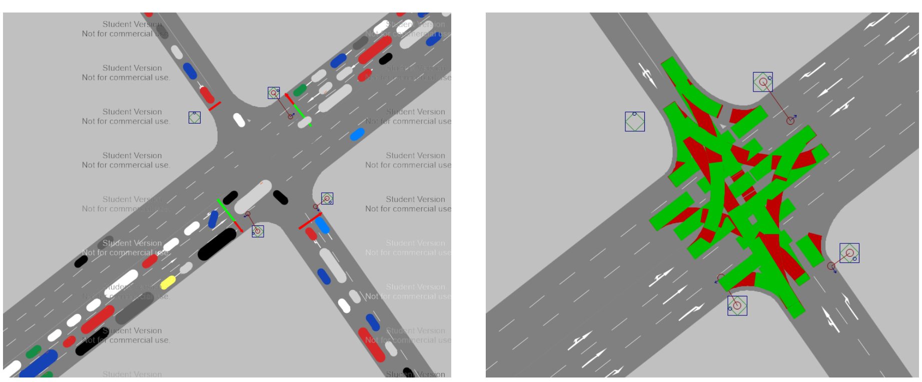
– to determine the efficiency of the intersection and compile practical recommendations regarding the use of simulation modeling results.

4. The study materials and methods

The object of research in this work is the regulated intersection of city streets. Due to the specificity of its functioning, the study of the main characteristics of traffic flows on it is carried out in two stages. The first is full-scale observations at the site, which involve physical fixation of the intensity of movement in the directions and composition of the traffic flow. The results of information processing are represented in the form of a diagram with average hourly values of the intensity of movement in directions, as well as derived calculations (composition of the flow by type of vehicle and distribution by directions of movement).

The main hypothesis of the study assumes that there are certain critical values of the fraction of left-turning vehicles at certain traffic intensities at which the value of the length of the queues before the intersection is critical. Therefore, it is worth, upon reaching these values, to revise the type of permitted maneuvers from the extreme lanes of traffic. In order to test such hypotheses and assumptions, the second stage of research is carried out – motion modeling. This method involves the creation of an idealized digital copy of the object of research, taking into consideration the parameters of its functioning, which were determined at the first stage of observations.

The model of the intersection was created in the PTV Vissim software package. It makes it possible to develop at the micro level different combinations of interaction of all road users with different input data [11]. When building a simulation model, the priorities of the intersection are fixed in places of vehicle conflicts (Fig. 1). For a regulated intersection, in accordance with the traffic management scheme, traffic lights are placed and the corresponding phase durations in the control cycle are set. For modeling, meters for measuring traffic delays, queue lengths should also be arranged, and the routes of passage of the intersection are recorded on the stop lines to determine the time of travel of vehicles.



a *b*

Fig. 1. Simulation model of the intersection in the PTV Vissim environment: *a* – the process of imitation; *b* – prioritization of conflicting flows

Having made sure that the model is functioning correctly, further activites are aimed at variation of its input parameters and observation of changes in the studied characteristics of TFs (duration of delays, length of queues, etc.).

The data obtained for processing and analysis in the process of research can be divided into two groups: those that were collected in the process of field studies, and those that are generated during motion modeling. The processing of the first type of data was carried out by aggregating the values of traffic intensities in the directions and composition of the traffic flow. The processed results are represented in the form of tables, graphic diagrams of intensity, and a plot. The data obtained in the full-scale way (intensity of movement in directions, composition of TF) are input information for building a viable simulation model.

Experimental data obtained in the modeling process (the value of the length of the queues) are generated by the computer program, each time the input parameters change (traffic intensity, distribution of TFs by directions). To obtain a sufficient array of experimental data, an aggregation of the values of the change in the length of the queues before the intersection for 10 traffic light cycles was carried out for each of the 4 options for the proposed organization of traffic at the intersection. Modeling work of the intersection in each variant also involves obtaining values of the average and maximum queue lengths for 3 ranges of traffic intensity, including 5 proposed values of the share of left-turning vehicles.

These data sets underwent an aggregation process into their respective spreadsheets (MS Excel), convenient for further statistical processing.

The results of data processing, which indicate the identified patterns of queue change on approaches to the intersection, are represented in the form of regression curves. Three-dimensional graphical dependences and multiple regression equations were constructed in the Statistica environment, which uses imported data from the corresponding spreadsheets.

5. Analysis of traffic flow indicators and results of modeling the work of a regulated intersection

5. 1. Results of full-scale studies of traffic flow parameters at a regulated street intersection

The analysis of the planning characteristics of the studied regulated intersection is carried out and the geometrical parameters of the lanes on each approach to it are determined. A graphic image of the allowed driving directions at the intersection is shown in Fig. 2. The main road at the intersection is the main street with regulated traffic (street A). It consists of two approaches (approach No. 1 and No. 3) and has a three-lane carriageway (lane width, 3.75 m), which are partially channeled. Adjacent streets to the main road have a lane width of 3.5 m. From the approach of street No. 2 there are two lanes (V and VI) of which the extreme right lane is allocated only for the movement of right-turning vehicles, and on the other lane the movement of forward-moving and left-turning TFs is combined. From the approach of street number 4, there is one lane where all directions of movement are allowed.

According to the results of field studies, the traffic light signaling mode was established at an adjustable intersection, which is graphically shown in Fig. 3.

According to the results of field studies at this regulated street intersection, the distribution of the intensity of TFs along the directions was established (Fig. 4).

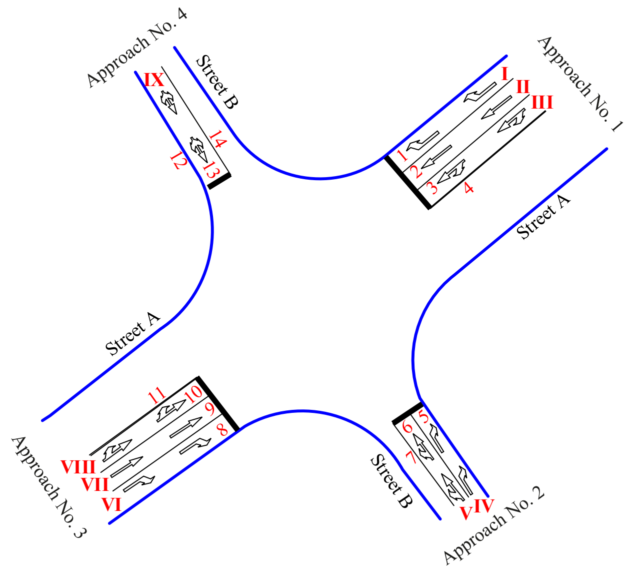


Fig. 2. Actual scheme of traffic flows at the studied intersection

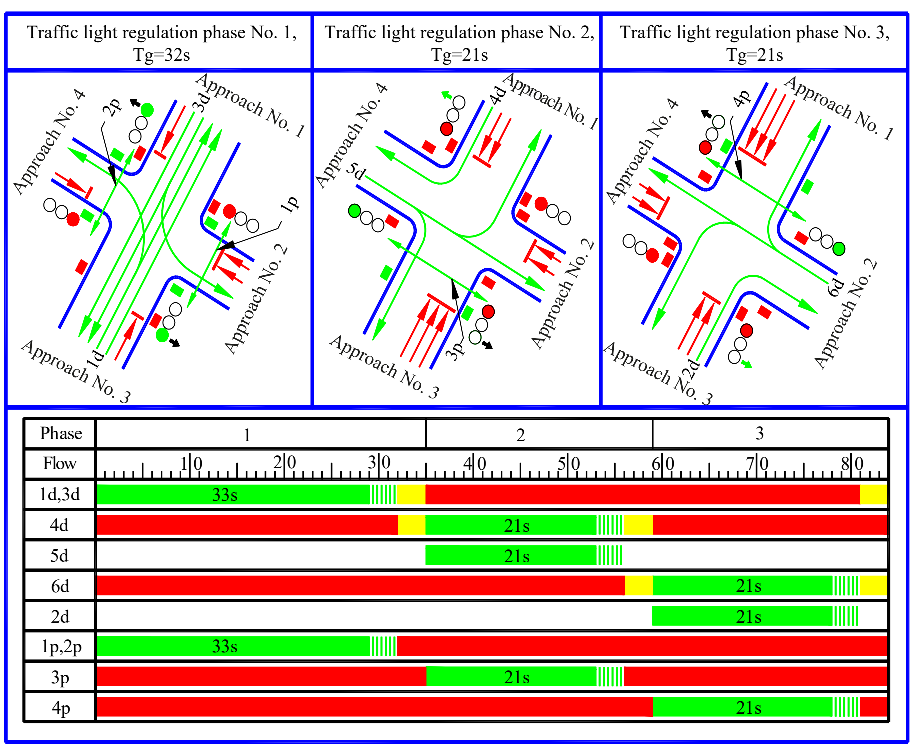


Fig. 3. Phase-by-phase traffic of vehicles at street intersections and a cyclogram of traffic light regulation

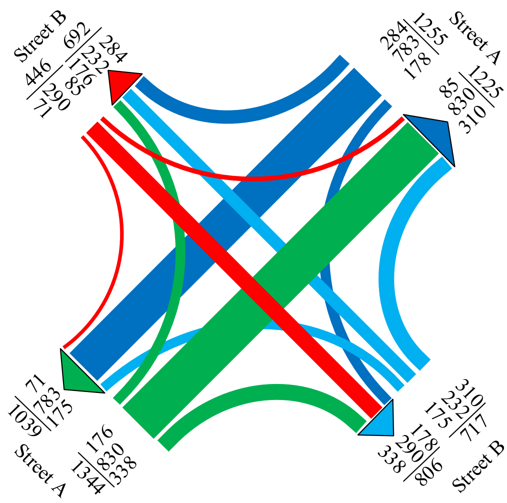


Fig. 4. Diagram of traffic intensity at the studied street intersection

Table 1

Percentage distribution of TFs by driving directions on approaches to a regulated intersection

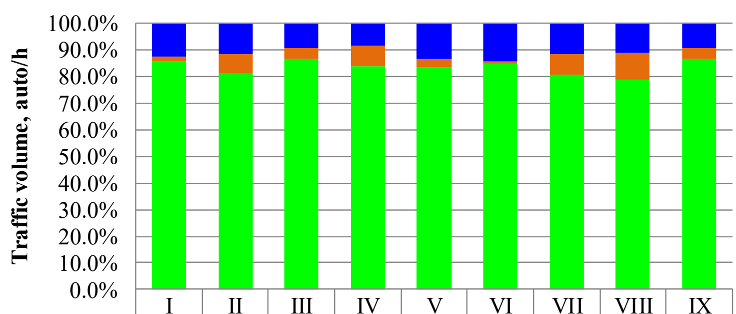
Type of maneuver	Approach to a regulated intersection			
	Approach No. 1	Approach No. 2	Approach No. 3	Approach No. 4
Right-turning Vs	23 %	43 %	25 %	16 %
Forward-moving Vs	60 %	31 %	59 %	65 %
Left-turning Vs	17 %	26 %	16 %	19 %

If we take into consideration the main direction of the road at the studied intersection, then, in this case, the TF is dominated by vehicles moving in the direction «forward». The share of right-turning flows ranges from 23 to 25 % depending on the approach. In the main direction of the intersection, there is also a significant proportion of left-turning flows, which is 16–17 % of the total traffic intensity on the approach.

When analyzing the intensity of TFs on the approaches to the intersection, its composition on each lane of traffic is determined, which is graphically shown in Fig. 5.

According to the results of field studies, it was found that cars predominate in all lanes of traffic at a regulated intersection. The largest share of them is observed on secondary streets adjacent to Street A.

For each approach of a regulated intersection, the distribution of TFs by directions of movement was established, which is represented as a percentage in Table 1.



	I	II	III	IV	V	VI	VII	VIII	IX
Cargo car	12.3%	11.8%	9.2%	8.4%	13.5%	14.2%	11.5%	11.2%	9.4%
Bus	1.8%	7.2%	4.1%	7.7%	2.9%	0.9%	7.8%	9.8%	4.0%
Passenger car	85.9%	81.0%	86.7%	83.9%	83.5%	84.9%	80.7%	79.1%	86.5%

Fig. 5. Distribution of traffic flow by composition for each lane of traffic at the studied street intersection

5. 2. Model of operation of an adjustable intersection under existing driving conditions

In the PTV Vissim environment, an intersection model has been created to study the dependence of the length of queues on approaches to it under existing driving conditions, in particular:

– the departure takes place in three phases;

– the duration of the adjustment cycle is 84 s;

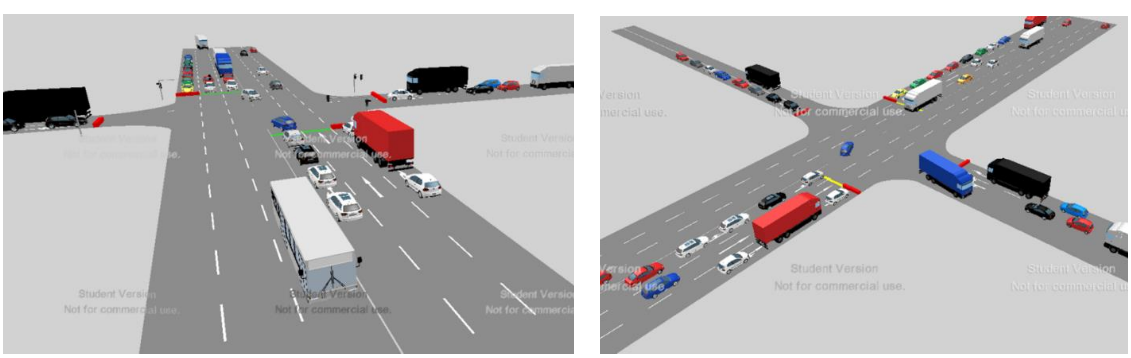
– the duration of the main cycle for the passage of TFs on the main road is 33 s, and on secondary streets – 21 s;

– the width of the lane on the main road is 3.75, on the secondary road – 3.5 m.

The model of the adjustable intersection is shown in Fig. 6.

The results of modeling the length of queues on approaches to the studied intersection under the existing traffic intensities of TFs are shown in Fig. 7. When modeling traffic at an adjustable intersection, the degree of saturation in each direction (lane) of traffic and in each phase of regulation varies between 0.6–0.7 a.u.

Thus, on approach No. 1 (street A), the longest queue length is observed; it is 98.8 m. On this approach, traffic is carried out in three lanes (I–III) with an average degree of saturation in the adjustment phase (duration 33 s) and with a total traffic intensity of 1255 vehicle/h.



a *b*

Fig. 6. Model of traffic flow junction at a regulated street intersection: *a* — view from the main direction; *b* — general view of the intersection

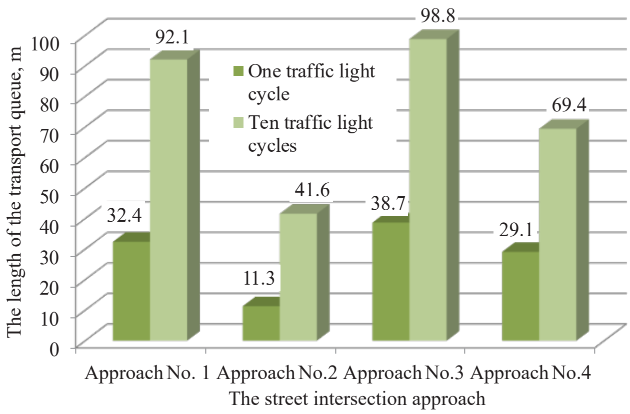


Fig. 7. Changing the length of the queue of cars at an adjustable intersection under existing conditions

This length of the vehicle queue in the main direction is explained by a significant proportion of turning TFs and the presence of public transport. This situation is also noticeable in the opposite direction of traffic from approach No. 3 in lanes VII and VIII. These are the lanes from which the movement of turning TFs is allowed and there is a share of buses and trucks, which is more than 15 %. On the approach from lane IX with a traffic intensity of more than 446 vehicle/h, there are insignificant queues of vehicles with a length of 29.1 m in one adjustment cycle. If we take a larger number of imitation cycles, the maximum queue on this approach will be formed, up to 70 m long. Such an accumulation of a queue of 13–15 cars is insignificant due to the fact that turning and forward-moving vehicles are allowed to move from one lane. On approach number 2, where there are two lanes of traffic and one of them is provided only for right-turning flows, and the far left for forward-moving and left-turning, the queue length is the smallest among all approaches; it is 41.6 m.

According to the research results, with the existing traffic intensity, the vehicle queues before the intersection are significantly affected by the composition of TF and its share of turning vehicles. In traffic lanes where the share of low-speed vehicles and turning vehicles is more than 15 %, the values of the queue length are much larger than in other lanes where more uniform TFs move.

Modeling the work of the intersection, taking into consideration the change in the intensity of movement and the duration of the cycle, will make it possible to obtain patterns of change in the length of vehicle queues at different proportions of turning flows. Since a significant proportion of turning vehicles move simultaneously with forward-moving flows and there is a heterogeneity of the entire TF, there is an increase in the queue at the approaches to the intersection.

5. 3. Change in the length of queues, taking into consideration the proportion of turning vehicles

The selected regulated street intersection under urban traffic conditions is a typical intersection of main regulated traffic and district streets with a three-phase traffic light cycle. Therefore, for such traffic conditions, it is important to check at what specialization of traffic lanes on the main road and changes in the intensity of TF, the queues of the vehicle on the approaches to the main road will be the smallest. Thus, in the PTV VISSIM environment, to determine the maximum length of vehicle queue in front of the stop line, a simulation of the intersection was carried out under various options for organizing the movement of flows on Street A (Fig. 8).

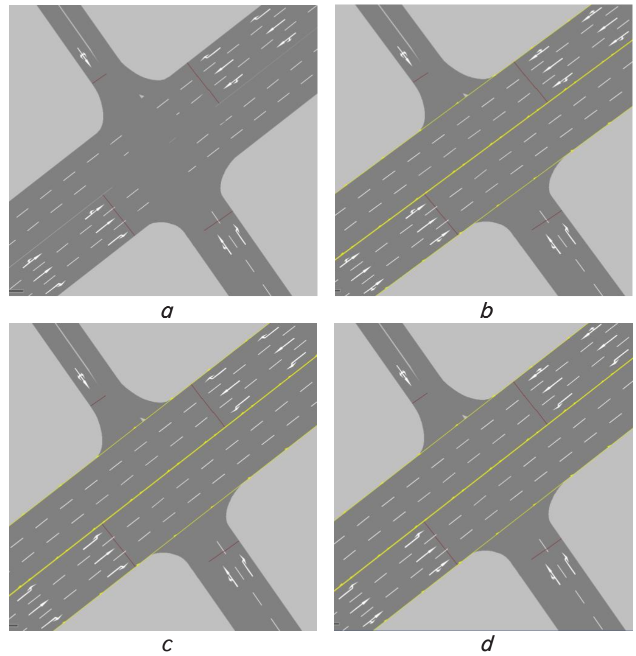


Fig. 8. Organization of permitted directions from traffic lanes on the main street A: *a* – actual condition; *b*–*d* – proposed options

Fig. 8 demonstrates that we modeled the work of the regulated intersection for four options for organizing turning flows from the main road:

– option 1 – from the extreme left lane, traffic is allowed for forward-moving and left-turning flows, the middle lane is designed for forward-moving traffic, and the extreme right lane is for traffic on the right;

– option 2 – from the extreme left lane, traffic is allowed for forward-moving and left-turning flows, the middle lane is designed for forward-moving traffic, the extreme right lane is for forward-moving traffic and to the right;

– option 3 – from the leftmost lane, traffic is allowed only on the left, the middle lane is intended for forward-moving traffic, and the rightmost lane is on the right;

– option 4 – from the leftmost lane, traffic is allowed only on the left, the middle lane is designed for forward-moving traffic, from the extreme right lane, it is allowed to move forward and to the right.

In the basic model, intersections of TFs consist of cars, trucks, and buses (trolleybuses). The model accommodates the following parameters: the share of passenger vehicles in the flow is 85 %, the share of turning flows from the lane on the main road is 30 % (5 % – right-turning; 0–25 % – left-turning), there are no longitudinal slopes on the approaches to the intersection. For all modeling options, the duration of the traffic light control cycle was 84 s, as well as according to the results of field studies. During the simulation, the intensity of TF in the lane changed from 400 to 1000 vehicle/h. The simulation of the intersection operation took place at the duration of the permitting signal for the main direction of the road of 33 seconds.

Under the actual regulatory cycle, there are no congestion events in the secondary directions of the intersection. Therefore, during the simulation, the key is information about the average and maximum queue length on approaches No. 1 and No. 3 from street A. Modeling involved the creation of various options for organizing the permitted directions of movement on the three-lane roadway. The simulation results are given in Table 2.

Table 2

The length of the queue on the approaches to the intersection (street A) with different options for organizing the permitted directions from the lanes

Intensity of movement	The share of left-turning Vs, %	The length of the queue at the approaches of the main road							
		Variant No.1		Variant No. 2		Variant No. 3		Variant No. 4	
		Mean	Max	Mean	Max	Mean	Max	Mean	Max
400–600	5	10.2	17.9	14.3	18.2	10.8	16.3	10.4	14.7
	10	12.7	23.4	14.9	26.4	12.1	21.9	14.1	25.1
	15	21.4	50.9	25.4	54.7	24.9	42.1	21.7	48.6
	20	41.6	62.7	28.8	69.3	38.1	54.4	54.6	74.9
	25	50.9	71.5	45.3	79.0	44.9	69.2	61.4	84.1
600–800	5	14.6	24.7	18.7	24.4	12.7	21.5	16.4	23.5
	10	30.7	55.7	36.2	54.1	24.5	45.4	29.9	53.2
	15	61.2	69.4	69.8	73.1	41.9	57.6	52.8	66.7
	20	80.1	87.1	84.7	94.6	62.7	89.4	78.4	90.1
	25	84.1	90.1	102.3	102.3	77.4	94.7	91.7	107.4
800–1000	5	54.4	84.6	71.3	91.8	48.9	78.8	57.8	93.1
	10	72.7	87.9	78.1	98	64.4	85.9	75.1	104.6
	15	80.9	114.2	89.4	129.7	69.1	104.5	85.4	124.4
	20	90.6	120.3	109.9	135.9	84.6	115.6	100.9	140.6
	25	107.7	134.7	120.2	153.6	107.3	132.4	114.5	149.9

Table 2 illustrates that the length of vehicle queues on the main road significantly depends on the organization of permitted traffic directions in the lanes of approaches to the intersection. There is also a dependence of the change in the queues of vehicles on the share of left-turning flows from the main road. However, with an increase in the share of the left-turning flow with a not significant intensity of TF movement (up to 600 vehicle/h), the length of the vehicle queue changes insignificantly.

The mean and maximum queue lengths based on the results of 10 simulations for different variants of traffic management schemes change with increasing share of left-turning flows. With a low traffic intensity (up to 600 vehicle/hour) and a small proportion of left-turning flows (up to 15 %), the mean and maximum queue lengths for different modeling options do not differ significantly. In this case, the difference between the values of the average queue length does not exceed 10 %. However, with the intensity of traffic on the approaches from the main road of 800–1000 vehicle/h, the value of the mean and maximum length of the queue begins to grow already with a share of more than 10 % of left-turning flows.

According to the results of our modeling the work of the intersection, the dynamics of changes in the average length of the vehicle queue on approaches (approach No. 1 and No. 3) from the share of left-turning flows and taking into consideration the intensity of movement of the TF were established (Fig. 9–11).

With a low traffic intensity and the share of left-turning flows up to 20 %, the average queue is insignificant and ranges from 15 to 35 m, regardless of the option of organizing the allowed directions of movement. This is due to the relatively long duration of the permitting signal (more than 30 s) and the ability of all turning flows to maneuver at low values of the intensity of traffic of oncoming direct flow from the main road.

The largest queues are observed for the intensity of movement on the approach of more than 800 vehicle/h and the share of left-turning vehicles of more than 20 %. However, with an increase in traffic intensity up to 800 vehicle/hour, the queue length. According to option number 3, the organization of permitted directions on approaches, when each direction of movement has a separate lane for maneuver, even with a significant traffic intensity, the average queue on the approach is the smallest. However, with a share of left-turning vehicles of more than 15 %, the mean queue begins to grow with all options for organizing the permitted directions of movement and reaches more than 100 m at an intensity of 800–1000 vehicle/h. According to option No. 2, when it is allowed for forward-moving TFs to move in three lanes, the length of the vehicle queue is the largest even with a share of the left-turning flow of 5 %; it is 85 m.

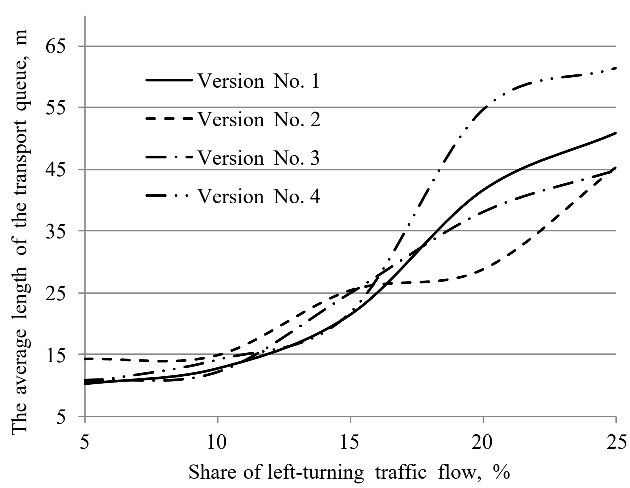


Fig. 9. Change in the mean length of the queue of vehicles on approaches to the intersection, taking into consideration the proportion of left-turning flows at an intensity of 400—600 vehicle/h

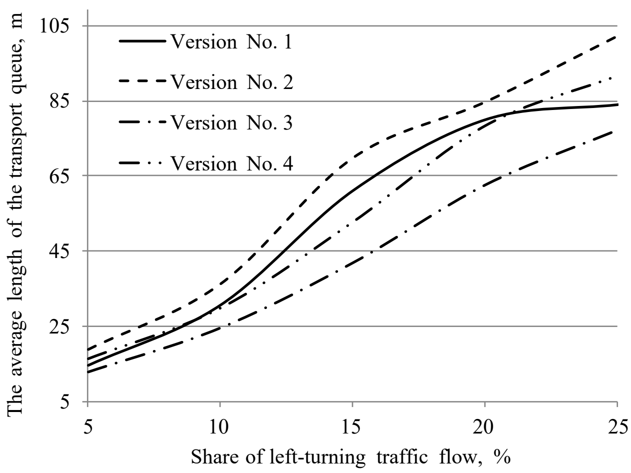


Fig. 10. Change in the mean length of the queue of vehicles on approaches to the intersection, taking into consideration the proportion of left-turning flows at an intensity of 600–800 vehicle/h

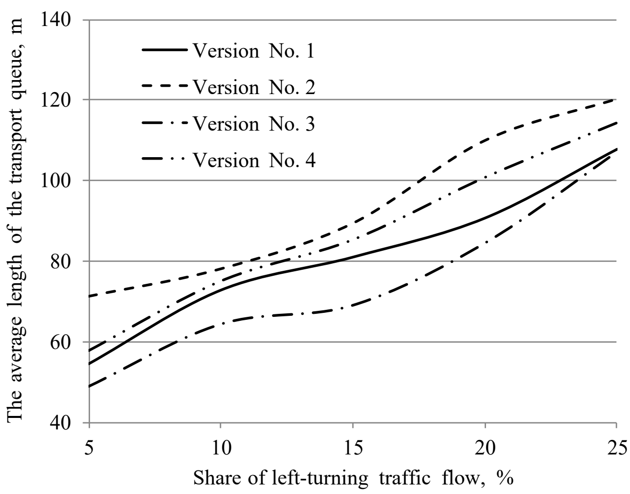


Fig. 11. Change in the mean length of the queue of vehicles on approaches to the intersection, taking into consideration the proportion of left-turning flows at an intensity of 800–1000 vehicle/h

5. 4. Patterns of changing the parameters of the intersection and practical recommendations for the use of modeling results

Traffic safety and the capacity of the intersection depend on the orderly organization of traffic on it. The best is such a planning solution, which provides for each direction of movement and TF a separate lane on the approach to the intersection. Given this, a study was carried out on the change in the queues of vehicles depending on the intensity of movement and taking into consideration the proportion of left-turning flows. The change in the efficiency of the intersection was investigated under various options for permitted directions of traffic from the lanes on the approaches of the main road. The defining parameter by which the efficiency of the adjustable intersection was evaluated is the length of vehicle queues. Evaluation of the change in the average value of this indicator at the time of switching on the permitting signal was carried out for 10 cycles of simulations. The results of the analysis of the relationship between the length of the queue, the intensity of TFs, and taking into consideration the share of left-turning flows from the main road are shown in Fig. 12.

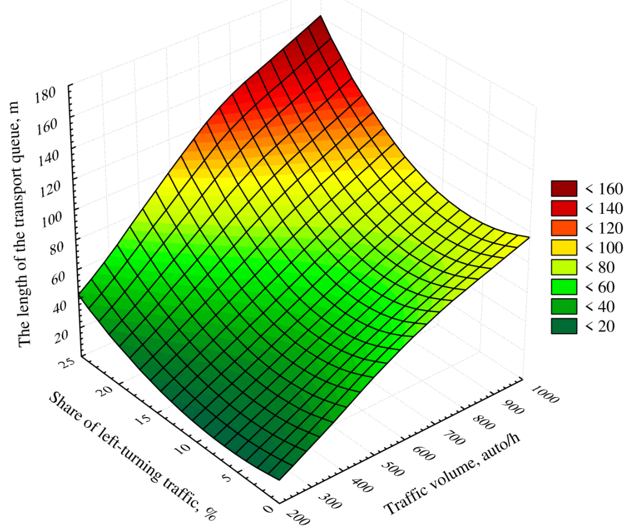


Fig. 12. Graphic dependence of the change in the average length of the queue on the approach to the intersection depending on the intensity of traffic flows and the share of turning vehicles in it

The three-dimensional geometric surface is built on an array of data obtained on the basis of modeling the lengths of queues on approaches to the intersection (street A) with different options for organizing the permitted directions from the lanes. The basis for the construction of this graphic dependence is an array of data regarding the average and maximum queue lengths for the variant of the traffic scheme No. 3. In this case, there is the slightest deviation of the mean and maximum values of the lengths of the queues with changes in the intensity of movement and the proportion of left-turning vehicles. This makes it possible in the future to more effectively reduce the total length of queues on the approaches to the intersection.

The plot that is shown in Fig. 12 indicates that there is a clear relationship between the average length of the queue and the intensity of movement, taking into consideration the proportion of left-turning vehicles. The resulting dependence characterizes the formation of significant queues on the main road with a traffic intensity of more than 600 vehicle/h and the share of left-turning flows of more than 15 %. If we consider the distribution of the queue length at an intensity of 800–1000 vehicle/h, then there is a tendency to increase the queues of Vs even with a not significant proportion of the left-turning flow up to 10 %. These values are explained by the fact that the simulation of the intersection was carried out under different options for permitted directions of movement from the lanes. The main condition is that the movement of forward-moving and turning flows occurs in one phase of regulation. Thus, during the simulation of the operation of the intersection, it was found that significant intensities in the lanes where there is a simultaneous movement of direct and turning flows significantly affects the formation of the length of the queues in front of the «stop line».

Arrays of experimental data obtained using simulation modeling are sufficient to construct an empirical dependence in the form of a multiple regression equation. In this equation, the dependent variable is the value of the queue length before the intersections, and the independent variable is the intensity of traffic on the approach to the intersection and the share of the left-turning flow.

$L_q = 0.11N + 0.87\mu - 14.03,$

where N is the intensity of TFs on the approach to the intersection; μ – the share of left-turning TFs on the approach to the intersection.

The adequacy of the derived dependence is confirmed by statistically significant values of the multiple correlation coefficient (0.815) and the coefficient of determination (0.664).

From the point of view of practical use of our results, it is recommended for simultaneous movement of forward-moving and turning flows in the main direction to reduce the length of the queue by specializing traffic lanes. At the same time, with a traffic intensity of up to 500 vehicle/h and a share of the left-turning flow up to 20 %, the length of vehicle queues on the approach to the adjustable intersection will not change significantly and will be up to 50 m (9–10 cars). In addition, when taking into consideration the results obtained during the implementation or change of traffic management schemes at regulated intersections, it is worth noting that an increase in traffic intensity of more than 800 vehicle/h, in the case of a share of left-turning flows of 15 %, causes an increase in the queue length of more than 80 m.

In order to assess the operation of the intersection under the existing planning features and parameters of traffic light regulation, it is recommended to simulate the operation of the intersection each time. This will make it possible to determine an effective scheme for organizing the movement of turning flows on the approaches to the main road, taking into consideration the intensity of traffic and the share of the left-turning flow. In this case, according to the results of the research, it was found that without changing the duration of the control cycle and the permitting signal, it is possible to increase the efficiency of the intersection and the practical capacity of traffic lanes on the approaches to the intersection.

In practice, the analysis of the length of the queue on the approaches to the intersection under conditions of saturated traffic using simulation will make it possible to establish the effectiveness of its work under various options for organizing the permitted directions of movement from the lanes.

Thus, the analysis of the queue length at an adjustable intersection, taking into consideration the intensity of traffic and the share of turning vehicles, is important in terms of an objective assessment of its functioning under existing traffic conditions. Such research results are important because they make it possible to more rationally redistribute permitted maneuvers from the lanes and reduce the total length of queues on approaches to the intersection.

6. Discussion of results of studying changes in the length of queues, taking into consideration the distribution of traffic flow along directions

Our simulation results are explained by the fact that in the process of managing the queues before the intersection at certain values of traffic intensity, there are such critical values of the share of left-turning vehicles (Fig. 9–11) at which this queue begins to grow disproportionately.

The advantages of this study are that in the process of modeling the movement, various options for organizing the exit at the intersection were checked and the difference in the values of the lengths of queues was obtained with an increase in the proportion of left-turning vehicles. Previous studies related to the optimization of the operating modes of the traffic light alarm focused on the need to change the time parameters of traffic light cycles or introduce adaptive regulation. At the same time, as noted above, with an inadequate traffic management scheme, significant delays in movement are created precisely on the approaches to intersections. In such cases, it is often proposed to change the planning parameters of intersections. However, within settlements, in particular under conditions of dense infrastructure, there is often no physical possibility to expand the carriageway. In addition, existing scientific approaches often propose to take into consideration the presence of turning and forward-moving flows interacting in the same phase of regulation. This is due to the fact that under such conditions it is possible to create a queue of vehicles waiting for the proper interval to complete their maneuver. However, according to the simulation results, it was established that with a small proportion of left-turning TFs, there is no need to arrange dedicated lanes for them. Thus, to increase the efficiency and capacity of regulated intersections, the priority is to analyze the existing parameters of TFs and the use of modern software for modeling the operation of various options for traffic management schemes.

This study takes into consideration the fact that for each number of phases there is a certain recommended cycle duration, which is applied in practice by road engineers. Based on this, there are situations when the time parameters cannot be changed, then one needs to look for alternative solutions, such as changing the specialization of traffic lanes.

The established dependences of changes in queue lengths before the intersection in Table 2 provide an opportunity to make informed decisions on the choice of permitted directions of movement in the lanes at regulated intersections, paying attention to the distribution of traffic intensity. The criterion of the length of a queue is especially important in cases where the distance to the next intersection is insignificant (up to 100 m), which, in the event of additional delays in the flow, can block adjacent nodes of SRN.

The simulation results can be used in cases where the issue of optimizing traffic at X-shaped intersections is considered, where the main direction has 3 lanes in each direction, as is shown in Fig. 8. Accordingly, under other conditions of traffic management, a combination of phase-by-phase travel or the duration of the traffic light cycle, as well as the composition of TF, the patterns of formation of queue lengths will be different.

The disadvantages of the study are in that if there are public transport units in the left-turning flows, especially trolleybuses, the length of the queue may increase already at lower values of traffic intensity. It is also worth noting that changing the combination of traffic signals while maintaining the total duration of the cycle can also affect the change in the patterns of queue formation before the intersection.

In the future, it is worth considering various combinations of phases of the traffic lights, namely two-phase and four-phase travel at the recommended durations of the traffic light cycle (50–60 s and 90–100 s, respectively). In the future, the consolidated results of additional studies will provide an opportunity to make decisions on the organization of traffic at regulated intersections based on already tested template options.

7. Conclusions

1. During field studies at a regulated intersection, the intensity of TFs on approaches to it was determined. In addition, we established the composition of TF and its dis-

tribution along the directions of movement. The phase-by-phase departure and the duration of the regulatory cycle and its elements were determined. The planning features of the intersection were analyzed. In this case, the share of passenger cars was more than 80 %, the share of left-turning vehicles from the main road fluctuated within 16–17 %, and right-turning ones – 23–25 %.

2. A simulation model of an adjustable intersection has been developed to determine the average length of the vehicle queue on approaches to it. This made it possible to analyze the effectiveness of its work for this indicator. The analysis of the obtained data indicates that the largest queues per cycle and the accumulation of a queue for 10 cycles are observed on the approaches of the main road. At the same time, the average line of Vs over a longer modeling period on the approaches of the main road is 92.1–98.8 m, depending on the approach. It has also been established that with the existing traffic intensity, the proportion of turning flows from the lane significantly affects the queues of vehicles on approaches to the intersection. In lanes where the share of low-speed vehicles and turning vehicles is more than 10 %, the values of the length of the queue of cars are much larger than in the lanes where TFs that are more uniform in composition move.

3. The dependence of the change in the length of the queues of vehicles on the approach of the main road on the share of left-turning flows has been established. With a low traffic intensity (up to 600 vehicle/h) and a small proportion of left-turning flows (up to 15 %), the mean and maximum queue lengths under different options for organizing the allowed directions of movement change insignificantly. However, with the intensity of traffic on the approaches to the main road of more than 900 vehicle/h, the average and maximum queue lengths increase even with a share of left-turning flows of more than 10 %. Based on this, the dependence of the change in the average line of Vs on the approaches to the intersection under different schemes of organization of permitted maneuvers from the lanes and the share of left-turning flows from the main road was revealed.

4. The simulation results can be used in the design of traffic management schemes and the reconstruction of regulated intersections where the main road has a three-lane carriageway. Evaluation of the operation of the intersection during modeling with different options for permitted maneuvers on the main road makes it possible to choose the optimal traffic pattern for changes in the proportion of left-turning flows. Such research results are important when assessing saturation flows at regulated intersections. They make it possible to more rationally redistribute the permitted directions of traffic on the main road (without changing the duration of the permitting signal in the regulatory cycle) and reduce the total queues on the approaches to the intersection.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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