signalized intersection; traffic light;
fuzzy traffic control; traffic simulation

Zinoviy STOTSKO
Lviv Polytechnic National University, Institute of Engineering Mechanics and Transport,
Electronic Machinery Construction Department
1 Professorska str., Lviv, Ukraine
Yevhen FORNALCHYK, Ihor MOHYLA*
Lviv Polytechnic National University, Institute of Engineering Mechanics and Transport,
Transport Technology Department
32 Bandera Str., Lviv, Ukraine
**Corresponding author*. E-mail: ihor.mohyla@gmail.com

SIMULATION OF SIGNALIZED INTERSECTION FUNCTIONING WITH FUZZY CONTROL ALGORITHM

Summary. In the course of research the fuzzy algorithm for traffic control at signalized intersection has been developed. Based on the results of simulating of intersection functioning during an hour and a day it has been established that using of developed fuzzy algorithm enables to reduce average and maximal queue lengths of vehicles before the intersection owing to adaptation of control system parameters to traffic flow volumes.

МОДЕЛИРОВАНИЕ РАБОТЫ РЕГУЛИРУЕМОГО ПЕРЕКРЕСТКА С НЕЧЕТКИМ АЛГОРИТМОМ УПРАВЛЕНИЯ

Аннотация. Разработан нечеткий алгоритм управления движением на регулируемом перекрестке. По результатам моделирования работы перекрестка на протяжении часа и на протяжении дня установлено, что использование этого алгоритма позволит уменьшить средние и максимальные длины очередей транспортных средств перед перекрестком за счет адаптации параметров системы управления к интенсивности транспортных потоков.

1. INTRODUCTION

The efficient traffic control at signalized intersection anticipates adjusting of traffic light parameters with traffic volume consideration. It is known that volume changes during a day and its fluctuation might be considered with using of time-responsive (inflexible multiprogram) or traffic-responsive (traffic-actuated) control [1, 2]. Meanwhile second control use is more reasonable since control parameters are calculated in real-time. The top priority issue in adaptive system creating is choice of traffic control algorithm or array of algorithms [3].

Recently the fuzzy logic algorithms have started to be applied in traffic control systems. Fuzzy logic allows describing and simulating of complex systems behavior, which can be hardly achieved by means of mathematical models. Notwithstanding the sufficiently wide application of fuzzy logic in traffic control systems this direction is new in Ukraine (there exist only few works which are conceptual [4, 5]).

2. EXISTING CONTROL ALGORITHMS REVIEW

First known attempts to use fuzzy logic in traffic control were done by *Pappis* and *Mamdani* in 1977 [6]. They simulated functioning of controller with fuzzy control algorithm on isolated intersection (2 lanes, one-way traffic without turning movements) and established that developed algorithm was more effective than algorithm of gap-seeking in traffic flow.

Nakatsuyama, *Nagahashi* та *Nishizuka* (1984) found out the possibility of using fuzzy controller on consecutive intersections on highway. Results of fuzzy coordination of traffic lights showed the increase of capacity by 10% in comparison with commonly accepted coordinating methods [7].

Niittyymaki (1998) developed fuzzy controller FUSICO (Fuzzy Signal Control) for two-stage isolated junction [8]. Fuzzy control algorithm works on two levels. On higher level there are determined current traffic conditions (normal or oversaturated) based on traffic volume value during last 5 minutes and detector utilization during this 5 minutes (input variables). The goal of lower level is the adjustment of green lights duration (to continue or to terminate). It is established that efficiency of FUSICO controller functioning is higher by 10-20% in comparison with functioning of controller which uses algorithm of gap-seeking in traffic flow.

Murat (2003) developed Fuzzy Logic Multi-phased Signal Controller (FLMuSiC) for isolated intersection and the benefit of the latter in comparison with FUSICO is the possibility of phase sequence optimizing at multi-phased signalized intersections [9]. It consists of two parts: fuzzy logic signal time controller and fuzzy logic phase sequencer. First part determines green light duration based on data from detectors which are set at each approach of intersection while the second one determines phase order. Both parts have different rule bases (64 fuzzy rules for first part and 37 rules for second).

Input variables of fuzzy controller of green light duration:

- maximal queue on red light;
- arrivals to intersection during green light;
- green light time indicator.

Decision about green signal is the output variable of this part (to decrease much, to decrease, do not change, to increase, to increase much).

Input variables of fuzzy phase sequencer:

- maximal queue on red signal;
- maximal queue in the next phase;
- duration of red signal for maximal queue.

Decision about changing of phase sequence is the output variable of this part.

The author simulated functioning of four-armed intersection with two lanes on each approach. Operation of FLMuSic controller compared with operation of controller which uses vehicle-actuated algorithm. There has been determined that results of both controllers operation during low traffic volume are almost the same. But if volume is high fuzzy controller is more efficient (delays are decreased by 20%). Operation of FLMuSiC controller was also compared with operation of FUSICO controller. There has been established that results of simulation did not differ among themselves under the same traffic volume values.

Yulianto (2003) suggested fuzzy algorithm for traffic control at isolated four-armed intersection [10]. In this algorithm on the basis of maximal lengths of queues and average occupancy of detectors there are determined the weights which shows the demand degree green light for each signal group. Duration of green lights in phases is calculated on the basis of weights values. And in comparison with previous researches [6, 8] this work studies mixed traffic flows. As it was determined the usage of developed control algorithm permits reduction of average delay by 5-40% in comparison with optimized pre-timed control.

Madhavan and *Cai* (2007) developed fuzzy controller for isolated signalized four-armed intersection [11]. The intersection has 4 phases and phase sequence is invariable. The input variables of control system is the average queue length at direction with red signal, ratio of green time, left at current phase, arrival of vehicle during green signal and average green discharge time. Decision about impact on green signal (to decrease much, to decrease, do not change, to increase, to increase much) is output variable. It was established that usage of fuzzy controller leads to the reduction of delays in comparison with controller which uses vehicle-actuated control, particularly, with abnormality near the intersection (road particularly or completely blocked, poor road conditions).

Zhang, *Li* and *Prevedouros* (2008) developed fuzzy controller which decides to extend or terminate current green signal based on values of average queue lengths on lanes which served in current green, average queue lengths with red which may receive green in the next phase and average arrival rate on lanes with green [12]. Moreover, there is set minimal and maximal duration of green signal in it. Fuzzy controller based on 48 fuzzy rules checks the decision to extend or to terminate current phase after end of minimal green signal. If the decision to extend a phase is taken the next check will be in time interval Δt. Otherwise it will turn on the next phase. The decision is taken on the basis of 48 fuzzy rules.

To check the controller operating there was created program for microscopic simulation of intersection functioning. It was determined that usage of fuzzy controller results delay reducing and rise of speed and besides increase of efficiency of intersection functioning is more appreciable with increase of traffic volume.

Stainek (2011) proposed fuzzy control algorithm which takes decision to extend green signal or to go to the next phase based on arrival volume and number of vehicles in a queue [13]. For this 4 fuzzy rules to make solution are used. It was established that average delay and number of stops were smaller with fuzzy control at the intersection than in comparison with pre-timed control.

In general structure of fuzzy traffic control system at isolated intersection is typical for adaptive traffic control systems (fig. 1). Data from transport detectors comes to the input of fuzzy control system. At the output there is formed the set of values of parameters which are forwarded to controller and as result the traffic lights signs changes It influences on traffic conditions improvement.

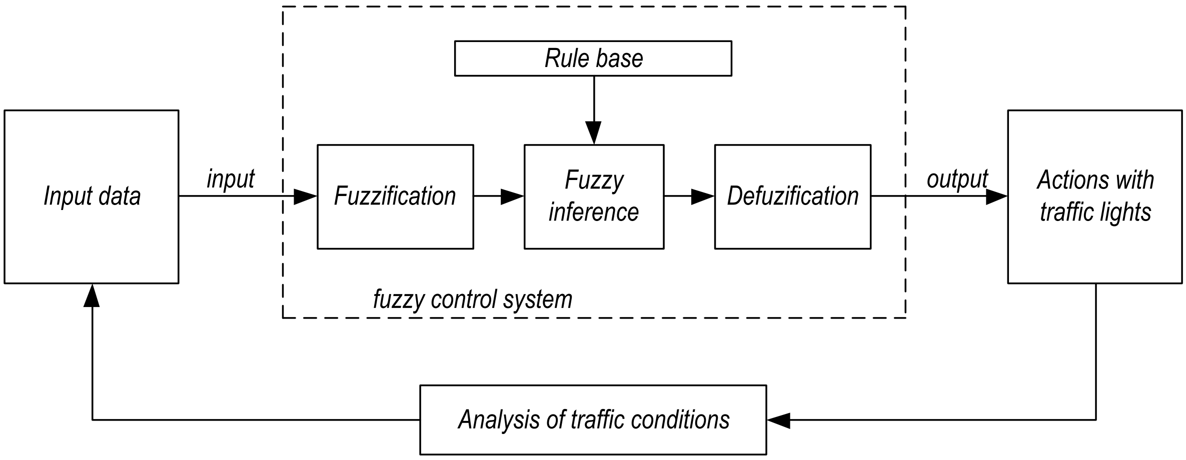


Fig. 1. Structure of fuzzy traffic control system at isolated intersection
Рис. 1. Структура нечеткой системы управления движением на изолированном перекрестке

Typical control actions in traffic control systems with fuzzy logic are:

1) calculation of green light duration;
2) decision about extension or termination of green light;
3) decision about degree of extension or reduction of green light;
4) choice of next stage;
5) determination of traffic conditions on the intersection.

Thus, application of fuzzy logic permits to improve efficiency of signalized intersection functioning. At the same time researchers have different approaches to fuzzy traffic control systems creation. There are used different input and output parameters, various membership functions, considered both imaginary and real intersections, etc. It is apparent from given analysis that there is permanent search of fuzzy control algorithm which will ensure efficient functioning of intersection in particular conditions.

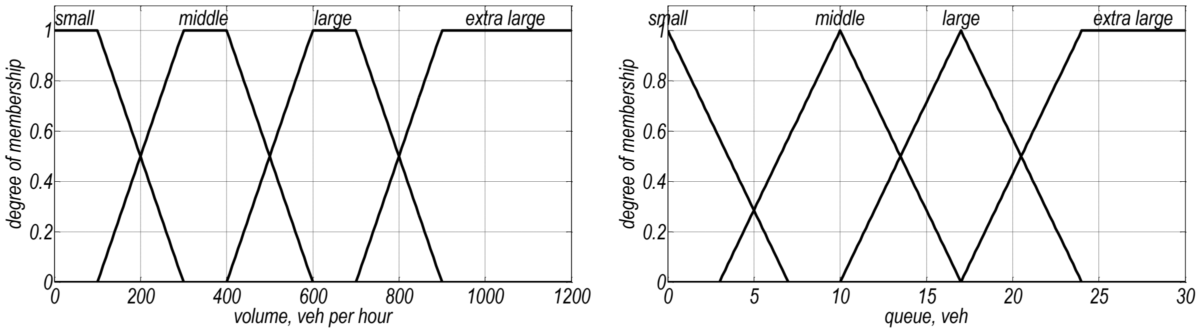
3. CHARACTERISTICS OF DEVELOPED FUZZY CONTROL ALGORITHM

Traffic delay is one of the criteria in given researches. In spite of this parameter importance it is not considered as determinant for solving of some transport issues (for example, delay can not be the valuation of traffic congestion in street network). Vehicle queue length (average and maximal) is also important parameter of intersection functioning which allows estimating network utilization. As a result there was developed fuzzy traffic control algorithm for signalized intersection in which length of vehicle queue is one of the input parameters.

Fuzzy control algorithm is implemented in MATLAB with usage of Fuzzy Logic Toolbox. Estimation of green light duration is the check solution this algorithm. Volume of arriving vehicle and queue length on proper direction are taken as input linguistic variables.

There are introduced fuzzy variables *small*, *middle*, *large* and *extra-large* for volume of arriving flow and queue length and *very short*, *short*, *middle*, *long* and *very long* for green light duration. Membership functions for volume and queue are shown in fig. 2, for green light – in fig. 3. Rule base consists of 16 fuzzy expressions (table 1). Mamdani method is used for the fuzzy inference system. The centroid method is used for defuzzification.

The found dependence of green light duration on queue length and arrival volume (response surface) shows (fig. 4) that green light duration increases when volume of arrival vehicles and queue length increases too.



a) b)

Fig. 2. View and parameters of membership functions of input variables: arrival volume (a) and queue (b)

Рис. 2. Вид и параметры функций принадлежности входящих переменных: интенсивности прибытия (a) и очереди (b)

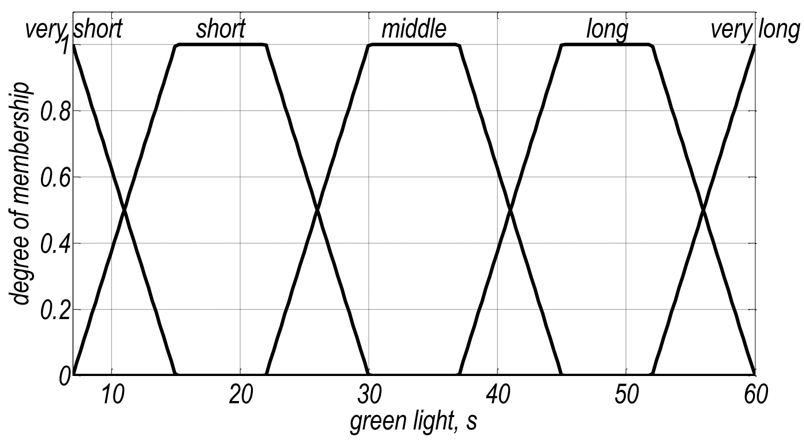


Fig. 3. View and parameters of membership functions of green light duration

Рис. 3. Вид и параметры функций принадлежности длительности зелёного сигнала

Table 1

Rule base of fuzzy traffic control algorithm at signalized intersection

# of rules	Volume	Queue	Green light
1	small	small	very short
2	small	middle	short
3	small	large	short
4	small	extra large	middle
5	middle	small	short
6	middle	middle	middle
7	middle	large	middle
8	middle	extra large	long
9	large	small	middle
10	large	middle	long
11	large	large	long
12	large	extra large	very long
13	extra large	small	middle
14	extra large	middle	long
15	extra large	large	very long
16	extra large	extra large	very long

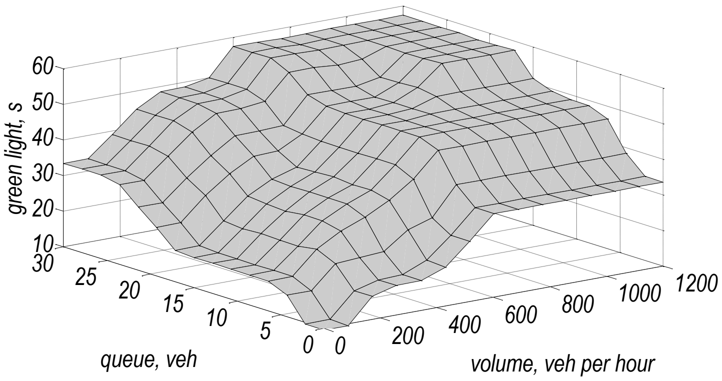


Fig. 4. Dependence on green light duration on queue length and arrival volume on intersection approach

Рис. 4. Зависимость длительности зелёного сигнала от интенсивности прибытия и длины очереди на подходе к перекрестку

4. DESCRIPTION OF INTERSECTION FUNCTIONING SIMULATION MODEL

During the research of signalized intersection with developed control algorithm functioning the use simulation is the best method [14]. For simulating of signalized intersection functioning researches use specialized software VISSIM [10, 13], multipurpose environment MATLAB [11] or other software [9, 12]. So far as fuzzy algorithm was implemented in Fuzzy Logic Toolbox there was chosen MATLAB for simulating of intersection functioning, in which model is written as function in M-file.

Simulating was carried out for signalized Levytskoho – Tersakovtsiv – Dorosha intersection (Lviv). The intersection is isolated (distance to the nearest upstream intersection in Levytskoho Street is 700 m, in Tershakovtsiv Street – 420 m). There is one-way movement in Levytskoho Street and Dorosha Street and two-way movement in Tershakovtsiv Street. Cycle duration is 58 seconds. Flows from Levytskoho Street move in the first phase, from Tershakovtsiv Street – in the second phase.

Detailed description of simulation model of signalized intersection functioning is expounded in fig.[15]. In this model there is utilized an algorithm with deterministic step (principle Δt). In created model there is adopted $\Delta t = 0.1$ s, because smaller values require considerable hardware resources.

For simplification while simulation the following conditions are adopted:

- duration of intergreen period is 3 seconds;
- pedestrian movement is not taken into consideration;
- vehicle categories in traffic flow are not taken into consideration;
- headways between cars which arrive to the intersection have gamma distribution.

Amount of vehicles that passes intersection in each direction and average and maximal queue lengths on each lane are the results of simulating. It was determined that developed simulating model is appropriated because the discrepancies between the received results of simulation and field investigation and also the results of simulating of this junction in VISSIM [15]. Thus, this model is appropriate for use for research of intersection functioning with different control systems, including fuzzy control.

5. INVESTIGATION OF INTERSECTION FUNCTIONING WITH FUZZY CONTROL SYSTEM DURING AN HOUR

Vehicles arrival volume to the intersection is not constant, it has different fluctuations. Therefore, 7 possible cases have been considered on the matter:

- traffic volume is permanent during an hour (case *1*);
- one of the flows has inconsiderable volume rise during 30 minutes (cases *2* and *4*);
- one of the flows has sharp volume rise during 30 minutes (cases *3* and *5*);
- both flows have little volume rise during 30 minutes (case *6*);
- both flows have sharp volume rise during 30 minutes (case *7*).

Functioning of control system, which uses fuzzy algorithm (fuzzy control system), has been compared with functioning of time-fixed control systems: actual at the intersection and calculated by methods, given in [16].

Traffic flows volume, which arrive to the intersection during an hour, are given by 10 minutes intervals (table 2).

Table 2

Flows volume at intersection approaches

Case	**Flow in Levytskoho str., veh per hour**	**Flow in Tershakovtsiv str., veh per hour**
1	700-700-700-700-700-700	300-300-300-300-300-300
2	700-700-**1000-1000-1000**-700	300-300-300-300-300-300
3	700-700-**1500-1500-1500**-700	300-300-300-300-300-300
4	700-700-700-700-700-700	300-300-**500-500-500**-300
5	700-700-700-700-700-700	300-300-**800-800-800**-300
6	700-700-**1000-1000-1000**-700	300-300-**500-500-500**-300
7	700-700-**1500-1500-1500**-700	300-300-**800-800-800**-300

Intersection functioning has been modeled during an hour (number of simulations for each case – 100). As a result, it has been established that the type of control system doesn't influence the number of vehicles that passes intersection. But quality and efficiency of intersection functioning depends on it (tab. 3). If volumes of approaching flows are permanent, it's better to use fixed-time control system, calculated for this traffic condition. Usage of another fixed-time system or fuzzy system leads to higher values of average and maximal queue. If traffic volume has little rise, operating of time-fixed control system, calculated on given traffic conditions, is satisfactory (average queue length value is 1.5…4 vehicles, maximal – 8…14 vehicles for the given volume of traffic flows). But if traffic volume has sharp rise (even short-term), usage of time-fixed systems is unsuitable because of sharp rise average and maximal queue length. In this case, fuzzy system greatly adapts to the traffic conditions at the intersection and under little increase of queue in one direction (i.e. red light duration increase) lesser values of queue length are reached in another one (green light duration per cycle is distributed more rationally).

Table 3

Results of simulation of intersection functioning

Case	Control system	Queue length, veh					
		Levytskoho str., right lane		Levytskoho str., left lane		Tershakovtsiv str., right lane	
		average	maximal	average	maximal	average	maximal
1	actual	2,61	8	3,15	9	2,77	9
	calculated	1,33	6	1,61	6	1,34	6
	fuzzy	2,22	8	2,69	9	2,22	8
2	actual	3,15	9	3,83	11	2,78	8
	calculated	1,74	8	2,04	10	1,34	6
	fuzzy	2,66	9	3,23	11	2,63	8
3	actual	4,53	22	5,67	24	2,80	8
	calculated	17,04	71	16,79	81	1,33	5
	fuzzy	3,45	14	4,14	17	2,97	10
4	actual	2,58	7	3,19	9	3,77	12
	calculated	1,34	6	1,61	6	1,80	8
	fuzzy	2,58	9	3,13	11	2,96	10
5	actual	2,61	8	3,17	10	21,32	86
	calculated	1,32	6	1,60	6	12,21	69
	fuzzy	3,02	11	3,69	12	4,14	17
6	actual	3,16	11	3,85	11	3,73	12
	calculated	1,77	9	2,07	9	1,84	8
	fuzzy	3,26	13	3,99	14	3,61	14
7	actual	4,49	20	5,82	26	21,35	101
	calculated	16,21	78	17,95	95	12,22	77
	fuzzy	5,23	30	6,80	33	6,87	57

6. INVESTIGATION OF INTERSECTION FUNCTIONING WITH FUZZY CONTROL SYSTEM DURING A DAY

6.1. Input data generation

Research results provided above pertains to intersection functioning during only one hour under the limited range of volume change. But it's known that there are morning and evening peaks during work days, sharp drop at night, increase of volume till Friday and its reduction at the weekend [1-2, 17]. In other words, volume changes considerably range during a day even at one intersection approach. Because of that functioning of Levytskoho – Tersakovtsiv – Dorosha intersection has been researched during a day.

Values of traffic flow volume, arriving at the intersection, were the input data for simulation of the intersection functioning. Diagram of their change during a day in Levytskyy str. and Tershakovtsiv str. are shown on fig. 5. Volume values have been received using the results of traffic flows research at this intersection and as well as the results received in [17]. This diagram represents typical change in traffic flow volume during a day with unequivocal morning peak and time-extended evening peak. Traffic volume is almost unchangeable from 09:00 a.m. till 04:00 p.m.

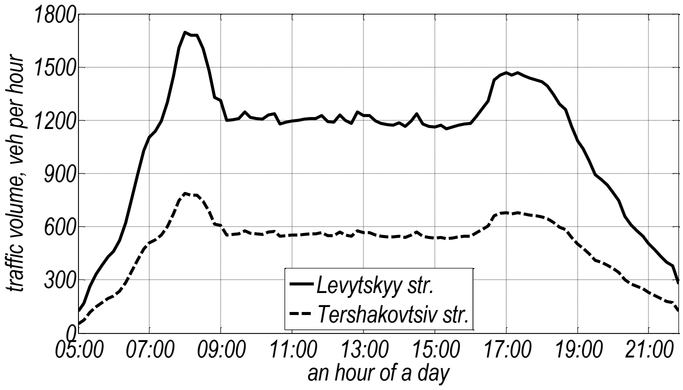


Fig. 5. Change of volume of traffic flows which arrives at the intersection during the day
Рис. 5. Изменение интенсивности транспортных потоков, прибывающих к перекрестку на протяжении дня

Since the traffic flow volume at the intersection approach isn't permanent, it is obviously that using of single-program time-fixed control is inefficient. It is more reasonable to use time-responsive or traffic-responsive control.

As follows from the shown volume change diagrams, it is necessary to use 5 programs of traffic light operating by time-responsive control during a day for:

- morning volume increase (05:00 a.m. - 07:00 a.m.);
- morning peak (07:00 a.m. - 09:00 a.m.);
- unchangeable volume during a day (09:00 a.m. – 04:00 p.m.);
- evening peak (04:00 p.m. - 07:00 p.m.);
- evening volume decrease (07:00 p.m. - 10:00 p.m.).

All of programs of traffic light operating are calculated for the averaged volume within the period of its working using methods, shown in [16]. Since the traffic flow volume from 10:00 p.m. till 05:00 a.m. is inconsiderable, and it's reasonable to switch traffic lights to flashing yellow light within this period, the research of intersection functioning for this period wasn't carried out.

6.2. Research results analysis

10 imitations were carried out in the research of intersection functioning from 05:00 a.m. till 10:00 p.m. for each traffic control systems. Changes of cycle duration and queue length were established at the moment of switching on green light at each intersection approaches.

Each imitation is a stochastic process [14], so simulation results for equal input data will be different between themselves. Duration of cycles and their amount during a day will always be the same for time-responsive control, but queue length will change. Therefore, a number of imitations and averaged values of queue lengths have been carried out. Duration and amount of cycles for traffic-responsive control is different each time. So, in this case not only queue lengths for distinctive periods of day were averaged, but also the amount of cycle duration for each of these periods.

The diagram was received due to the change of cycle duration over a day for one of the imitations for time-responsive and traffic responsive control (fig. 6). It shows that in the second case the cycle duration isn't permanent. It changes with the increase and decrease of arriving volume, but it is virtually invariable for unchangeable volume during a day from 09:00 a.m. till 04:00 p.m. As the diagram shows, the cycle duration for traffic responsive control is larger under small volume and lesser under large volume in comparison with time-responsive control. As a result, the amount of cycles in each of the periods under consideration will be lesser in the first case and larger in the second case for traffic-responsive control (tab. 4).

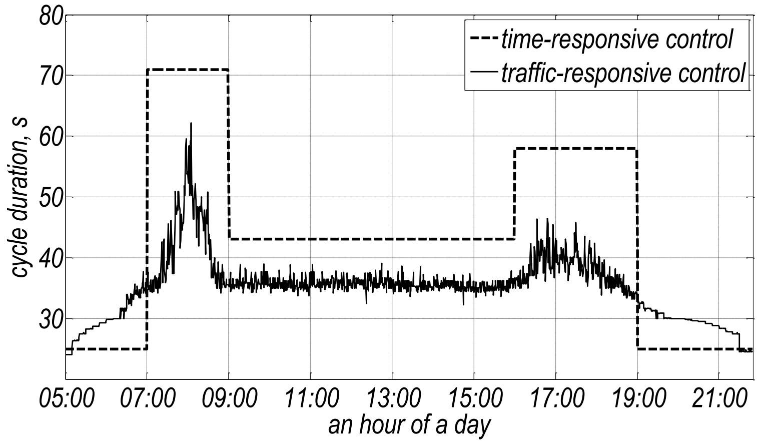


Fig. 6. Change of cycle duration over a day
Рис. 6. Изменение длительности светофорного цикла на протяжении дня

Table 4

Change of light signal cycle amount

Average amount of cycles for each control systems	Distinctive period of day					
	05 a.m. - 07 a.m.	07 a.m. - 09 a.m.	09 a.m. - 04 p.m.	04 p.m. - 07 p.m.	07 p.m. - 10 p.m.	For the whole period
time-responsive	336	101	586	186	408	1617
traffic-responsive	294,7	170,6	706,4	283,8	349,8	1805,3

Determinant parameter in this research, according to which the efficiency of intersection functioning has been evaluated, is the length of vehicle queue at each intersection approaches. Change of the queue length at the moment of switching on green light on the right lane of Levytskoho str. for one of imitations is shown in fig. 7. It's clear that lesser queue lengths during the day reach under traffic-responsive control.

Average and maximal queue lengths according to the results of 10 imitations for different control systems are shown in tab. 4. These parameters practically don't distinguish from each other during morning increase and evening decrease of volume (difference between values of average queue length doesn't exceed 10%). But during the period from morning till evening peaks values of average and maximal queue length for traffic-responsive control are smaller than for time-responsive (average queue length decreases by 0.5…2.5 vehicles or 15-45%, maximal – by 2-3 vehicles). The advantage of traffic-responsive control is particularly visible under sharp volume increase in the period of morning peak, when maximal queue length in Levytskyoho str. diminishes by 6-8 vehicles.

7. CONCLUSIONS

Volume of traffic flows isn't permanent during the day, it has relevant fluctuations and disturbance. At the same time algorithms of adaptive traffic control permit adjusting modes of traffic light control according to current traffic conditions. The authors created and implemented in software MATLAB an adaptive algorithm of traffic control at signalized intersection, which uses fuzzy logic. Simulation of intersection functioning for different possible cases during an hour showed that using of this algorithm would allow improving quality and efficiency of intersection functioning at the expense of more rational allocation of green light duration in the cycle, which in the end would minimize queue length at the intersection approaches.

In addition, simulation of intersection functioning with different control systems during the day was carried out. It is established, that using of traffic responsive control with fuzzy algorithm is more efficient, insomuch as in this case parameters of control system adjust to traffic flow volume that causes reducing of average and maximal queue length of vehicle before intersection (by 0.5…2.5 and 2-8 vehicles respectively), traffic delays and negative environmental impact.

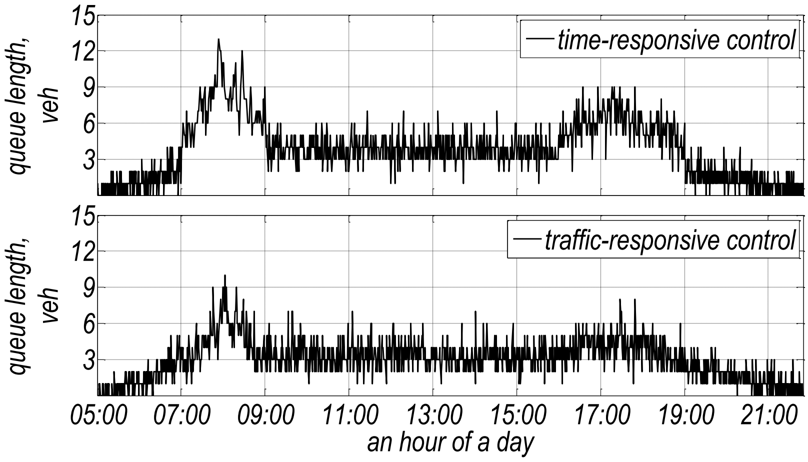


Fig. 7. Change of queue length on the right lane of Levytskoho str. in moment of switching on green light
Рис. 7. Изменение длины очереди на правой полосе ул. Левицького во время включения зеленого сигнала

Table 5

Values of average and maximal queue length

Queue type	Period of day	Queue length, veh					
		Levytskyoho str., right lane		Levytskoho str., left lane		Tershakovtsiv str., right lane	
		time-responsive	traffic-responsive	time-responsive	traffic-responsive	time-responsive	traffic-responsive
average	05:00-07:00	0,934	1,052	1,024	1,109	0,932	1,005
	07:00-09:00	7,717	5,113	7,363	4,801	7,161	5,026
	09:00-16:00	3,771	3,297	3,604	3,137	3,502	2,995
	16:00-19:00	5,606	3,923	5,404	3,759	5,308	3,648
	19:00-22:00	1,210	1,390	1,262	1,427	1,178	1,329
	for a day	2,994	2,831	2,920	2,730	2,819	2,642
maximal	05:00-07:00	6	6	5	5	5	5
	07:00-09:00	26	18	25	19	8	9
	09:00-16:00	10	11	9	7	8	8
	16:00-19:00	12	10	12	9	12	10
	19:00-22:00	7	6	6	5	6	6
	for a day	26	18	25	19	12	10

Bibliography

1. Пржибыл, П. & Свитек, М. *Телематика на транспорте*. Москва: МАДИ. 2003. 540 p. [In Russian: Przhibyl, P. & Svitek, M. *Telematika na transporte.* Moskva: MADI.]
2. Koonce, P. & Rodegerdts, L. & Quayle, S. & et al. *Traffic Signal Timing Manual*. 2008. Washington: Federal Highway Administration. Kittelson & Associates, Inc., Report FHWA-HOP-08-024.
3. Брайловский, Н.О. & Грановский Б.И. *Управление движением транспортных средств.* Москва: Транспорт. 1975. 112 p. [In Russian: Brajlovskij, N.O. & Granovskij B.I. Upravlenie dvizheniem transportnyh sredstv. Moskva: Transport.]
4. Манькут, А.А. & Смолянкін О.О. Моделювання роботи світлофора методом нечіткої логіки з врахуванням пішоходів. *Луцький національний технічний університет. Наукові нотатки.* Vol. 2. No. 25. P. 147-149. Available at: http://www.nbuv.gov.ua/portal/natural/Nn/ 2002_2009/ naunot19.htm. [In Ukrainian: Man'kut, A.A. & Smoljankin O.O. Modeljuvannja roboty svitlofora metodom nechitkoi' logiky z vrahuvannjam pishohodiv. *Luc'kyj nacional'nyj tehnichnyj universytet. Naukovi notatky*.]
5. Славич, В.П. *Методи і моделі системи автоматизованого управління транспортними потоками міста.* PhD thesis. Херсон: ХНТУ. 2009. 193 p. [In Ukrainian: Slavych, V.P. *Metody i modeli systemy avtomatyzovanogo upravlinnja transportnymy potokamy mista.* PhD thesis. Herson: HNTU.]
6. Pappis, C. & Mamdani, E. A fuzzy logic controller for a traffic junction*. IEEE transactions on systems, man and cybernetics.* 1977. Vol. SMC-7. No. 10. P. 707-717.
7. Syed Masiur, R. & Nedal, T.R. Review of the fuzzy logic based approach in traffic signal control: prospects of Saudi Arabia. *Journal of transportation Systems engineering and information Technology.* 2009. Vol. 9. No. 5. P. 58-70.
8. Niittymaki, J. *Fuzzy traffic signal control – Principles and applications.* PhD thesis. Helsinki: Helsinki University of Technology, Transportation Engineering. 2002. No. 103. 71 p.
9. Murat, Y.S. & Gedizlioglu, E. A fuzzy logic multi-phased signal control model for isolated junctions. *Transportation Research, Part C.* 2005. Vol. 13. P. 13-36.
10. Yulianto, B. Application of fuzzy logic to traffic signal control under mixed traffic conditions. *Traffic Engineering and Control.* Vol. 44. No. 9. P. 332-336.
11. Madhavan Nair, B. & Cai, J. A fuzzy logic controller for isolated signalized intersection with traffic abnormality considered. In: *Proceedings of 2007 IEEE Intelligent Vehicles Symposium*. Istanbul, Turkey. 2007. P. 1229-1233.
12. Zhang, L. & Honglong, L. & Panos, P. Signal control for oversaturated intersections using fuzzy logic. In: *Proceedings of the First International Symposium on Transportation and Development Innovative Best Practices.* Beijing, China. 2008. P. 23.
13. Staniek, M. The crossroads lights fuzzy controller development principles in VISSIM environment. *Transport. Zeszyty Naukowe*. Gliwice: Politechnika Śląska. 2011. No. 73. P. 87-95.
14. Дрю, Д. *Теория транспортных потоков и управление ими*. Москва: Транспорт. 1972. 424 p. [In Russian: Drju, D. *Teorija transportnyh potokov i upravlenie imi.* Moskva: Transport.]
15. Могила, І.А. & Форнальчик, Є.Ю. Моделювання роботи регульованого перехрестя з використанням MATLAB та VISSIM. Вісник СНУ ім. В. Даля. 2011. No. 5 (159). Part. 1. P. 232-242. [In Ukrainian: Mogyla, I.A. & Fornal'chyk, Je.Ju. Modeljuvannja roboty regul'ovanogo perehrestja z vykorystannjam MATLAB ta VISSIM. Visnyk SNU im. V. Dalja.]
16. Teply, S. & Allingham, D.I. & Richardson, D.B. & Stephenson, B.W. *Canadian Capacity Guide for Signalized Intersections. Third Edition.* Washington: Institute of Transportation Engineers. 2008. 230 p.

17. Могила, І.А. & Білоус, А.Б. & Крамажевський, Я.Р. Прогнозування інтенсивності руху з використанням часових рядів. *Вісник Донецької академії автомобільного транспорту*. 2011. Nr 3. P. 15-25. [In Ukrainian: Mogyla, I.A. & Bilous, A.B. & Kramazhevs'kyj, Ja.R. Prognozuvannja intensyvnosti ruhu z vykorystannjam chasovyh rjadiv. *Visnyk Donec'koi' akademii' avtomobil'nogo transportu.*]

Received 28.06.2011; accepted in revised form 24.01.2013