Improvement of Traffic Flow Management at Intersections Using Cluster Analysis and Fuzzy Logic

Vladimir Shepelev
Ph.D.
Head of the Educational Program
"Technology of Transport Processes"
Advanced Engineering School of Engine
Building and Special Equipment
"Heart of the Urals", South Ural State
University
Russia

Aleksandr Glushkov
Ph.D.
Department of Mathematical and
Computer Modeling
South Ural State University
Russia

Olga Fadina
Ph.D.student
Educational Program "Technology of
Transport Processes"
Advanced Engineering School of Engine
Building and Special Equipment
"Heart of the Urals"
South Ural State University
Russia

Signal-controlled intersections of urban transport highways are the busiest and most problematic places in the urban road network because of vehicle delays at intersections reducing their traffic capacity, as well as a sharp change in the nature of traffic (braking-waiting-acceleration), which worsens the environmental situation. This paper develops a mathematical model for calculating the recommended vehicle speed at signal-controlled intersections for non-stop passage, in order to increase the traffic capacity and safety, taking into account various factors. The authors carry out a preliminary single-factor analysis of the influence of the length of the space interval between intersections, the operating time of traffic light cycles, the number of cars in the queue, the road surface condition, and the category of the most inertial vehicles. The study involved a cluster analysis, which allowed identifying groups of lanes at intersections with similar traffic characteristics. The authors derived coefficients for the quantitative assessment of the influence of various factors on the recommended speed: the coefficient of queue passing dynamics (k_d), which takes into account the road surface condition, and the coefficient of vehicle inertia in the queue (k_i). The analysis showed that changes in the road surface conditions reduce the speed by 20–40%, an increase in the number of cars in the queue by more than five units reduces the speed by 15–30%, and the presence of vehicles of categories III (trucks from 3.5 to 12 tons) and IV (trucks over 12 tons) in the queue reduces the recommended speed by 10–25%. The multi-factor approach is based on the fuzzy logic method, which allows taking into account probabilistic fluctuations in the input parameters and their interrelationships. The obtained results can be used to optimize urban traffic, reduce the number of stops before intersections, increase the traffic capacity of signal-controlle.

Keywords: *traffic capacity; cluster analysis; recommended speed; mathematical modeling; fuzzy logic method.*

1. INTRODUCTION

Modern cities face the problem of traffic congestions, which has negative consequences [1,2]. The main challenge is the stop of vehicles at signal-controlled intersections, which reduces the traffic capacity, increases travel time, and worsens the urban environ–mental setting [3–5]. Effective traffic management requires the development of models, which take into account various factors affecting traffic and offer optimal solutions for its organization [6]. A solution is intelligent traffic management systems that use data on road loads and weather to optimize traffic flows [7-10].

Coordinated traffic flow control effectively increases the traffic capacity of the road network and should take into account the actual number of vehicles in the queue [11]. The papers [12-14] present a decentralized multi-agent system developed for adaptive traffic light control and the formation of the 'green wave' effect. The studies analyze the interaction of decentralized agents to coordinate the operation of each intersection using theoretical decision-making models. Wada et al. [15], focused on the optimal coordinated control of road signals taking into account both deterministic and stochastic factors.

The existing methods for assessing traffic capacity based on statistical data have weaknesses, since they do not take into account the current state of the traffic flow and weather conditions, which makes them less reliable [16]. Studies on the improvement of methods for increasing traffic capacity, the efficiency of transport services, and corresponding environmental improve–ment remain relevant.

Many microscopic traffic simulation models have been proposed, the most widespread of which are SUMO [17], VISSIM and CORSIM [18], AIMSUN, and PARAMICS [19]. Each model has its own specific characteristics that make it more or less suitable for certain simulation purposes. Therefore, there are some difficulties in choosing a suitable simulation platform.

The traffic capacity of a signal-controlled intersec–tion is affected by many factors. Liu et al. [20] found

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Correspondence to: Vladimir Shepelev
Department of Automobile Transportation,
Lenin prospekt 76, 454080 Chelyabinsk, Russia
E-mail: shepelevvd@susu.ru
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that under light snowfall conditions, the traffic capacity of intersections decreases by 7%, and the average delay increases by 32.9%.

Yazici et al. [21] and Xiong et al. [22] showed that the nature of delays at signal-controlled intersections varies both spatially and temporally.

To improve traffic efficiency, in [23], drivers are encouraged to adhere to the recommended speed in VANETs conditions. This approach minimizes travel delays and reduces fuel consumption and CO2 emis–sions. Such methods have significant limitations, since they do not take into account weather conditions, pos–sible emergency situations, and other factors [24]. The recommended speed depends on many factors: the length of the space interval, the delay time of adjacent traffic light cycles, the number of cars in the queue and the category of the most inertial vehicle, as well as the road surface condition.

This paper proposes a comprehensive approach to the analysis of traffic flows at intersections, including: statistical data analysis; cluster analysis; formation of a reference intersection based on average parameters; modelling of the recommended speed using fuzzy logic methods. It considers a mathematical model for cal–culating the recommended speed between adjacent intersections based on the above factors. A multi-factor approach based on the fuzzy logic method is used for a more accurate prediction of values. It allows taking into account the uncertainty of the input parameters and their probabilistic variations.

2. MATHEMATICAL MODEL OF THE AVERAGE SPEED OF THE LEADING GROUP OF VEHICLES

To ensure continuous traffic of vehicles approaching the next intersection, the speed should be adjusted in advance to a specified value. This value determined by the average travel speed within the section between road junctions should be displayed on the dynamic sign '6.2' as a recommended speed [25].

If there are non-group vehicles at the intersection before the stop line, the recommended average speed will depend on the following factors:

- the length of the space interval, i.e., the distance between the traffic lights of adjacent intersections (L_i^n), m;
- the shift time of the go traffic light signal (t_s), s;
- the time it takes the leading vehicle to pass from the activation of the go traffic light signal until crossing the far boundary of the analyzed intersection (t_{lv}, s):

$$t_{lv} = t_{lv}^{sl} + \sqrt{\frac{2 \cdot S_{\text{int}}}{a_{lv}}} + \tau_d \qquad (1)$$

where t_{lv}^{sl} is the time it takes the leading vehicle to reach the stop line from the activation of the go traffic light signal, s; S_{int} is the length of the analyzed inter–section, m; a_{lv} is the acceleration of the leading vehicle when crossing the intersection, m/s^2; τ_d is the reaction time of the driver of the leading vehicle (vehicle start delay), s;

- the time it takes the queue of non-group vehicles waiting for the go traffic light signal to pass by (t_{ng}), s:

$$t_{ng} = \sqrt{\frac{2 \cdot \left(1.5 + D_i \cdot \left(n_i - 1\right)\right)}{a_i}}, \qquad (2)$$

where D_i is the dynamic clearance of the i-th vehicle, m; n_i is the number of vehicles in the queue before the next intersection, units; a_i is the acceleration of the i-th vehicle, m/s^2.

The advantage of non-stop traffic lies both in the increase in the traffic capacity of the intersection, and road safety due to the smooth crossing of the inter–section. When the leading group stops because of the queue of non-group vehicles that have not managed to leave the intersection, the vehicles are forced to move and stop repeatedly, which forms a percussion wave that can lead to a traffic accident and a traffic jam.

Changes in the current state of the road surface (e.g. in case of rain, snow, ice) and the presence of trucks and buses in the queue significantly affect the time the queue of non-group vehicles needs to pass by. The following coefficients were developed in this study to take into account these significant factors:

- the coefficient of the dynamics of the queue pas–sing, taking into account the road surface condition (k_d);
- the coefficient taking into account the category of the most inertial vehicle in the queue (k_i).

To obtain these coefficients, we analyzed statistical data obtained from 22 lanes of eleven intersections. A 'reference' intersection was determined using the average value method to identify the basic starting acceleration of the first vehicle in the queue. To quantify the influence of road surface conditions on acceleration, we use the coefficient of passing dynamics (k_d), which is defined as the ratio of vehicle acceleration under given conditions to acceleration under base conditions. To quantify the influence of the queue com–position on acceleration time, we introduce a coefficient taking into account the vehicle category (k_i), which is defined as the ratio of the acceleration time of the vehicle of a given category to the base acceleration time.

All these factors were taken into account when developing a mathematical model for the average speed of the leading group of vehicles. The developed model can be used to optimize traffic organization in the urban environment, which helps improve the transport situation and reduce the negative environmental impact:

$$V_{av} = \frac{3.6 \cdot L_i^n}{t_s - \left(t_l^{sl} + \sqrt{\frac{2 \cdot S_{\text{int}}}{a_{lv}}} + \tau_d\right) + \sqrt{\frac{2 \cdot \left(1.5 + D_i \left(n_i - 1\right)\right)}{a_i \cdot k_d}} + \frac{\left(n_i - 1\right) \cdot t_d}{k_d} \cdot k_i} \qquad (3)$$

where V_{av} is the average speed of the leading group of vehicles (km/h); L_i^n is the length of the i-th space inter–val to the next intersection (m); t_{lv}^{sl} is the time it takes the leading vehicle to reach the stop line from the acti–vation of the go traffic light signal (s); S_{int} is the length of the analyzed intersection (m); a_{lv} is the acceleration of the leading vehicle when passing the space interval of the intersection (m/s^2); τ_d is the reaction time of the driver of the leading vehicle (vehicle start delay) (s); D_i is the dynamic clearance of the i-th vehicle (m); n_i is the number of vehicles in the queue before the next intersection (m); a_i is the acceleration of the i-th vehicle (m/s^2); t_d is the average start delay time of the next vehicle in the queue, which is given to it by the previous vehicle (s); k_d is the coefficient of the queue passing dynamics, taking into account the road surface condition; k_i is the coefficient taking into account the category of the most inertial vehicle in the queue.

3. STATISTICAL ANALYSIS OF THE INITIAL DATA

The set of initial data from the video stream used in the study, as well as the calculated variables, include L_1 is the distance from the stop line to the intersection area; S_{int} is the width of the intersection being crossed; V_{av} is the average speed of a passenger car leaving the intersection; a_i is the average acceleration of the first vehicle of categories I (cars), II (vans and minibuses up to 3.5 tons) passing the intersection (calculated para–meter).

The research methodology includes the selection of variables to collect and theoretically assess data, the data collection method, the use of statistical methods to process the collected information, and the interpretation of the results.

3.1 Initial data collection

The study collected data for several large urban inter–sections in Chelyabinsk (Russia). Traffic lanes corres–ponding to the straight movement of vehicles were se–lected at each intersection. Both the geometric para–meters of these lanes and the dynamics of vehicles cros–sing the intersections were recorded. Twenty-two lanes were selected from eleven large urban inter–sections.

The data were collected using the AIMS eco soft–ware [26] suite, which processes real video streams from stationary street surveillance cameras (Fig. 1).

Table 1 presents the set of initial data from the video stream used in the study, as well as the calculated variables: W_i is the width of the intersection being crossed; V_{av} is the average speed of a passenger car leaving the intersection; a_f is the average acceleration of the first vehicle of categories I, II passing the intersection (calculated parameter).

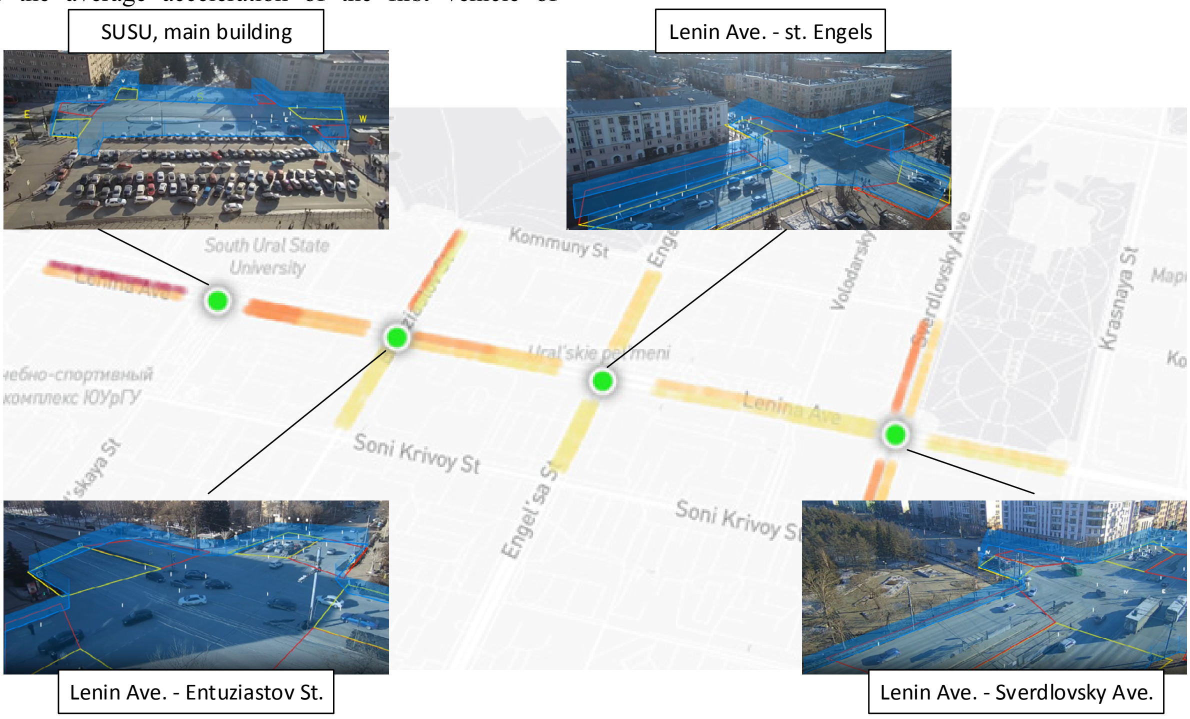


Figure 1. Vehicle detection and tracking by the AIMS eco convolutional neural network, Chelyabinsk (Russia)

Table 1. Initial data for the model experiment

No. of item	Direction of street intersections	L_1 (m)	W_i (m)	V_{av} (km/h)	a_{sr}, m/s^2
1	Kir_Kal_N	24.0	40.0	54.75	1.81
2	Kir_Kal_S	14.0	35.0	48.20	1.83
3	Gag_Rust_NE	17.0	31.0	43.85	1.55
4	Gag_Rust_S	18.0	30.0	43.90	1.55
5	Koms_Vor_E	20.0	33.0	49.73	1.80
6	Koms_Vor_W	17.0	30.0	46.47	1.77
7	Koms_Svred_E	24.0	54.0	59.15	1.73

8	Len_Eng_W	23.0	50.0	57.38	1.74
9	Len_Eng_E	20.0	48.0	56.90	1.84
10	Len_Svob_W	27.0	42.0	59.81	2.00
11	Len_Svob_E	25.0	51.0	61.57	1.92
12	Pob_Kraszn_W	19.5	33.0	54.43	2.18
13	Pob_Kraszn_E	20.0	34.0	51.79	1.92
14	Mol_Pob_N	40.0	75.0	27.55	0.25
15	Chich_Pob_NW	33.5	80.0	21.69	0.16
16	Chop_Khokhr_N	24	43	53.93	1.67
17	Chop_Khokhr_S	25	41	45.72	1.22
18	Saltzm_1Elton_NE	15	33	39.06	1.23
19	Saltzm_1Elton_SW	16	34	46.37	1.66
20	Saltzm_1Elton_SE	21	40	48.44	1.48
21	Saltzm_1Elton_NW	16	35	47.16	1.68
22	Truda_NW	40	50	35.10	0.53

3.2 Statistical processing of the initial data

We should assess the similarity degree of the nature of traffic flows at the intersections selected for analysis. The best method therefor is cluster analysis imple–mented in the professional Statistical Package for the Social Sciences (SPSS).

A single type of the analyzed groups of traffic lanes is determined by the measure of proximity or difference in the values of their characterizing parameters by the square of the normalized Euclidean distance. We chose Ward's method as the most correct approach to the formation of 'spherical' clusters to determine the dis–tance between clusters.

The clustering procedure represents the sequential combination of initial objects into similar groups – a tree diagram indicating the agglomeration distance as a measure of clustering stability.

The dendrogram (Fig. 2) clearly shows that the lower group of three traffic lanes (14,15,22) differs sig–nificantly from the main data array due to the presence of tram tracks intersected by motor vehicles, which leads to a significant difference in the nature of traffic, in particular, a slowdown in passing the intersection area.

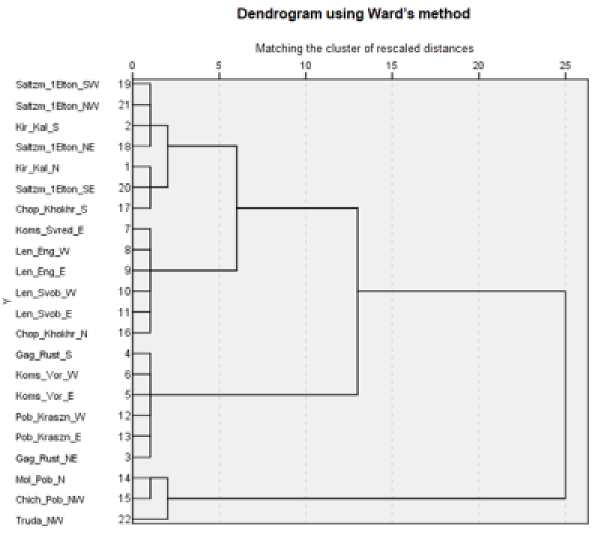


Figure 2. Tree diagram of the similarity of the analyzed intersections

The additional analysis of the average values of the initial parameters in clusters 4, 3, and 2 showed that cluster 4 has a statistically significant difference from the other clusters at the level of 0.0% (at the generally accepted threshold of no more than 5%). This is explained by the significant difference in the average values of all parameters for cluster 4 (Table 2).

Table 2. Average parameter values in four clusters

Ward's Method		L_1 (m)	W_i (m)	V_{av} (km/h)	a_1 (m/s^2)
Cluster 1	Aver.	18.71	36.85	47.10	2.11
	N	7	7	7	7
Cluster 2	Aver.	18.58	31.83	48.36	1.08
	N	6	6	6	6
Cluster 3	Aver.	23.83	48.00	58.12	2.57
	N	6	6	6	6
Cluster 4	Aver.	37.83	68.33	28.11	1.03
	N	3	3	3	3
Total	Aver.	22.68	42.81	47.86	1.81
	N	22	22	22	22
	Stand. devia-tion	7.225	13.443	10.13	0.693

Such intersections having interferences to the natural vehicle movement are excluded from the analysis of general patterns in this study, since they should be considered using other specific research approaches.

The remaining 19 traffic lanes were also subjected to the clustering procedure, the results of which are shown in Fig. 3.

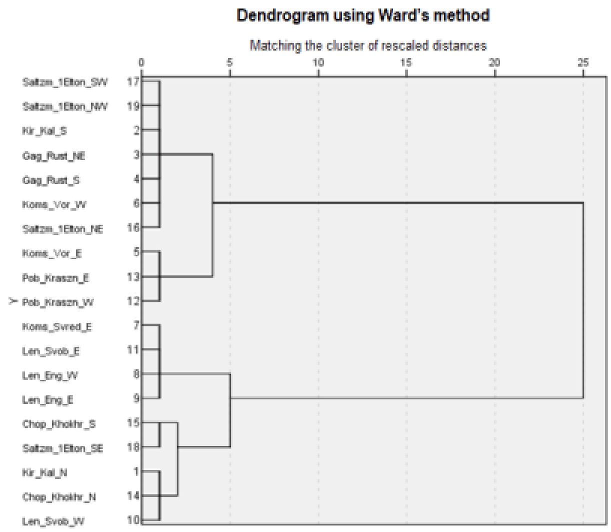


Figure 3. Tree diagram of the similarity of the intersections without tram tracks

The Fig. 3 clearly shows two clusters of similar intersections. Their average parameters are shown in Table 3, and the statistical significance of the diffe–rences in each of the parameters for these two clusters is presented in Table 4.

Table 4. Averaged parameters for two clusters

Ward's Method		L_1	W_i	V_{av}	a_f
Cluster 1	Average	23.8571	46.8571	57.6414	1.8157
	N	7	7	7	7
	Standard deviation	2.11570	5.24177	2.74364	0.11530
Cluster 2	Average	18.2083	34.0833	47.0933	1.6558
	N	12	12	12	12
	Standard deviation	3.05598	3.44986	3.97639	0.27533

Based on the calculations, the two clusters of intersections differ in their geometric parameters and, accordingly, in the average speed of vehicles leaving the intersection. However, accelerations differ insignifi–cantly, which preliminarily suggests the identical nature of vehicle movement at all analyzed intersections. These assumptions provide for statistical verification, the results of which are reflected in Table 5. The differences were analyzed using the parametric method of 'variance analysis' for the average values of the samples.

Table 5. Statistical significance of differences in the initial parameters for two intersection clusters

	Sum of squares	Degrees of freedom	Mean square	F	Signifi-cance
L_1	141.072	1	141.072	18.507	0.000
W_i	721.384	1	721.384	41.463	0.000
V_{av}	491.897	1	491.897	38.167	0.000
a_f	0.113	1	0.113	2.103	0.165

As expected, the two intersection clusters differ significantly in geometry, as well as in the speed of vehicles leaving the intersections. However, the acce–lerations of the vehicles remain within the confidence interval, as evidenced by the insignificant difference between them (the significance of 16.5% exceeds the statistically acceptable threshold of 5%). Consequently, the nature of the vehicle movement determined by their accelerated movement after a complete stop before the stop traffic light signal remains the same for all the analyzed intersections.

The acceleration range is 0.80–2.80 m/s^2 with the average value of 1.93m/s^2. These values are taken as a basis for further model studies.

4. PREDICTING THE AVERAGE SPEED OF THE NON-STOP PASSAGE OF THE INTERSECTION

We will conduct model experiments of the influence of the parameters on the recommended speed of passing the intersections for a 'reference' intersection, which was determined using the average value method. This method is based on collecting data from several real intersections and calculating the average values of key parameters.

The basic (average) values of the 'reference' inter–section include:

- recommended cruising speed of the vehicle in the space interval – 50 km/h;
- length of the space interval to the next intersection – 500 m;
- shift time of the go traffic light signal – 26 s;
- number of vehicles in the queue before the next intersection – 8 units.

The experiment plan provides for a single-factor analysis of the influence of each model parameter on the cruising speed, as well as a multi-factor analysis of the influence of simultaneous variations of the most significant model parameters.

To conduct the analysis, we should identify a refe–rence point – 'base point' V_0, relative to which we will make predictive calculations of the influence of distur–bing factors. This is the recommended cruising speed in the space interval between intersections for a passenger car of category I at the average values of all model parameters and normal road surface condition.

3.3 Single-factor analysis

We are interested in the analysis of the particular influ–ence of the following parameters (factors) on the re–commended cruising speed in the following formu–lation:

$$V_{av} = f\left(L_n; t_s; n_i; k_d; k_i\right), \quad (4)$$

where: L_n is the length of the space interval to the next intersection (m); t_s is the shift time of the go traffic light signal (s); n_i is the number of vehicles in the queue before the next intersection.

FACTOR 1: Analysis of the influence of L_n. Other factors are considered to correspond to V_0: $V_{av} = f(L_n)$.

When L_n changes in the range (100 m; 1000 m), the graph is shown in Fig. 4.

The base point corresponds to the value L_n =500 m, wherein V_{av} = 50 km/h.

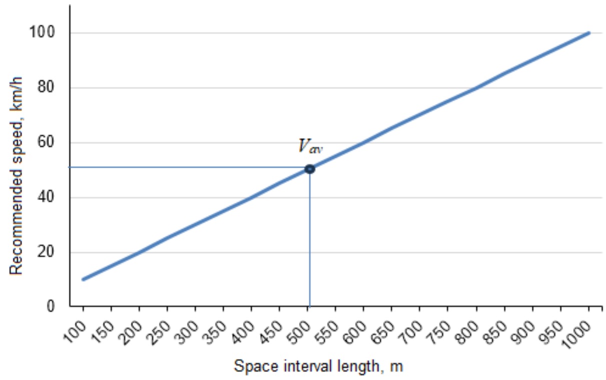


Figure 4. The influence of the space interval length on the recommended speed

The Fig. 4 shows that when the space interval length increases from 100 m to 1000 m, the recommended speed increases linearly. The actual value of 500 m corresponds to the recommended speed of 50 km/h. When the space interval increases to 1000 m, the recommended speed increases to 60km/h, and when it decreases to 100 m, the recommended speed decreases to 30 km/h.

FACTOR 2: Analysis of the influence of t_s. Other factors are considered to correspond to V_0: V_{av} = f(t_s).

When t_s changes in the range (0 s; 50 s), the graph is shown in Fig. 5. The base point corresponds to the value t_s =26 s, wherein V_{av} = 50 km/h.

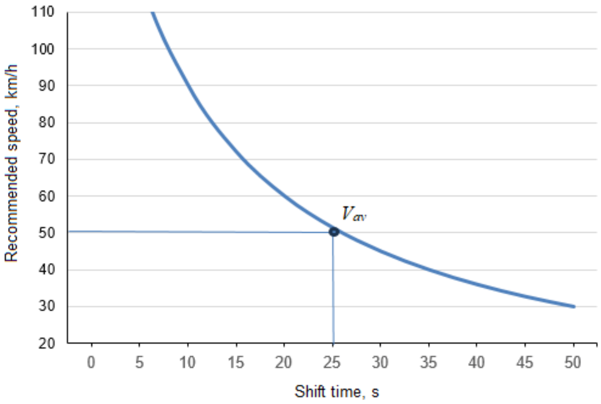


Figure 5. The influence of the shift time between adjacent intersections

Variations in the shift time of the go signal of adjacent traffic lights in the range of 0–50 seconds show that an increase in this parameter leads to a decrease in the recommended speed. The actual shift of 26 seconds corresponds to the basic recommended travel speed within the space interval of 50 km/h. When the shift increases to 50 seconds, the recommended speed within the space interval drops to 35 km/h.

FACTOR 3: Analysis of the influence of n_i. Other factors are considered to correspond to V_0: $V_{av} = f(n_i)$.

When n_i changes in the range (0; 15), the graph is shown in Fig. 6. The base point corresponds to the value n_i = 8 of passenger cars, wherein V_{av} = 50 km/h.

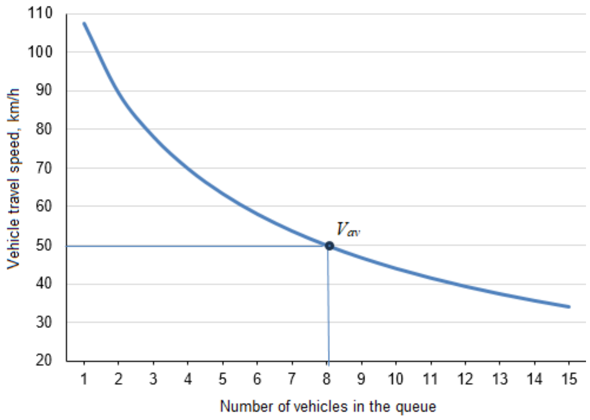


Figure 6. The influence of the number of vehicles in the queue at the next intersection

The Fig. 6 shows that when the number of vehicles before the intersection increases from 0 to 15, the travel speed tends to decrease. The optimal speed is 50 km/h for the basic calculated value of 8 vehicles. If there are 15 vehicles, it already decreases to 35 km/h, and if there is no queue, it reaches the permitted limit of 60km/h.

FACTOR 4: Analysis of the influence of k_d. Other factors are considered to correspond to V_0: $V_{av} = f(k_d)$.

To quantify the influence of the road surface con–dition on acceleration, we use the dynamics coefficient (k_d), which is defined as the ratio of the acceleration of the vehicle under given conditions to the acceleration under normal conditions. The following ranges of coef–ficients were established based on the experimental studies (Table 6).

Table 6. k_d values

Road surface condition	a_{lv} (m/s²)	k_d
Normal conditions	2.8 – 0.8	1.133 – 0.324
Wet surface	2.5 – 0.7	1.012 – 0.283
Slippery surface	1.5 – 0.5	0.607 – 0.202

When k_d changes in the ranges specified in the table for three situations, the graph is shown in Fig. 7. The base point corresponds to the value k_d = 1, wherein V_{av} = 50 km/h.

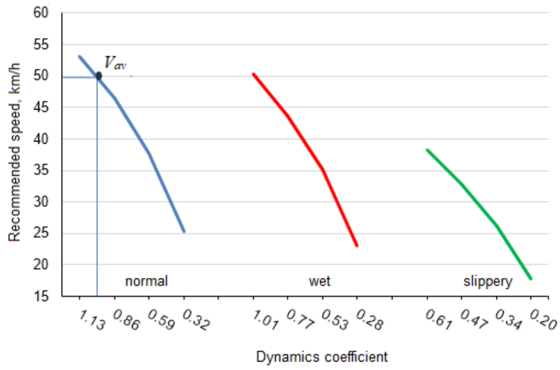


Figure 7. The influence of weather conditions on the recommended travel speed

Fig. 7 shows three curves for different conditions: normal driving conditions, wet road surface, and slip–pery surface. Under normal conditions, the basic reco–mmended speed is 50 km/h, on wet surfaces it is reduced to 40 km/h, and on slippery surfaces it is reduced even more – to 30 km/h.

FACTOR 5: Analysis of the influence of k_i. Other factors are considered to correspond to V_0: $V_{av} = f(k_i)$.

Notably, the inertial vehicle in the queue at the next intersection determines both the k_i coefficient, and the acceleration a_i. Therefore, we should determine the synchronous change of k_i and a_i depending on the vehicle category.

The following coefficient was established based on the experimental studies (Table 7).

Table 7. k_i values

a_i (m/s^2)	Normal conditions	Wet surface	Slippery surface	k_i
Category I, II	(2.80 – 0.80)	(2.5 – 0.7)	(1.5 – 0.5)	**1.0**
Category III, IV, V	1.78 – 0.47	1.5 – 0.4	1.0 – 0.3	**1.64**

When a_i changes in the ranges specified in the table for the ‘normal’ situation, the graph $V_{av}=f(a_i)$ for two values k_i=1 and k_i=1.64 in shown in Fig. 8. The base point corresponds to the value k_i=1; a_i=2.47 m/s^2, wherein V_{av} = 50 km/h.

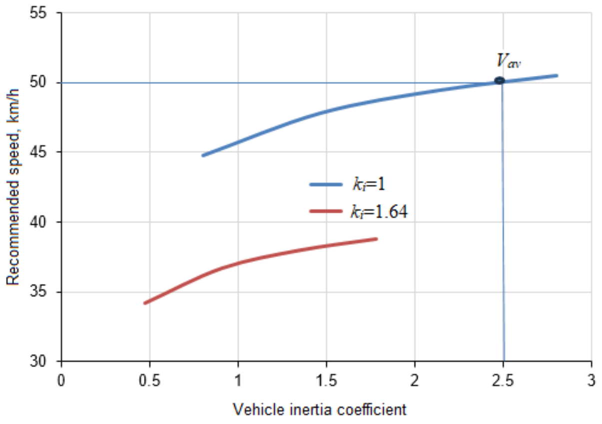


Figure 8. The influence of vehicle inertia

The graph in Fig. 8 shows that the presence of at least one inertial vehicle (category III–V) in the queue reduces the speed. If the queue consists only of pas–senger cars (category I), the recommended speed is 50 km/h, and when a bus or truck appears, it decreases below 40 km/h.

4.1 Multi-factor analysis (probabilistic approach based on the fuzzy logic method)

In a probabilistic setting, we are interested in the ana–lysis of the dispersion field of recommended speeds V_{av} relative to the base point V_0 when two factors vary si–multaneously. We will consider modeling for the 're–ference' intersection, when L_n = const. We also neglect the factor k_i, since inertial vehicles move almost along a carpool lane in many situations. Then three factors will be analyzed:

$$V_{av} = f\left(t_s; n_i; k_{met}\right), \tag{5}$$

The ranges of factor variations are:

- t_s (20 s – 50 s);
- n_i (3 – 14) passenger cars;
- k_{met} (normal = 1; wet surface = 0.65; slippery surface = 0.4) is three gradations of the road surface condition.

The variation range of the output variable V_{av} is de–termined by the values of the factors – 'simultaneously minimizing' and 'simultaneously maximizing' values of the output variable.

Let us consider the predictive visualization of the dispersion field of the recommended speeds V_{av} for vehicles within the space interval between intersections, taking into account the following assumptions: the input factors are considered independent, and their mem–bership functions are Gaussian, which most adequately reflects the real behavior of random factors.

The predictive model for assessing the influence of input factors on the recommended speed V_{av} is based on the fuzzy logic method and the fuzzyTECH computer program. The dependent variable V_{av} (the recommended speed for vehicles within the space intervals between intersections) is predicted depending on the independent variables t_s (the shift time between the cycles of traffic lights bordering the space interval), n_i (the number of vehicles in the queue at the next intersection), and k_{met} (the road surface condition).

Fig. 9 shows the structural diagram of the cons–tructed model.

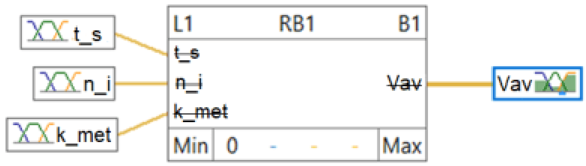


Figure 9. Structural diagram of the model using the fuzzy logic method

Gaussian membership functions were used as splines at the stage of variable phasing. This maximally corres–ponds to the problem statement in the stochastic ver–sion. The parameters of the Gaussian terms were deter–mined by the authors' expert assessments based on their practical dealing with traffic flow data.

The number of terms is taken to be 3 for inde–pendent variables and 5 for the dependent variable. The distribution of values by the terms of the independent variable t_s (similarly for n_i; k_met) and the dependent variable Vav is shown in Fig. 10, respectively.

The fuzzy logic model for predicting the values of the dependent variable was defined by a table of its relationships with independent variables using the Speadsheet rule editor block (Fig. 11).

Notably, a complete consideration of all relation–ships in the table of rules can lead to some anomalies in the model, since there may be some inconsistent or even contradictory rules of relationships [27]. In general, to solve this problem, it is advisable to determine the measure of similarity 'in a system based on rules'.

However, this practical study, which is the initial stage of assessing situations in the urban transport network under several uncertainties, has not developed a solution to the noted problem yet. Although in the further, more detailed application of fuzzy logic methods, it is planned to check fuzzy rules both in the static and dynamic approaches.

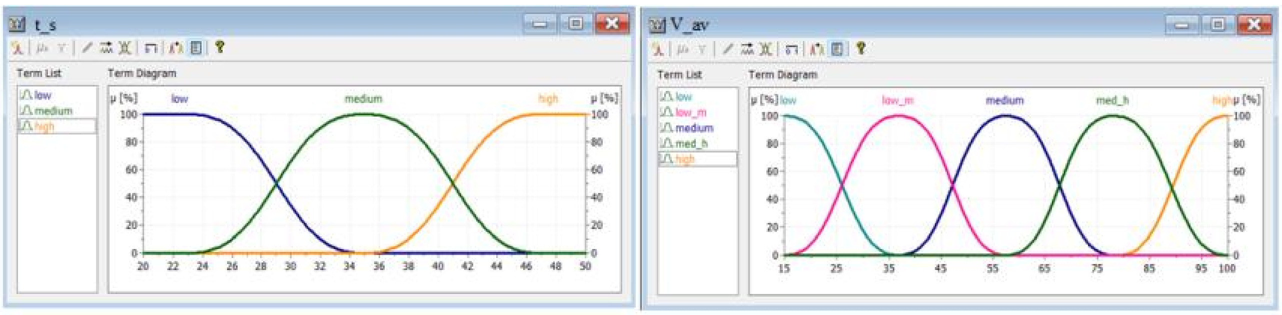


Figure 10. Distribution of term values for variables

	If	And	And	Then
B1.G1.R1	t_s.low	n_i.low	k_met.low	Vav.med_h
B1.G1.R2	t_s.low	n_i.low	k_met.medium	Vav.high
B1.G1.R3	t_s.low	n_i.low	k_met.high	Vav.high
B1.G1.R4	t_s.low	n_i.medium	k_met.low	Vav.medium
B1.G1.R5	t_s.low	n_i.medium	k_met.medium	Vav.med_h
B1.G1.R6	t_s.low	n_i.medium	k_met.high	Vav.med_h
B1.G1.R7	t_s.low	n_i.high	k_met.low	Vav.low
B1.G1.R8	t_s.low	n_i.high	k_met.medium	Vav.low_m
B1.G1.R9	t_s.low	n_i.high	k_met.high	Vav.low_m
B1.G1.R10	t_s.medium	n_i.low	k_met.low	Vav.medium
B1.G1.R11	t_s.medium	n_i.low	k_met.medium	Vav.medium
B1.G1.R12	t_s.medium	n_i.low	k_met.high	Vav.med_h
B1.G1.R13	t_s.medium	n_i.medium	k_met.low	Vav.low_m
B1.G1.R14	t_s.medium	n_i.medium	k_met.medium	Vav.medium
B1.G1.R15	t_s.medium	n_i.medium	k_met.high	Vav.medium
B1.G1.R16	t_s.medium	n_i.high	k_met.low	Vav.low
B1.G1.R17	t_s.medium	n_i.high	k_met.medium	Vav.low
B1.G1.R18	t_s.medium	n_i.high	k_met.high	Vav.low
B1.G1.R19	t_s.high	n_i.low	k_met.low	Vav.low
B1.G1.R20	t_s.high	n_i.low	k_met.medium	Vav.low
B1.G1.R21	t_s.high	n_i.low	k_met.high	Vav.low_m
B1.G1.R22	t_s.high	n_i.medium	k_met.low	Vav.low
B1.G1.R23	t_s.high	n_i.medium	k_met.medium	Vav.low
B1.G1.R24	t_s.high	n_i.medium	k_met.high	Vav.low_m
B1.G1.R25	t_s.high	n_i.high	k_met.low	Vav.low
B1.G1.R26	t_s.high	n_i.high	k_met.medium	Vav.low
B1.G1.R27	t_s.high	n_i.high	k_met.high	Vav.low

Figure 11. Table of variable relationship rules in the model.

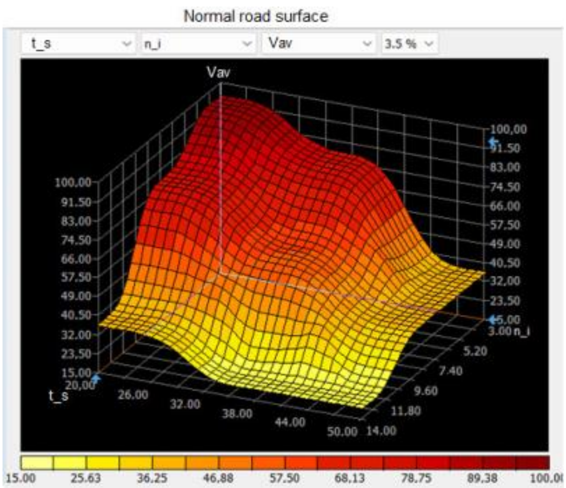
The experimental studies of the constructed model allow predicting the dependent variable based on the actual values of the independent variables, as well as presenting graphically the distribution field of the mutual influence of variables in the form of volumetric surfaces.

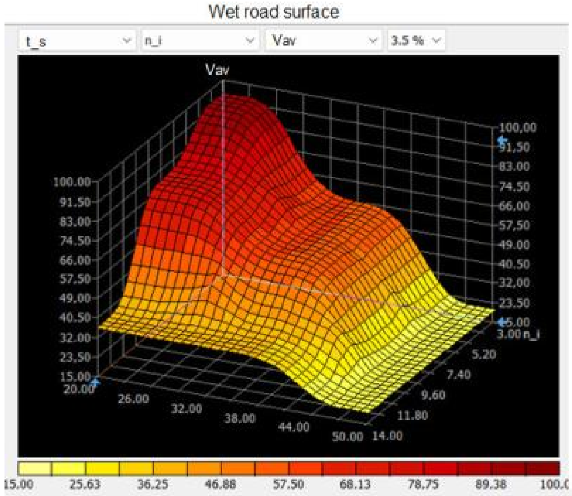
In light of this task, we focus on the recommended speed within the space interval between intersections Vav for two approaches:

1) informative pair of factors t_s – n_i with the variation of factor k_met;

2) informative pair of factors n_i – k_met with the variation of factor t_s.

For the first analytical approach, Fig. 12 shows the graphs of the dependent variable Vav from the influence of the shift time of traffic light cycles t_s and the size of the vehicle queue n_i (independent variables) when the road surface condition changes in the studied range (‘normal’; ‘wet’; ‘slippery’).





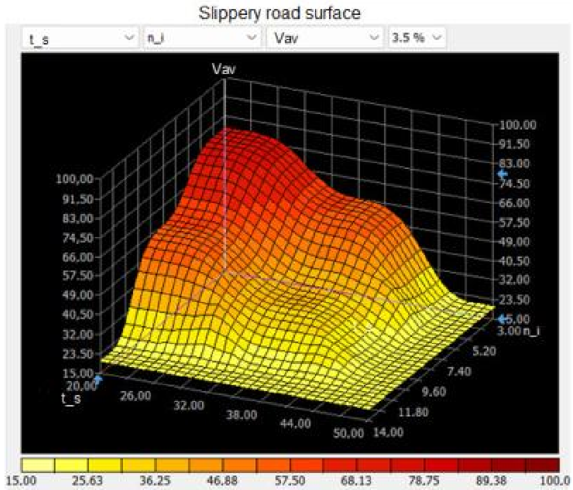


Figure 12. First approach: graphs of the mutual influence of changes

A slightly different angle of view is given by the graphical representation of the influence of the situation at the subsequent intersection on the recommended speed Vav – the size of the vehicle queue (n_i) and weather conditions determining the time possibilities for the passage of these vehicles (k_met), with variations in the shift time of traffic light cycles t_s. Figure 13 shows these graphs.

The analysis of the results of two approaches in the model experiments based on fuzzy logic shows the nature of changes in the recommended speed within the space interval between intersections with the random variation of three fundamentally different factors:

- the shift time of traffic light cycles at the intersections bordering the space interval;
- the size of the vehicle queue at the next intersection;
- the road surface condition determining the nature of traffic.

The conducted study confirms that the fuzzy logic method allows taking into account complex relation–ships between input parameters based on their influence on the recommended speed depending on the variation of current traffic conditions.

This can serve as a good basis for making informed decisions on urban traffic organization to ensure the non-stop movement of vehicles and the corresponding environmental improvement due to the reduction of vehicle-related pollutant emissions.

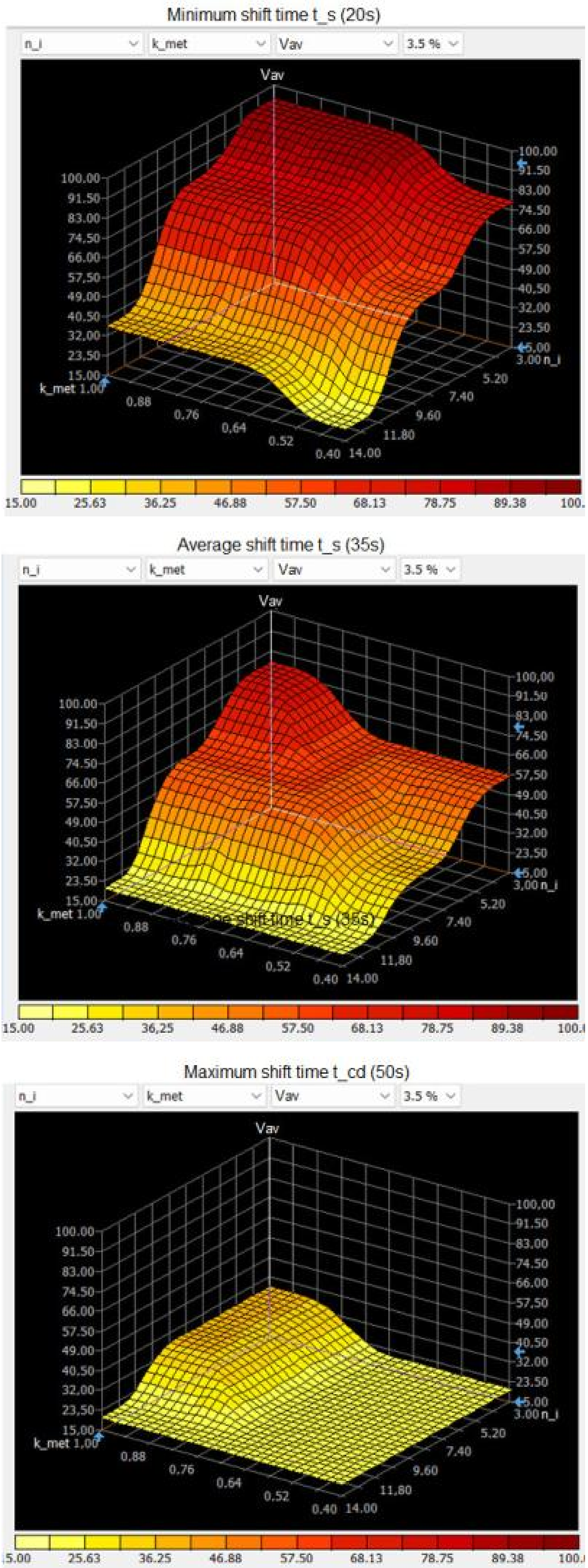


Figure 13. Second approach: graphs of the mutual influence of variables

5. DISCUSSION

The results of the cluster analysis showed that inter–sections can be divided into groups with different traffic characteristics. Notably, the presence of tram tracks has a substantial impact on the dynamics of traffic flows, which is confirmed by statistically significant diffe–rences in the average values of speed and acceleration.

The analysis of the interrelations of factors showed that an increase in the distance (space interval length) from 100 m to 1000 m increases the recommended speed from 30 km/h to 60 km/h (by 100%); an increase in the shift time of the go traffic light signal from 0 to 50 seconds reduces the speed from 60 km/h to 35 km/h (by 42%); an increase in the number of cars in the queue before the intersection from 0 to 15 reduces the speed from 60 km/h to 35 km/h (by 42%); deterioration of the road surface condition (the transition from ‘basic’ to slippery) reduces the speed by 40%; the presence of trucks and buses in the vehicle queue reduces the speed by 10–25%.

The derived coefficients allowed assessing more accurately the influence of these factors. The coefficient of the passing dynamics reflects the influence of the road surface condition on the acceleration of vehicles. Under normal conditions, its value varies within the range of 1.133–0.324, on a wet surface – from 1.012 to 0.283, and on a slippery surface – from 0.607 to 0.202. As a result, the speed decreases by 20–40%. The coefficient of the vehicle inertia characterizes the influence of heavy vehicles in the queue. If the queue consists only of passenger cars, k_i = 1.0, and if there are trucks and buses, it increases to 1.64, which reduces the speed by 10–25%. The fuzzy logic method allowed taking into account complex nonlinear dependencies between the factors and predict recommended speeds for various situations.

6. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

The study developed a mathematical model to calculate the recommended vehicle speed within a space interval between adjacent intersections, taking into account the key factors, such as the length of the space interval, the delay time of adjacent traffic light cycles, the number of vehicles in the queue and the category of the most inertial vehicle, as well as current weather conditions. The single-factor approach allowed considering the modifications of the calculation algorithms and carrying out relevant studies into the influence of the variation of each factor on the recommended speed within the space interval. The multi-factor approach used the fuzzy logic method for a comprehensive analysis of the influence of these parameters, which allows taking into account the uncertainty and probabilistic variability of the input data based on the assumption of their Gaussian distributions.

The cluster analysis confirmed the differences in traffic characteristics at different intersections, which allowed identifying reference groups of intersections. The formation of a ‘reference’ intersection allowed generalizing the key parameters for modeling. The single-factor analysis revealed the main dependencies between traffic parameters and the recommended speed: an increase in the number of vehicles in the queue by more than 5 reduces the speed by 15–30%; deterioration in the road surface condition reduces the speed by 20–

40%; the presence of trucks and buses in the queue reduces the speed by 10–25%.

We derived the coefficients that allow quantitatively assessing the influence of the road surface and the composition of the traffic flow on the acceleration dynamics. The multi-factor analysis using fuzzy logic allowed predicting the range of recommended speeds, which varies from 30 to 60 km/h depending on the conditions.

Thus, our contribution to this study consists in the following points:

1. A mathematical model has been developed that integrates cluster analysis and fuzzy logic methods to calculate the recommended speed of movement. This model takes into account factors such as the length of the segment, the state of the road surface, the composition of the traffic flow, and the timing of traffic light cycles.

2. New coefficients have been introduced that quantitatively assess the impact of road surface conditions and vehicle inertia on traffic dynamics, significantly enhancing the accuracy of calculations.

3. The practical application of the proposed model has been demonstrated for optimizing traffic light operations and reducing pollutant emissions, as confirmed by the results of modeling experiments.

The practical application of the obtained data will optimize the operation of traffic lights, improve the smoothness of traffic flows, and reduce pollutant emissions.

The obtained results can be used to develop intelligent traffic flow management systems, predict road congestion, and optimize the operation of traffic lights, which will reduce the number of stops before intersections and travel time.

In the presented study, the following promising directions for further research are proposed:

1. Adapting our model for use in intelligent transportation systems (ITS) with real-time data integration. This will improve traffic management and make it more efficient.

2. Investigating the impact of additional factors, such as pedestrian flows and emergency situations, on the recommended speed of movement. This will broaden the model's applicability and make it more universal.

3. Developing pilot projects to test the model in real urban conditions, including collaboration with municipal traffic management authorities. This will help validate the effectiveness of our model in practice and make any necessary refinements.

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УНАПРЕЂЕЊЕ УПРАВЉАЊА САОБРАЋАЈНИМ ТОКОМ НА РАСКРСНИЦАМА КОРИШЋЕЊЕМ КЛАСТЕР АНАЛИЗЕ И ФАЗИ ЛОГИКЕ

В. Шепелев, А. Глушков, О. Фадина

Раскрснице градских саобраћајних аутопутева конт–ролисане сигналима су најпрометнија и најпроб–лематичнија места у мрежи градских путева због кашњења возила на раскрсницама која смањују њихов саобраћајни капацитет, као и због нагле промене у природи саобраћаја (кочење-чекање-убрзање), што погоршава еколошку ситуацију. У овом раду развија се математички модел за изра–чунавање препоручене брзине возила на раскр–сницама контролисаним сигналима за непрекидни пролаз, како би се повећао саобраћајни капацитет и безбедност, узимајући у обзир различите факторе. Аутори спроводе прелиминарну једнофакторску анализу утицаја дужине размака између раскрсница, времена рада циклуса семафора, броја аутомобила у реду, стања површине пута и категорије нај–инерцијалнијих возила. Студија је обухватила кластер анализу, која је омогућила идентификацију група трака на раскрсницама са сличним карак–теристикама саобраћаја. Аутори су извели коефи–цијенте за квантитативну процену утицаја разли–читих фактора на препоручену брзину: коефицијент динамике проласка поред реда (kd), који узима у обзир стање површине пута, и коефицијент инерције возила у реду (ki). Анализа је показала да промене у условима површине пута смањују брзину за 20–40%, повећање броја аутомобила у реду за више од пет јединица смањује брзину за 15–30%, а присуство возила категорије III (камиони од 3,5 до 12 тона) и IV (камиони преко 12 тона) у реду смањује препоручену брзину за 10–25%. Вишефакторски приступ је заснован на методи фази логике, која омогућава узимање у обзир вероватносних флук–туација улазних параметара и њихових међусобних односа. Добијени резултати могу се користити за оптимизацију градског саобраћаја, смањење броја заустављања пре раскрсница, повећање саобраћајног капацитета сигнализационог система.