Fuzzy Logic Timing Control for Standard Crossroad Lights

Mohammad Hasan Shojaeefard [1], Morteza Mollajafari [2]* and Majid Talebi[3]

Abstract— **Fuzzy logic can be arranged concerning practical experiences and blended with conventional control techniques. Even though it is not the replacement of conventional control methods in many cases, a fuzzy control system eases the implementation and design process. It has also been put in use in other matters like traffic control. Increasing vehicles and insufficiency of passages capacity have led to widespread traffic emergence. While it is very difficult to widen existing roads, optimizing traffic like control schemas is still possible. This paper assumes a common four-directional crossroad where vehicles can move in a bidirectional way from each direction. A Sugeno fuzzy logic set of rules is presented to regulate the timing schedule of green lights for the crossroad concerning the vehicle accumulation at each line.**

Index Terms—Fuzzy logic, Crossroad, Traffic lights control

I. Introduction

Traffic problem is a major inconvenience in most urban areas around the world. This transportation issue can affect the economy, slow development, reduce production, increase cost, and distort every aspect of social life. This phenomenon causes increasing vehicles, insufficient roads and highways, and unfit traffic lights control strategies. All of these factors can create traffic congestion in the intersection, but a traditional traffic light system is one of the major factors. Traffic signals are common features of urban areas worldwide; their main purpose is to improve the traffic qualities at the intersection, maximizing the capacity at the intersection and minimizing the delays by controlling the number of vehicles that can pass at each timing phase [1]. A fuzzy logic controller allows linguistic and inexact traffic data to be applied in controlling the signal timings. A fuzzy control system is a rule-based control system characterized by expressing an expert's control rules using a fuzzy theory and determining a control command by a fuzzy inference program.

The idea of a fuzzy traffic signal controller is about modeling a control strategy based on expert human knowledge [2, 3]. In a conventional traffic light controller, the traffic lights change at a constant cycle time which is not the optimal solution when the density of passing vehicles varies with time. Obviously, it would be more feasible and sensible to pass more cars at the green interval if fewer cars were waiting behind the red lights at other lines [4, 5]. The fuzzy logic theory is introduced for the traffic controller to adopt a green interval response based on dynamic traffic load inputs instead of default pre-set timing. In this paper, we proposed a new fuzzy traffic light control system that can effectively handle confusing traffic situations with interference and a long queue of vehicles waiting at the red light. It can adaptively manage green phase lengths according to the traffic frequency and waiting for a queue. The rest of the paper is organized as follows. In the next section, some previous and close works on this problem are presented and discussed. In Section 3, the proposed method is formulated, and its algorithm is presented in detail. The simulation results are provided and discussed in Section 4, and finally, the paper is concluded in section 5.

II. Previous Research

Many researchers have already researched fuzzy logic control methods; in [6], researchers have established fuzzy rule base and expert systems to control various traffic situations, which began to apply fuzzy control algorithms in traffic management. Based on this in [7], the authors designed a multi-level fuzzy controller that may even alter the fuzzy logic upon severe condition changes [8]. In [9], researchers applied fuzzy logic to control two adjacent intersections with the same situations. This controller determined the extension or termination of the green signal based on the upstream traffic. In [10], a fully distributed system with local cooperative controllers to self-organizing traffic signal control is applied in a multi-intersection network.

In [11], a two-layer fuzzy control algorithm for traffic control of the network is proposed, which is supposed to have a large traffic flow and a high possibility of congestion. This work is also reviewed and improved in [12]. This paper indicated better performance of fuzzy-based controllers than traditional traffic signal controls, specifically during uneven and heavy traffic conditions.

Researchers in [13] have presented a hybrid algorithm that combines Fuzzy Logic Controller and Genetic Algorithms. The Genetic Algorithm has been used to adapt the decision rules of Fuzzy Logic Controllers (FLC). Others have also done some research on the finite-time adaptive fuzzy tracking control issue [14, 15]. Others proposed an optimal general type-2 fuzzy controller for urban traffic networks [16]. The general type-2 fuzzy logic sets and the modified backtracking search algorithm

1- Iran University of Science and Technology
2- Iran University of Science and Technology
3- Iran University of Science and Technology
Corresponding author: mollajafari@iust.ac.ir

techniques control the traffic signal scheduling and phase. Aiming at the coordination and dynamic uncertainty problem in arterial traffic, other scholars offered a type-2 fuzzy coordination arterial traffic control method [17]. Aiming at the situation that the timing cycle changes with time, Mo Hong used the time-varying universe and parallel system theory to study the dynamic linguistic trajectory of the timing evolution process [18,19].

The traditional control strategy of traffic lights mostly uses a fixed timing method, whose cycle, green time and phase structure are invariable [20,21]. But all researchers agree that it is hard to achieve optimal control for the variable and complicated traffic flow [22–25]. It is imperative to optimize the phase structure and select the appropriate timing method to adapt to the changing traffic flow [26-27].

For the fuzzy logic system, Q-learning and neural networks commonly used in traffic control, scholars have compared their control effect in traffic control [28]. The results show that fuzzy logic has better performance than other methods. Thus in the current work, the fuzzy control under time-varying conditions is used to realize an adaptive timing table for a traffic signal. Compared with the traditional fixed timing order, the results show that a rationally tuned adaptive approach will improve the traffic qualities under asymmetric traffic flow.

In addition, Cang Zhou in [26] has used the Mamdani-type of the fuzzy logic system, a timing project with phase optimization based on the time-varying universe proposed for the situation where the traffic control is unreasonable. Firstly, the cycling universe is determined by the base word combination of traffic flow in each lane. Secondly, the key traffic volume and average maximum queue length are inputs to determine each phase's green time. Thirdly, when the phase structure does not match the traffic flow, the phase structure is optimized by adding additional phases or merging phases. Finally, VISSIM and MATLAB simulation software compares the original and optimization timing projects proposed in this paper. The delay increases the capacity during peak hours.

In [29], a predictive controller is proposed for urban traffic in which state-space dynamics are used to estimate the number of vehicles at an isolated intersection and its queue length. The simulation results show that traffic volumes and car crashes are reduced by controlling traffic on an urban road using model predictive control.

The authors of the previous research proposed a new stable TS (Takagi–Sugeno) fuzzy controller for urban traffic [30]. Their approach formulates the state-space dynamics for the vehicle's average waiting time at an isolated intersection and the length of queues. Then, a fuzzy intelligent controller is used to control the lights based on the queue length. The results show that the performance of the control and its stability are proved using the Lyapunov theorem.

[31] developed a method based on the fuzzy factors of the intensity of pedestrian flow and flow discontinuity to improve the accuracy of modeling and predicting the traffic capacity of intersections. The results are analytical, and no simulation results are provided.

The main contribution of this paper is using the fuzzy logic in predicting, optimizing and reducing the traffic and the number of stopped cars at crossroads. Meanwhile, in many recent projects, artificial smart or intelligent vision systems have been used. The results obtained according to the fuzzy inference output chart are clear: the number of stopped cars increased, whether in total, in total mean, or even in separate mode. Moreover, in the proposed approach, each car's waiting time is less than those of smart modes and system controls.

III. Current work

The field of operation is presumed to be a common crossroad with four directions of passages, as shown in Fig. 1. In each direction, vehicles can either enter or leave the crossroad.

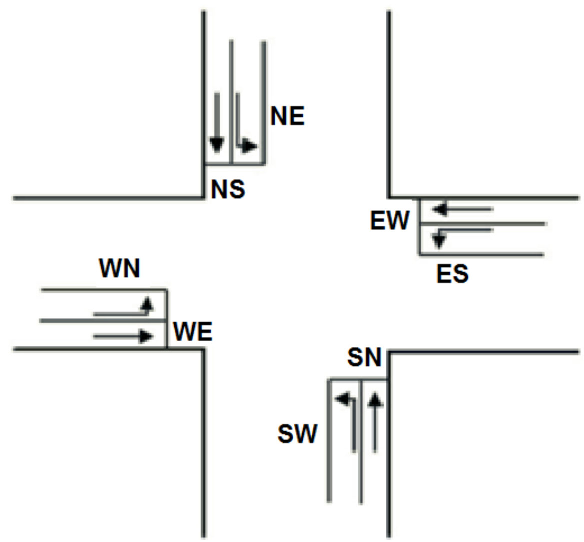


Fig. 1. The important directions of motion at this crossroad are considered from West to East (WN), West to North (WN), and similarly NS, NE, EW, ES, SN, and SW. Vehicles that leave the area or turn to the right don't have any deterministic effect on the traffic situation here.

Obviously, motions with the most queue should be given the most time. According to the practical data provided in [26] (driven from standard Chinese urban traffic scales), a total timing sequence of traffic lights in such a crossroad should be between 80-220[1] seconds, and vehicles queued in the line should count less than 100 for each direction and 600 for the whole quarter. It is assumed that the vehicle numbers are countably utilizing modern intelligent surveillance monitoring systems presented at each important passage.

Thus assuming the total cars in the quarter as our first input independent variable called TC, this parameter is a subset of Low (TC<200), Medium (200<TC<400) and High (TC>400) traffic density. Total cycle duration (TCD) is a dependent variable on the TC. According to the Fuzzy Inference System Act, it should be considered as three areas for the total car waiting time. Since the plan, the total period of stopping at the crossroads of 80 to 220 seconds can be reached in three-level

[1] Quantities may vary slightly considering a necessary tolerance

"low", "moderate," and "long" divided time intervals and also According to international law, the cars do not stop for the right-turn, so it is not considered in this article. The first set of fuzzy rules are now set as below:

TABLE I
Sugeno Fuzzy Logic Rules for TCD Concerning the TC

Rule 1	If TC is low, then TCD is short (80-120)	TCD=80+0.2*TC
Rule 2	If TC is medium then TCD is mediocre (120-160)	TCD=100+0.15*TC
Rule 3	If TC is high then TCD is long (160-220)	TCD=40+0.3*TC

The TCD parameter naturally contains all the crossroad's red, yellow and green light times. Considering the existing 8 lines, when the TCD is set to be 80 seconds, and the car queues at all lines are equal, it means that each line has 10 seconds of green light, 20 seconds of yellow and 50 seconds of red light.

After determining the cycle duration, it is now turned to dividing this duration between 8 lines. The direction with the highest Local Queue Density (LQD) should be allocated with the longest Green Light Duration, and the sum of all eight GLDs should not pass the authorized TCD. Here we take a simple solution to assign green time to each line according to its queued vehicle quantity. If TC_i is the number of waiting for cars at each line i, a ratio can be considered as a priority right like (1, 2):

$$P_i = \frac{TC_i}{TC} \quad (1)$$

Obviously:

$$\sum_{i=1}^{8} P_i = \frac{\sum_{i=1}^{8} TC_i}{TC} = \frac{TC}{TC} = 1 \quad (2)$$

Each Pi can be a real number between 0-1. The line with the highest priority can be let first to green light.

The time quota from the TCD for each car to pass among the whole TC can be assumed as:

$$Ct = \frac{TCD}{TC} \quad (3)$$

And finally, each line green timeshare can be calculated as:

$$GT_i = C_t * TC_i \quad (4)$$

And

$$\sum_{i=1}^{8} GT_i = TCD \quad (5)$$

However, this approach will cause an allocation time shortage when too few or too many vehicles are in line. For example, when there are less than ten cars in a line, the assigned GT may run below 3 seconds, which is insufficient to pass. Therefore, another set of fuzzy rules is introduced to compensate for this matter:

TABLE II
Sugeno Fuzzy Logic Rules to Assign Suitable GT for Each Line

Rule 1	If TCi is low (TCi<30), then GTi is short	$GT_i = A_i + C_t * TC_i$
Rule 2	If TCi is medium, then GTi is mediocre	$GT_i = B_i + C_t * TC_i$
Rule 3	If TCi is high (TCi>60), then GTi is long	$GT_i = C_i + C_t * TC_i$

For an instant, it seems that constants $A_i$between3-5, B_i between 5-10 and C_i between 10-15 seconds would suit well; however, these constants can be further optimized in practice noticing that the sum of all GTs should not pass 1.2*TCD. Consequently:

$$\sum_{i=1}^{8} A_i < 0.2 * TCD \quad (7)$$

The algorithm will re-assign A, B, and C for each line to adhere to the above condition. Beginning from the upper limit for each one and reducing it if necessary. Considering these, a better set of fuzzy rules for this stage can be written below.

TABLE III
Accurate Sugeno Fuzzy Logic Rules to Assign Suitable GT for Each Line

Rule 1	If TCi is low (TCi<33), then GTi is short	$GT_i = 3 + \frac{TC_i}{15} + C_t * TC_i$
Rule 2	If TCi is medium, then GTi is mediocre	$GT_i = 5 + \frac{TC_i}{12} + C_t * TC_i$
Rule 3	If TCi is high (TCi>66), then GTi is long	$GT_i = 10 + \frac{TC_i}{20} + C_t * TC_i$

This set of fuzzy rules must be applied for all GTs of all directions. After recalculating the GTs, the real cycling duration (RCD) will be the sum of all GTs. This may differ from the predicted TCD.

IV. Simulation and Results

While the proposed algorithm is not sensitive to daily cycles, its application will still be in daily life. Thus for the simulation, a 24 hours cycle is assumed, but the quantities of incoming cars are assumed as independent toward daily hours. At the end of each TC cycle, the TCi numbers are re-extracted the set of rules and parameters are updated.

The TC (and subsequently TC_i) is a random independent input variable that varies between 0-600. The TCD parameter is first considered constant and then recalculated with our fuzzy rules. Pi, Ct, GTi and AWT must be calculated for both cases. The simulation is repeated each time that TCD cycling time is passed and subtracted from the daily time duration in seconds.

In a sample simulation, the total number of 409 cycles was allocated (this number depends on the total passing cars as a random input variable and our fuzzy rules). The results are as follows.

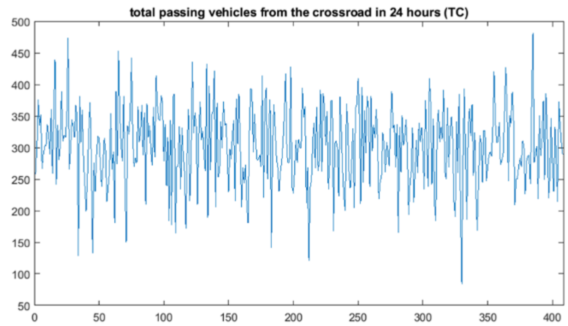


Fig. 2. The total quantities of passing cars per cycle were between 75 and 475

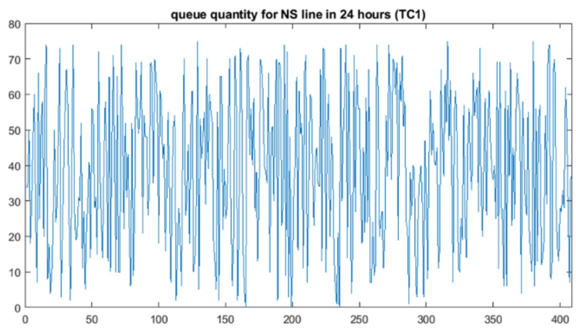


Fig. 3. The queued cars in the North to South line at each cycle

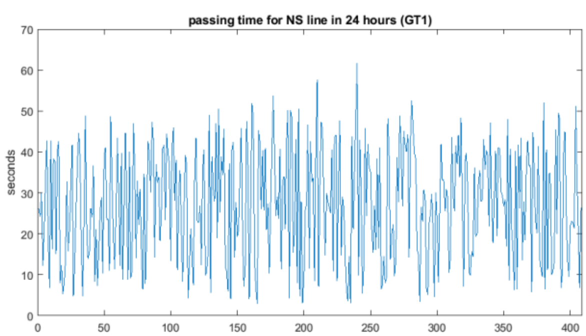


Fig. 4. The green light time for NS passage at each cycle has always been always been between 3-62 seconds

Each line's average green light time was about 30 seconds.

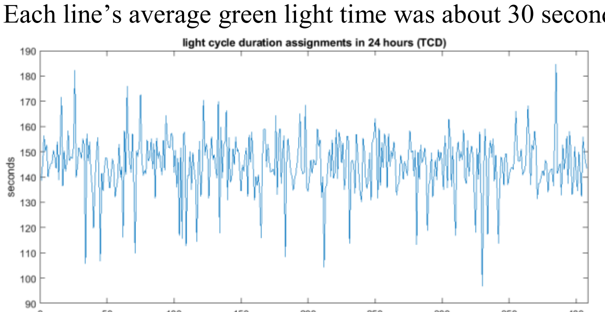


Fig. 5. Each cycle duration is in seconds. The threshold of 220 seconds has not been violated, and cycles were usually less than 3 minutes lengthened.

Fig. 6. is the most important parameter on the topic since it shows the time wasted at the crossroad for the vehicles. One may claim that a constant timing cycle, for example, at the length of 2 minutes, could be shorter on most occasions. Still, there are no guarantees that this constant timing of 15 seconds for each line to pass could suffice for all the vehicles in a queue to pass, and the line could be accumulated with incoming cycles. This will lead to an unpredictable situation of long queues which may be delayed up to many hours while the current fuzzy logic-based solution ensures that all the vehicles will receive enough time to pass and the crossroad will be vacant at the end of each cycle from the previous cycle's passengers even though it sometimes has violated the threshold of the maximum recommended light cycling time.

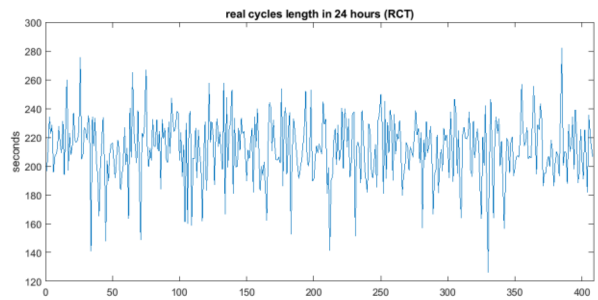


Fig. 6. The real length of each passing cycle per 24 hours

TABLE IV
Parametric Comparison Between Methods (seconds).

	Current method	The method presented in [25]	The method presented in [26]
average green light time	30	45	40
Average cycling time	200	240	220

This article is based on a fuzzy model of an urban traffic network designed for a single intersection. The model's state variables are the length of queues and the average waiting time for the vehicles. Moreover, the vehicle's average waiting time at an isolated intersection and the length of queues are considered controller inputs. Additionally, the effectiveness of the suggested controller is verified by simulation results. The percentage of improvement with attention to simulation results using the proposed method decreases the vehicles in each intersection phase to the fixed time Control, as shown in Figures 7 and 5.

Moreover, the presented method does not bind the situation to any specific time over the day-night conditions like early morning traffic. The current approach can quickly adapt itself to any unpredicted traffic conditions. However, interested researchers can still work on further optimizing the fuzzy rules set presented here. As seen in Figure 8, the proposed can effectively reduce the delay.

TABLE V
Vehicle Queue Length Performance Results from Fuzzy Intelligent and Fixed Time Control

Queue times	Fixed-time Controls [25]	Fuzzy Intelligent Control [Proposed]	Total Improvement Percentage
7:30 – 8:30	85	20	76.47
10:30 – 11:30	30	8	73.33
15:30 – 16:30	45	15	66.67
18:30 – 19:30	320	67	79.06
SUM	480	110	77.08

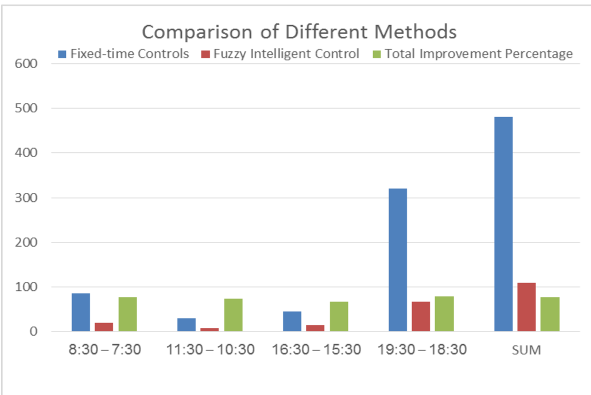
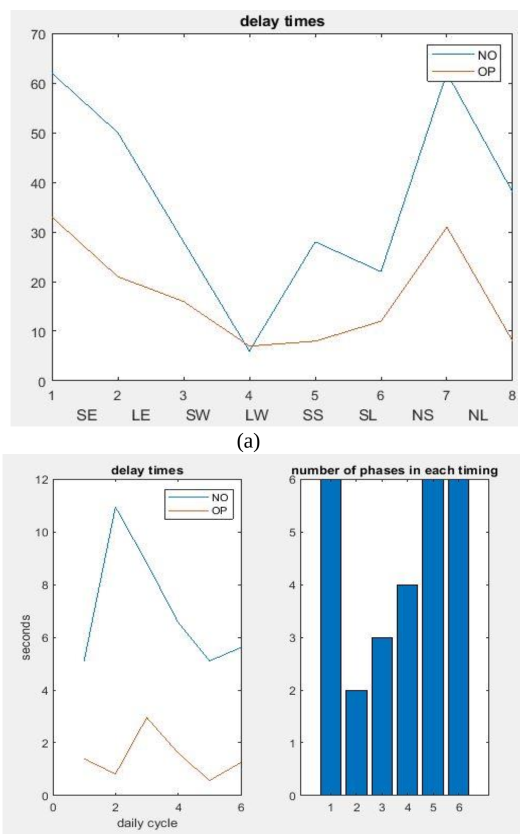


Fig. 7. Comparison of results in the length of the queue of vehicles using a fuzzy model.



(a)

(b)

Fig. 8. (a) Comparison of results in delay times between the method with and without optimization, (b) impact of the number of phases in each timing on the delay times.

The novelty of the proposed method using fuzzy logic in predicting, optimizing, and reducing traffic and stopping cars at crossroads. Meanwhile, in many recent projects, artificial smart or intelligent vision systems have been used. The results obtained according to the fuzzy inference output chart are quite clear: the number of car stops, whether in total and in total mean and even in a separate mode, each car's waiting time is less than smart mode and system controls. In addition, the presented method does not bind the situation to any specific time over the day-night conditions like early morning traffic. The current approach can quickly adapt itself to any unpredicted traffic conditions. However, interested researchers can still work on further optimizing the fuzzy rules set presented here.

V. Conclusion

This paper proposes a fuzzy logic predicting method that optimizes traffic and stopped cars at crossroads. The fuzzy inference output chart of the proposed method clearly shows that the amount of stopped cars and their waiting time at crossroads is less than those of intelligent vision-based controlling systems. Moreover, the presented method does not bind the situation to any specific time over the day-night conditions like early morning traffic. The current approach can quickly adapt itself to any unpredicted traffic conditions. In the future, we will work on further optimizing the fuzzy rules set presented here.

VI. Biographies

Prof. **Mohammad Hassan Shojaeefard** was born in 1950 in Jahrom, Iran. He completed his B.Sc. degree in mechanical engineering from the Iran University of Science and Technology (IUST) in 1977. He also successfully attained an M.Sc. degree in mechanical engineering from the University of Birmingham, UK, in 1983. Prof. Shojaeefard has held a Ph.D. in mechanical engineering from the University of Birmingham, the UK, since 1987. Now, he is the Professor and Head of Automotive Eng. Research Center (AERC) & Automotive Eng. Dept. (AED) (IUST). The Specific topics of interest of Prof. Shojaeefard are fluid dynamics, internal combustion engines and automotive engineering.

Morteza Mollajafari received his BS in electrical engineering from the Electrical Engineering Department at K.N. Toosi University of Technology in 2008; and his MSc. and a Ph.D. degree in electrical engineering from Iran University of Science and Technology (IUST) in 2011 and 2017, respectively. He is an assistant professor in the automotive engineering department at the IUST. His research areas include parallel and distributed computing systems, especially Cloud Computing, developing scheduling algorithms, Evolutionary Algorithms and autonomous vehicular systems.

Majid Talebi received BS degree from the Azad University of Bojnord, Bojnord, Iran, in 2006, where he is currently pursuing the master's degree in Digital Electronics Engineering with the school of Automotive Engineering, Iran University of Science and Technology. His research interests include machine learning, data mining, deep learning, machine vision, and optimization.

VII. References

[1] Rustem, S., Regina, N., "Traffic safety system management", *Transportat. Res. Procedia.* 36, 676–681 (2018)

[2] Mohan, D., “Traffic safety: Rights and obligations”, *Accidents Analysis and Prevent.* 128, 159–163 (2019)
[3] Li, Z.H., Cao, Q., Zhao, Y.H., Tao, P.F., Zhou, R., “Krill herd algorithm for signal optimization of cooperative control with traffic supply and demand”, *IEEE Access*. 7, 10776–10786 (2019)
[4] Dotoli, M., Fanti, M.P., Meloni, C., "A signal timing plan formulation for urban traffic control", *Control. Eng. Pract*. 42(3), 1297–1311 (2016)
[5] Akcelik, R., “Traffic signals: capacity and timing analysis”, *Transportat. Res*. 5(6), 505–505 (2011)
[6] Webster, F.V., “Traffic signal settings”, *Technical Report. HM, Stationery Office* (2018)
[7] Pappis, C.P., Mamdani, E.H., “A fuzzy logic controller for a traffic junction”, *IEEE. Transact*. Syst. Man. Cybernet. 7(10), 707–717 (2017)
[8] Chen, H., Chen, S.F., “A method for real-time traffic fuzzy control of a single intersection”, Informat. Control. 36(3), 227–233 (2017)
[9] Nakatsuyama, M., Nagahashi, H., Nishizuka, N., “Fuzzy logic phase controller for traffic junctions in the one-way arterial road”, *In IFAC proceedings series.* 2865C2870 (2015)
[10] Chiu, S., Chand, S., “Self-organizing traffic control via fuzzy logic”, In: Proceedings of the 32nd IEEE conference on decision and control. 2, 1897C1902 (2013)
[11] Zhang, W.B., Wu, B.Z., Liu, W.J., “Anti-congestion fuzzy algorithm for traffic control of a class of traffic networks”, In IEEE international conference on granular computing. 124 (2007)
[12] Rahman, S.M., Ratrout, N.T., “Review of the fuzzy logic-based approach in traffic signal control: prospects in Saudi Arabia”, *J. Transportat. Syst. Eng. In format. Technol*. 9, 5870 (2009)
[13] Odeh, S.M., Mora, A.M., Moreno, M.N., Merelo, J.J., “A hybrid fuzzy genetic algorithm for an adaptive traffic signal system”, *Adv. Fuzzy. Syst*., (2015).
[14] Sun, W., Wu, Y.Q., Sun, ZY, “Command filter-based finite-time adaptive fuzzy control for uncertain nonlinear systems with prescribed performance”, *IEEE. Transact*. Fuzzy. Syst. 10(1109), 2967295 (2020)
[15] Sun, W., Su, S.F., Wu, Y.Q., Xia, J.W., “A novel adaptive fuzzy control for output constrained stochastic non-strict feedback nonlinear systems”, *IEEE. Transact. Fuzzy. Syst.* 10(1109), 2969909 (2020).
[16] Khooban, M.H., Vafamand, N., Liaghat, A., Dragicevic, T., “An optimal general type-2 fuzzy controller for Urban Traffic Network”, *ISA. Transact*. 66, 335–343 (2017).
[17] Bi, Y.R., Lu, X.B., Sun, Z., Srinivasan, D., Sun, ZX, “Optimal type-2 fuzzy system for arterial traffic signal control”, *IEEE. Transact. Intell. Transportat*. Syst. 19(9), 3009–3027 (2018)
[18] Li, R.M., Jiang, C.Y., Zhu, F.H., Chen, X.L., “Traffic flow data forecasting based on interval type-2 fuzzy sets theory”, *IEEE/CAA J. Autom. Sinica*. 3(2), 141–148 (2016)
[19] Cao, X.L., Mo, H., Zhu, F.H., “Fuzzy control of timing for traffic lights based on the time-varying universe”, *Measure. Control. Technol*. 38(11), 115–120 (2019).
[20] Mo, H., Hao, X.X., Zheng, H.B., Liu, Z.Z., Wen, D., “Linguistic dynamic analysis of traffic flow based on social media case study”, *IEEE Transact. Intell. Transport. Syst.* 17(9), 2668–2676 (2016).
[21] Henrique, D., Norian, M., Furio, D., “Genetic algorithm-based traffic lights timing optimization and routes definition using Petri net model of urban traffic flow*”, IFAC. Proceed*. Vol. 47(3), 11326–11331 (2014).
[22] Talab, H.S., Mohammadkhani, H., Haddadnia, J., “Controlling multi variable traffic light timing in an isolated intersection using a novel fuzzy algorithm”, *Journal of Intelligent Fuzzy Systems* 25(1), 103–116 (2013).
[23] Maythem, K.A., Mohd, N.K., Madzlan, N., Brahim, BS, Marwan, A., “High accuracy traffic light controller for increasing the given green time utilization”, *Comput. Electri. Eng*. 41, 40–51 (2015).
[24] Shahhoseini, H. S., Saleh Kandzi, E., Mollajafari, M. “Nonflat surface level pyramid: a high connectivity multidimensional interconnection network,” *The Journal of Supercomputing*, 67(1), 31-46, (2014).
[25] Araghi, S., Khosravi, A., Creighton, D., “A review on computational intelligence methods for controlling traffic signal timing”, *Exp. Syst. Appl*. 42(3), 1538–1550 (2015).
[26] Cang Zhou, “Fuzzy Control under Time-Varying Universe and Phase Optimization in Traffic Lights (ICSSE 2020)”, *Int. J. Fuzzy Syst*. (2021).
[26] Mollajafari, M., Shojaeefard, M. H. “TC3PoP: a time-cost compromised workflow scheduling heuristic customized for cloud environments,” *Cluster Computing*, 24(3), 2639-2656, (2021).
[27] Mollajafari, M., Shahhoseini, H.S. “A repair-less genetic algorithm for scheduling tasks onto dynamically reconfigurable hardware.” *International Review on Computers and Software* 6.2, 206-212, (2011).
[28] Shojaeefard, M., Mollajafari, M., Mousavitabar, S., Khordehbinan, M., Hosseinalibeiki, H., "A TSP-based nested clustering approach to solve multi-depot heterogeneous fleet routing problem," Rev. int. métodos numér. cálc. diseño ing, 38 (1), pp. 1-14, (2022).
[29] Jafari, S., Shahbazi, Z., & Byun, Y. C. “Improving the Performance of Single-Intersection Urban Traffic Networks Based on a Model Predictive Controller,” Sustainability, 13(10), 5630, (2021).
[30] Jafari, S., Shahbazi, Z., & Byun, Y. C.. “Traffic Control Prediction Design Based on Fuzzy Logic and Lyapunov Approaches to Improve the Performance of Road Intersection. Processes," 9(12), 2205, (2021).
[31] Shepelev, V. D., Glushkov, A. I., Makarova, I. V., & Boyko, A. “Clustering Urban Transport Network Junctions Using Convolutional Neural Networks and Fuzzy Logic Methods,” Transportation Research Procedia, 62, 581-588, (2022).