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An Optimal Dynamic Control Method for an Isolated Intersection Using Fuzzy Systems

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Abstract

Traffic flow systems are nonlinear and uncertain, so it is very difficult to find their optimal points. In traditional traffic control systems, the traffic lights of crossings change in a fixed time period that is not optimal. On the other hand, most proposed systems are sufficiently capable of coping with the uncertainties of traffic flow. To solve this problem, there is a need to develop expert systems that can manage the traffic flow of intersections in terms of its actual conditions in a normal and emergency situation. This paper introduces an optimal dynamic and smart eight-phase traffic light control system using fuzzy controllers in which the capability of fuzzy systems with human-like decision-making process is exploited. This algorithm reduces the waiting time of the vehicles in intersection queues and in traffic congestion by the strategy of optimal green light durations and dynamic phasing based on the lanes with heavier traffic and the critical conditions like the entrance of emergency vehicles into the intersection. At the same time, it keeps the simplicity and avoids computational complexity. This method is simulated for an isolated intersection based on the traffic feature and the random data input rate to determine the dynamic timing of the traffic light and optimal phases with the smart fuzzy method using MATLAB Software Package (Matlab, 2013). This approach assessed the proposed method of intersection traffic control in terms of efficiency and traffic density against the constant-timing system and four-phase system proposed by some researchers. The results show that the proposed method can be effective in improving intersection traffic control systems.

Keywords:
traffic flow systems
intersection traffic light
fuzzy systems

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INTRODUCTION

A major challenge of today's world is the increase in traffic in cities, especially in metropolitan areas. Increasing population growth, increased use of vehicles, lack of adequate infrastructure, and lack of appropriate technology have turned traffic into a serious problem for economics, health and environment. Since traffic flow systems are non-linear and complex, it is not possible to control them with traditional methods and precise mathematical formulas. The traffic light-based intersection traffic control systems that work in traditional and conventional ways are not optimal, and/or are not well arranged to counteract the uncertainties of the traffic flow and are not able to respond to the current situation.

The most important considerations for optimizing intersection traffic control systems are the traffic lights cycles and phases. A traffic light cycle is a sequence of green, yellow, and red lights, and a phase refers to a set of allowed passing lanes. At present, most traffic lights have constant cycles since they are not determined on the basis of the actual traffic flows or the actual queue lengths. So, the green time of the phases has very inappropriate and unbalanced duration. In some cases, the density of vehicles is evaluated using ring detectors mounted under the road, but they are very difficult to repair and install, and also interrupt the service. In other cases, the phases of the traffic light are static, in which case a phase that is not critical receives an extra green signal. To overcome these constraints, the traffic lights phase sequence should not be static, but dynamically determined according to the real-time evaluation of the length of the queues.

To solve these problems, it is imperative to develop expert systems. Fuzzy logic systems, which act on the basis of the approximate and imprecise conditions of the environment and its decision-making and reasoning are similar to human, can be combined with the capabilities of wireless sensor networks to estimate the traffic for controlling and planning intersection traffic lights. This paper presents an optimum dynamic and smart control system of eight-phase traffic lights using fuzzy controllers, which reduces vehicle waiting time at intersections and traffic congestion. This is a two-stage hybrid system. In the first step, data are gathered through data acquisition tools such as wireless sensor network based on the input lanes and they are sent to a controller. In the second step, the controller tells the optimum timing and phasing to the traffic light by three consecutive actions of an assigned module, a fuzzy controller and a phase sorting module. Here, for fault tolerance, performance and flexibility, four fuzzy controllers are considered for each path or street to calculate the optimal green time. The advantage is that each controller works on its own path with a certain precision, or if the controller of a path is damaged, the other three controllers work correctly. As another advantage, the eight-phase technique is dynamic, in which the traffic light cycle with four output phases varies with traffic conditions. The result is the repetition of the light cycle in shorter times, which causes the traffic congested lanes to be discharged faster and the traffic flow to be smoothed in the intersection. The results indicate that the proposed system is effective in improving intersection traffic control systems.

In this paper, Section 2 is a review of relevant literature. Section 3 presents the suggested intersection traffic control system followed by the assessment of the system's performance in Section 4. Section 5 comes with concluding points and some recommendations for future works.

REVIEW OF LITERATURE

Using the developments in artificial intelligence technology, Kelsey and Bisset (1993) come up with new solutions for traffic control by a different approach based on artificial intelligence methods. Among artificial intelligence methods, fuzzy logic systems have been considered by researchers and scholars due to their human-like behavioral capabilities of decision making, and extensive studies have been conducted to optimize traffic flow control systems. In 1977, Pappis and Mamdani (1977) developed a fuzzy logic system for an intersection with two streets in this work; fuzzy rules were used for the dynamics of the green-time cycle and did not control the phases of the light. Trabia et al. (1999) introduced a two-step fuzzy logic control method in which a first fuzzy controller is first used to determine the phase that should be managed, and the second fuzzy controller manages the green lights of the traffic lights. This effect manages the phases of the traffic light. Niittymaki and Pursula (2000) developed a fuzzy signal control algorithm. This two-stage algorithm is to control the vehicles, to adjust cycle time, and to divide the cycle into green phases. They reported that the method works well in an area where traffic density is lower and compared to the Mamdani method, it works better and ensures higher traffic safety given the lower number of refueling stops. Niittymaki and Pursula (2000) presented a systematic method for fuzzy traffic control and deduced linguistic control rules based on technical knowledge. They found the results of the tested rules promising and reported that the fuzzy control algorithm measured most effects better than traditional traffic control system. Murat and Gedizlioglu (2005) introduced two fuzzy controllers for dynamic control of traffic light cycles and phases. Murat and Gedizlioglu (2005) and Trabia et al. (1999), both, used a two-stage scheme for the control of cycles and phases in which a controller is used to control cycles and the second controller is used to control the phases of the traffic light dynamically. Also, they use inference rings or camcorders to estimate the number of vehicles in traffic light queue. Their difference lies in the type of fuzzy controllers, i.e., the type of membership functions and the number of inference rules. Kulkami and Waingankar (2007) presented a fuzzy logic controller to extend the green light time with two objectives: improving vehicle power (the number of vehicles passing through the traffic light) and reducing waiting times in the queue.

Zou et al. (2009) proposed a fuzzy logic controller that can dynamically schedule the green light time of traffic light, but the phase sequence was considered statically. The systems presented by Zou et al. (2009) and Kulkarni and Waingankar (2007) does not manage the traffic light phases, and the fuzzy logic controller only controls the duration of a queue but the duration of a set of queues is not controlled for a certain phase. As a result, the fuzzy controller may extend the green light time of a phase unnecessarily. Because in the uncertainty conditions the sequence of the phase should not be static, this is a system limitation and will not work at crossings with more than two phases.

Zaied and Othman (2011) designed a fuzzy controller for dynamic adjustment of the green light time of an eight-phase traffic light at an isolated separate intersection. In this case, eight inputs (queues) and sixteen outputs (i.e. green light time calculated for each allowed direction) should be used. Fuzzy controller is specified by multiple input variables. Wilamowski (2012) used several fuzzy controllers instead of a single controller. Multiple-controller system improves the fault tolerance, performance and flexibility of the system. If an error occurs in one controller, the corresponding phase gets into trouble, but the control system works correctly in the other three phases. Shahraki et al. (2013) designed a fuzzy controller system for traffic lights in a four-way traffic junction with several successive intersections. The system consists of three modules: the next phase selector, the green light extender, and the decision maker. The first two modules are specified by a fuzzy controller, which determines the next phase and the green light allocation and the possible increase in the current green light. The controllers process the number of vehicles per link (in which a link refers to a road that connected to two adjacent intersections), the number of vehicles in queue waiting by the red light and the waiting time measured by a timer that estimates how long the first car has been waiting in the queue. The decision making module determines whether to increase the current green light time or to change to the next phase. The fuzzy logic controller is only used to decide upon the execution of the most immediate phase dynamically. In this regard, the main limitation of the reviewed works is that the increase in green light time is calculated by a single fuzzy controller for all phases, while Wilamowski (2012) states the need to consider one controller for each phase in determining green light time for better performance, error tolerance and flexibility.

Mario et al. (2015) proposed a dynamic four-phase traffic light control system that was a combination of wireless sensor networks for real-time monitoring of traffic with multiple fuzzy logic controllers, one for each phase of the traffic light to determine the dynamic management of the green light duration in each phase. This system operates in two steps. In the first step (receiving and processing of real-time traffic data), the number of vehicles in the queue that is estimated by the nodes of a wireless sensor network located near the traffic light is sent to a base station of the wireless sensor network (as a coordinator). Here, data are processed with two goals: first, to sort the phases of the traffic light according to the priority that depends on the number of vehicles in the queue, and second to select the first phases to run. In the second step (dynamic green light duration calculation), the green time of each phase is selected by the controller of the corresponding fuzzy logic using data about the number of vehicles in the selected fuzzy queue. Although this method shows acceptable performance as compared to other methods, the four output phases are a limitation for the system and do not function properly where the traffic is heavy. Instead, the dynamic eight-phase approach exhibits distinct, significant performance in normal and abnormal traffic congestion.

A NEW METHOD TO CONTROL JUNCTION TRAFFIC

The present study aims at creating a dynamic fuzzy control system to make the traffic flow more smoothly, prioritizing phasing based on emergency vehicles and high traffic lanes at an intersection in order to reduce vehicle delays in intersection queues and traffic congestion. It is of crucial importance to determine phase sequence correctly when dealing with very busy roads. It means that the highest number of vehicles in a queue would be granted with the highest priority and the longest green time. The proposed system is composed of

1. Traffic Data Collection Device (TDCD) (wireless sensor networks) for real-time traffic data acquisition,
2. A module to allocate data to fuzzy controllers,
3. Fuzzy controllers to estimate optimal green light time for each phase based on traffic data of the respective lines, and
4. Phase prioritization module to calculate the order in which the phases should be run based on the timing by the fuzzy controllers and the lane data.

Fig. 1 depicts the architecture of the suggested system. As shown in Fig. 1, TDCD (sensors) aggregates traffic data from the corresponding lanes. Data allocation module to fuzzy controller sorts the data based on the traffic congestion in lanes and transfers it to the controller. Each fuzzy controller determines the green light duration suitable for each phase with respect to the volume of traffic in the respective route. Phase prioritization module sends the phase running sequence to traffic light based on the number of vehicles in the intersection queue and the green light duration specified by the fuzzy system for each phase.

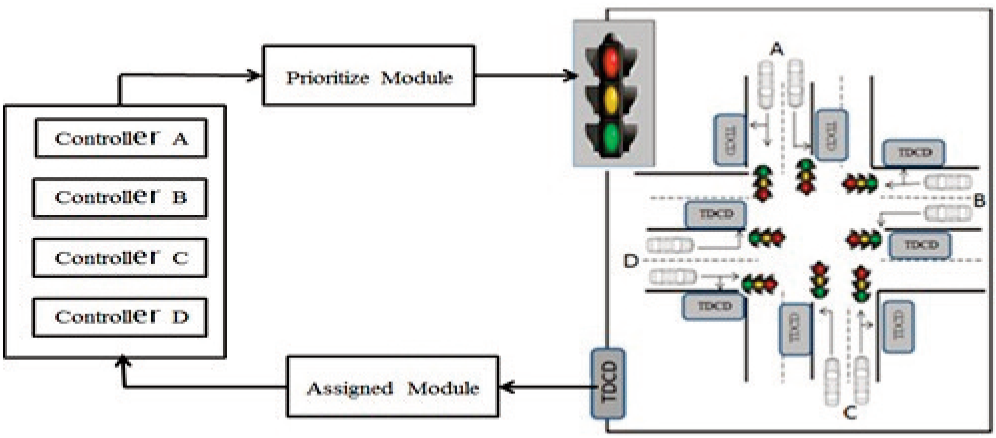

Fig.1.The recommended architecture

Fig. 2 shows a case study of a typical, isolated, signaled intersection. This crossroads has four paths and two lanes in each path with eight input queues. Thus, according to Fig. 3, the cars that enter the crossroads from either side of each path can only go straight ahead or turn left assuming that the right side is free.

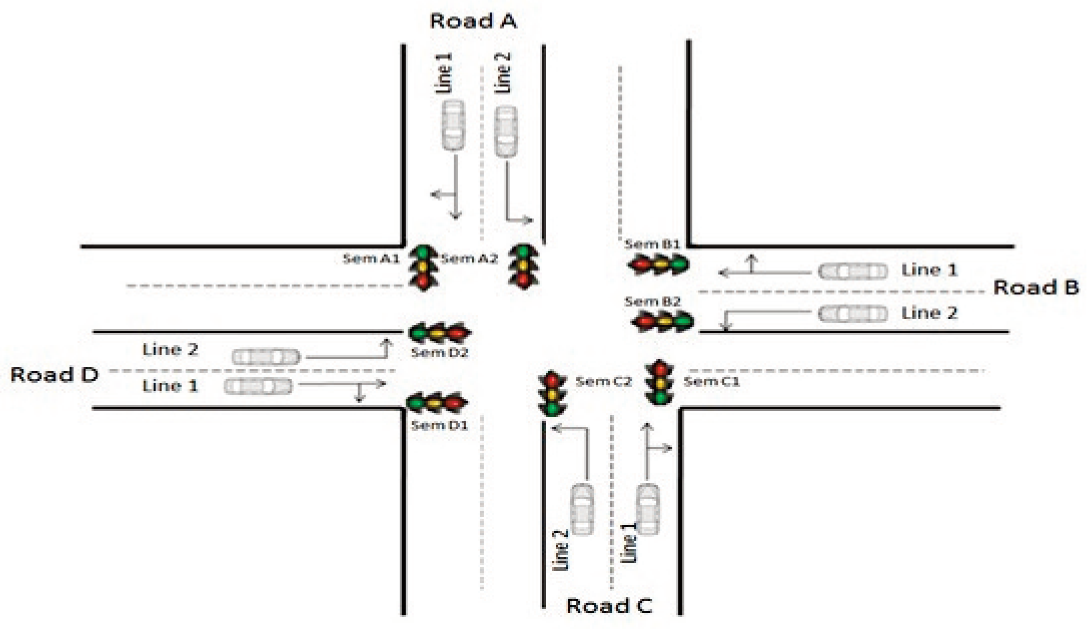

Fig. 2. A case study of an isolated intersection

Table 1 maps the traffic lights of the intersection in the lanes of the roads that they control and their allowed direction. As shown in Fig. 2, traffic lights are managed so as to ensure that the simultaneous access of cars from different lanes of a road to the intersection is prevented. This selection is to avoid collisions that may occur when two lanes intersect. Fig. 3 shows the traffic light phases of the intersection in question. According to Fig. 3, eight output phases are defined for eight input queues. In this sense, when phase 1 is active, only Ci and Ai paths are allowed to pass through and the red lights are on in the rest of the states. If phase 2 is active, only Ai and Aj paths are free, and the rest of the paths have red lights, and so on.

Table 1: Road crossings and their traffic lights (Mario et al., 2015)

Traffic lights	Road and lanes controlled	Allowed directions
SEM_A1	Road A-lane 1	Straight /right
SEM_A2	Road A-lane 2	Left
SEM_B1	Road B-lane 1	Straight /right
SEM_B2	Road B-lane 2	Left
SEM_C1	Road C-lane 1	Straight /right
SEM_C2	Road C-lane 2	Left
SEM_D1	Road D-lane 1	Straight /right
SEM_D2	Road D-lane 2	Left

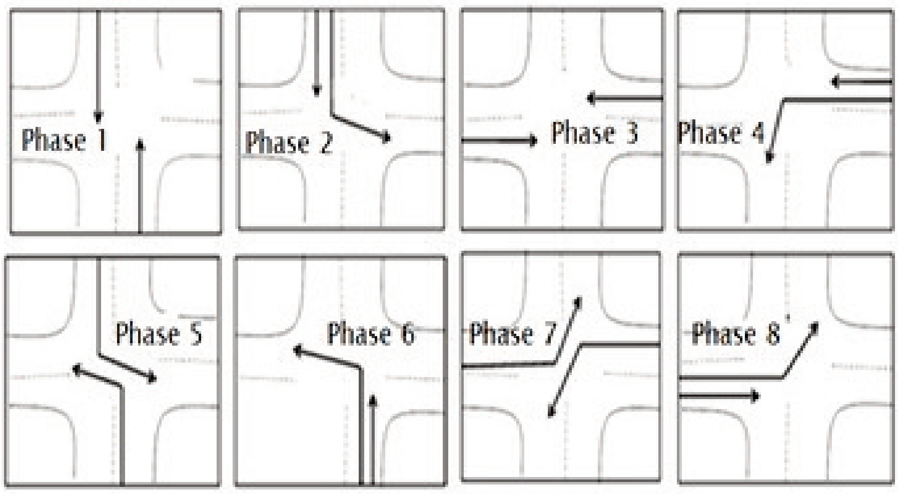

Fig. 3. The phases of the traffic light in the intersection in question

Fuzzy system design

The isolated intersection considered here is composed of eight phases. As shown in Fig. 3, a traffic light phase is the length of time during which the traffic is allowed for a given set of lanes. For example, assuming that the right side is free, when the phase is activated, according to Fig. 3, only the cars in two allowed lanes can go straight ahead or turn left, while for all other lanes, the red lights will be on. Table 2 summarizes the notation adopted in this study. In fixed-cycle traffic lights, each cycle can be approximated to a periodic work of period T, which is characterized by constant green time (T_g) and constant yellow time (T_y). The traffic lights show red light (T_r) for remaining time, as described by Equation (1).

$$T= T_g + T_y + T_r \quad (1)$$

Table 2: Notation adopted in the research

Traffic light cycle	T
Yellow light duration	T_y
Red light duration	T_r
Total road length	L
The length of a part of road	l_i
Normal queue length threshold	Th_N
Moderate queue length threshold	Th_M

In the method presented here, in order to fine-tune road traffic information as far as possible, each monitored section of the road with length L is divided into sub-sections, each one to the length li, as presented in Fig. 4.

Each sub-section, li, is monitored by a node. The presence of vehicles is detected with a magnetic sensor that measures the deformation of the magnetic field of the earth due to the vehicle. The length of the queue is estimated by the number of sub-sections of the road in which the cars are detected to be present. So, the length of the queue is expressed in terms of the number of queued cars.

Suppose that Th_N and Th_M are called threshold values, in which the queue length is considered normal and average, respectively. For values higher than Th_M, long queues are considered. Table 3 shows the queue classification according to the number of vehicles.

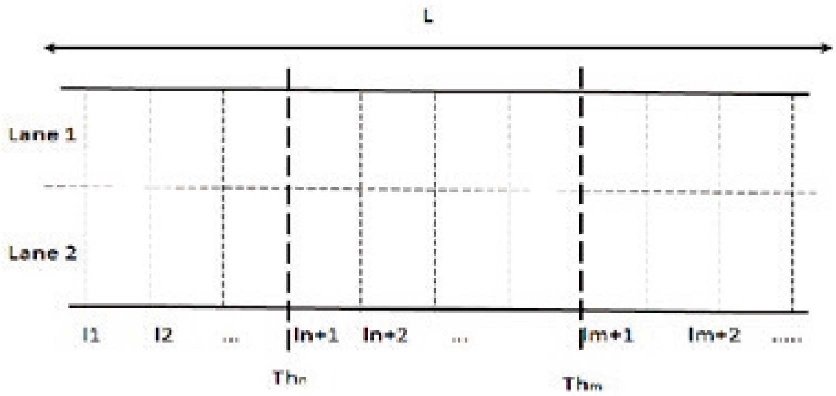

Fig. 4. A part of the monitored road

Table 3: Queue classification

The part of road	Interpretation
$l_i \leq Th_N$	Normal queue
$Th_N < l_i \leq Th_M$	Moderate queue
$l_i \geq Th_M$	Long queue

Fig. 5 displays a schema of the components of the proposed scheme in which a fuzzy logic controller is predicted for both input queues. However, the use of four parallel controllers instead of a single controller improves not only the fault tolerance and performance, but also the flexibility. The crossroads in question is assigned with eight input phases numbered from one to eight. Each controller manages its own two input phases in that the phase with higher traffic density is selected by data assignment module in each cycle based on the traffic load of the lanes. Accordingly, four dynamic phases out of the eight input phases are announced to the controller in order to be converted to the output phase, and the controller processes the two input variables to determine the green light duration ($i = 1,2$; $j = 1,2$; $i \neq j$) which conforms to the queue length pertaining to two controlled lanes.

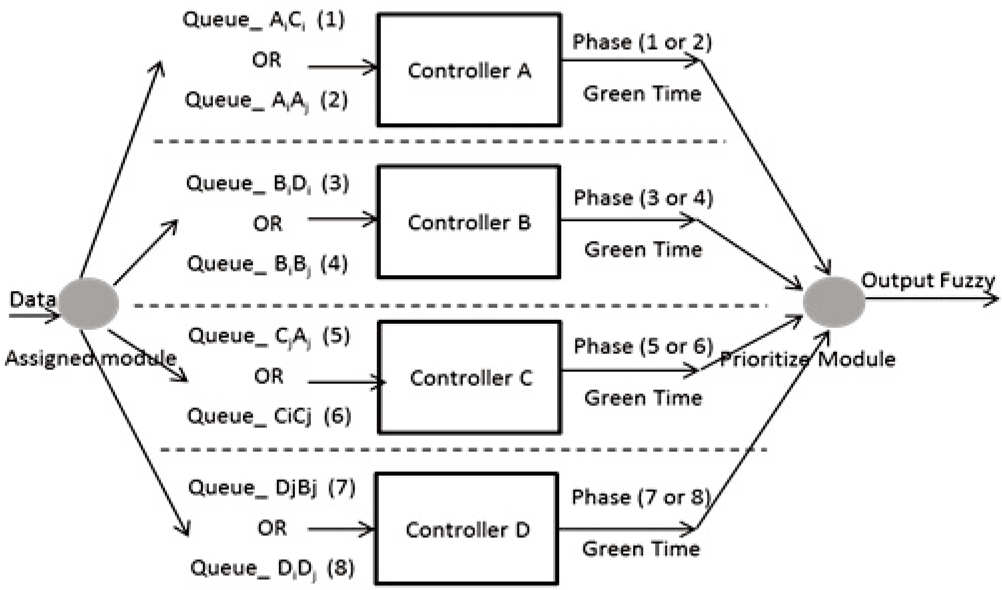

Fig. 5. A schema of the components of the recommended scheme

The fuzzy controller operates in three stages. In the first stage, called fuzzification, the input variables of the two queue length values are converted from their analog value to a definite value, which is determined by a particular degree of membership, from 0% up to 100%, in three membership functions (low, medium, high) (see Table 3). We address an isolated intersection in a city of medium size in our scenario.

The second stage is characterized by a fuzzy inference mechanism through which fuzzy data are is related to each other according to a linguistic approach based on the IF-THEN structure. If both lanes of a certain phase are congested, i.e. the length of their queues is long, then this phase needs the maximum green light duration to reduce the queue. In contrast, if at least one of the two lines is characterized by a normal queue length, it is not necessary to allocate the maximum green light duration to that phase. Table 4 summarizes the fuzzy inference rules used in this research. The last step is shown by non-fuzzification, which provides a definite output value from a space of the fuzzy solutions. This value represents the green light duration for the ith phase of the traffic light. Non-fuzzification is performed using the center of gravity method as expressed by Equation 2, in which O_i is the output of the ith base law and C_i is the center of the output membership function. In our approach, the yellow light duration is considered constant. For simplicity, assuming that the phase sequence is calculated in the order of {phase 1, phase 4, phase 5, and phase 8}, when whole sequence is completed in a cycle, the system will arrange the implementation of the new phase based on whole new priority calculated for each phase and will continue as described above.

Table 4: Fuzzy inference rules

Rule	Road (W), lane length (X)	Road (Y), lane length (Z)	Green light duration of ith phase
1	Normal	Normal	Minimum
2	Normal	Moderate	Minimum
3	Normal	Long	Moderate
4	Moderate	Normal	Minimum
5	Moderate	Moderate	Moderate
6	Moderate	Long	Maximum
7	Long	Normal	Moderate
8	Long	Moderate	Maximum
9	Long	Long	Maximum

$$\text{Green Light Duration}_{ith} = \frac{\sum_{i-1}^{n} O_i * C_i}{\sum_{i-1}^{n} O_i} \tag{2}$$

After expressing the basic structure of the fuzzy controller, a fuzzy system designed with two input and output time queues is depicted in Fig. 6. The system can be changed and even updated with new systems. Fig. 7 shows the input membership function of the fuzzy system. The main environment of the fuzzy system is two inputs and one output. In this research, in each run cycle, the number of the cars behind the red light is received, and the duration of stopping behind the red light is determined in output. Fig. 8 displays the output membership function to determine the green light duration, and Fig. 9 depicts an example of the rules designed for the fuzzy system.

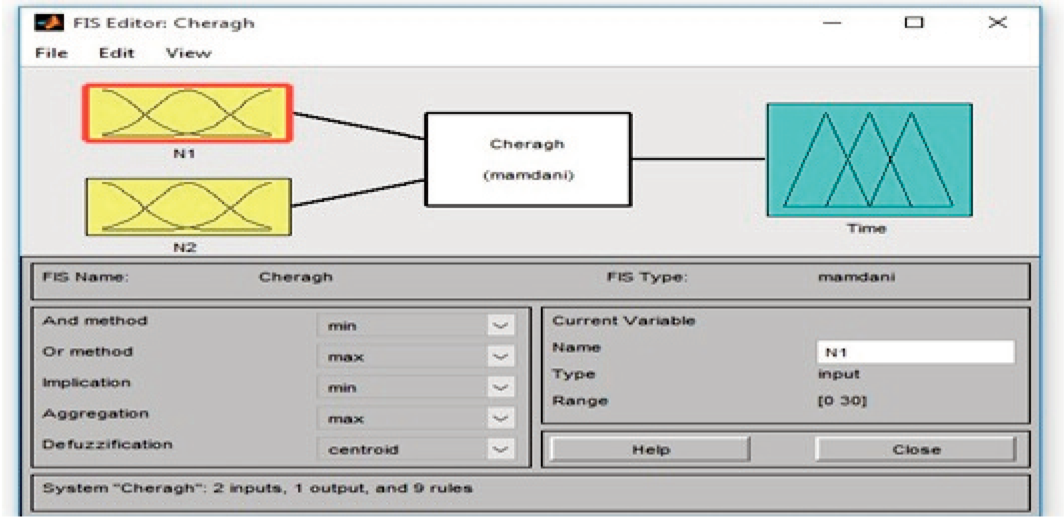

Fig. 6. Fuzzy system designed with two inputs (queues) and time output

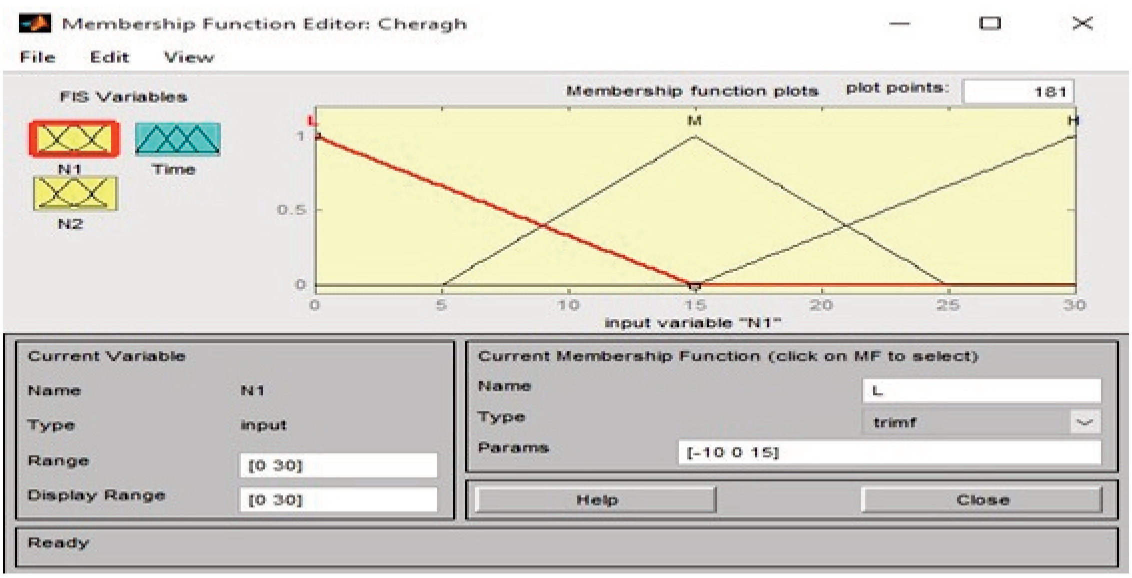

Fig. 7. Fuzzy functions designed for input

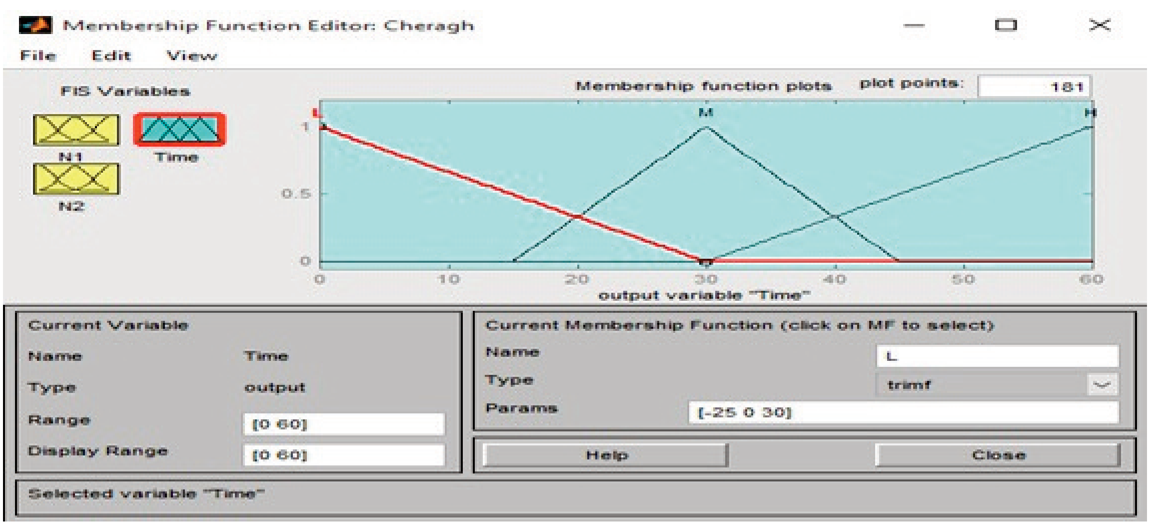

Fig. 8. Fuzzy functions designed for output

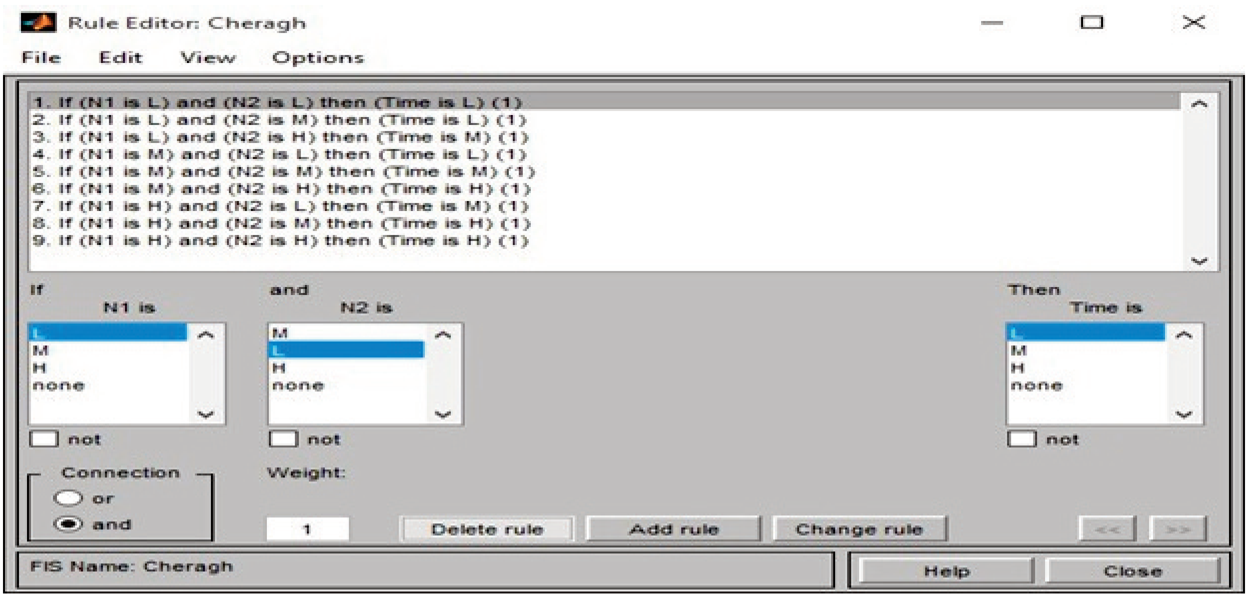

Fig. 9. A sample of rules designed by fuzzy system

The output of an example fuzzy system test is illustrated in Fig. 10. As is evident in this window, if there are 15 cars, then 30 time units will be considered for each phase. By changing the leverage of the car number, one can see that the fuzzy system gives the stopping duration of static cars.

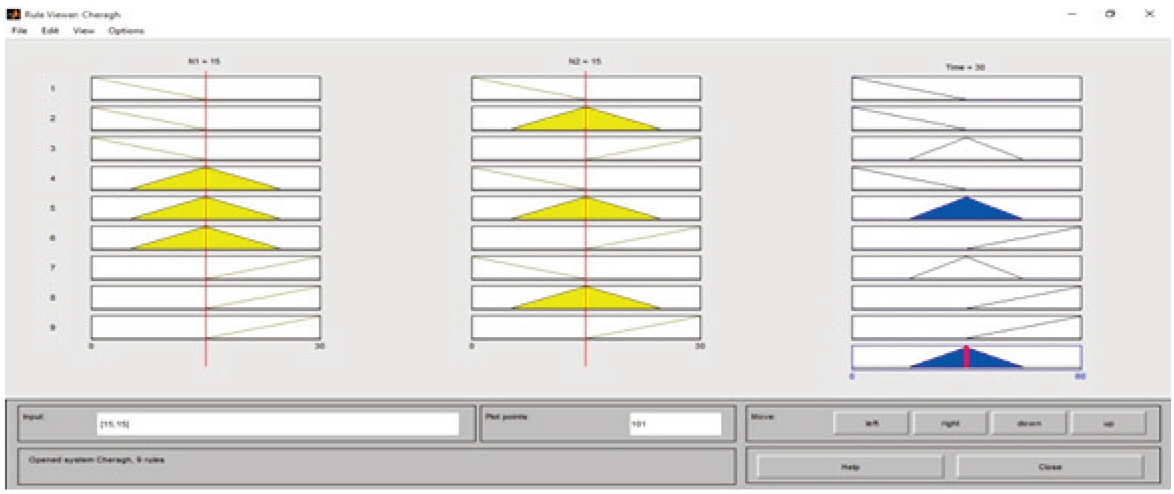

Fig. 10. A sample of fuzzy system test

PERFORMANCE ASSESSMENT

For assessment, the proposed system was simulated with traditional two-phase systems and four-phase systems presented in terms of the traffic characteristics and the input rate of random data at an isolated intersection with smart fuzzy method in MATLAT Software Package (Matlab, 2013). As shown in Table 5, initially a fixed time is considered for each cycle in all these models in the first step, and then, it is continuously changed. It is assumed that a number of cars with the same and constant initial conditions, which are inclined to randomly move in random directions, enter the crossroads and then continue to different paths.

Table 5: The values of the tested scenarios

System	Two-phase	Four-phase	Eight-phase	Emergency eight-phase
Number of vehicles	100	100	100	100
Number of emergency vehicles	0	0	0	5
Initial time (time unit)	20	20	20	20
Run duration (time unit)	400	359	389	389
Efficiency	-0.088	+0.016	+0.053	+0.023

Then, the indices of the measurement of intersection traffic density index and their efficiencies are evaluated by Equations 3 and 4, respectively, in which S represents the number of stationary cars, P represents the number of passing cars, and T represents the run duration.

$$\text{Density} = \frac{S}{P} \quad (3)$$

$$\text{Performance} = \frac{(P-S)/(S+P)}{T} \quad (4)$$

The results of the assessment of intersection traffic density with the parameters of the number of passing cars (P), static cars (S) and run duration (T) are displayed in Diagrams 1-4 for two-phase, four-phase, eight-phase and emergency eight-phase systems, respectively. According to Diagram 1, in the traditional and classical method adopted by the fixed-cycle approach, the queue of the static cars is longer, so its performance is very low. In Diagram 2, the four-phase system proposed by Mario et al. (2015) initially shows an optimum performance under normal traffic conditions, but its performance is unbalanced under heavy and abnormal traffic conditions. Consequently, the length of the queuing cars increases in which case its performance is reduced further. The method depicted in Diagram 3 consistently reduces the length of static cars queue under different conditions and traffic congestions, and gives better results with significant difference to the fixed-time cycle approach and the method proposed by Mario et al. (2015). Here, since green lights are scheduled dynamically and the phases are optimized in terms of actual traffic conditions, the length of the cars queuing behind the red light is significantly shortened, reducing the delay in intersection traffic. Diagram 4 shows the proposed eight-phase emergency system. In this system, the queue length of the static vehicles is initially reduced under normal traffic conditions, but as the situation is changed and the emergency vehicles arrive, the queue length of the static cars is slightly increased as compared to the eight-phase system. However, the system exhibits a better performance and reduces the intersection traffic as compared to conventional two-phase systems and four-phase systems proposed by different researchers. This means that the proposed method improves the intersection traffic control function.

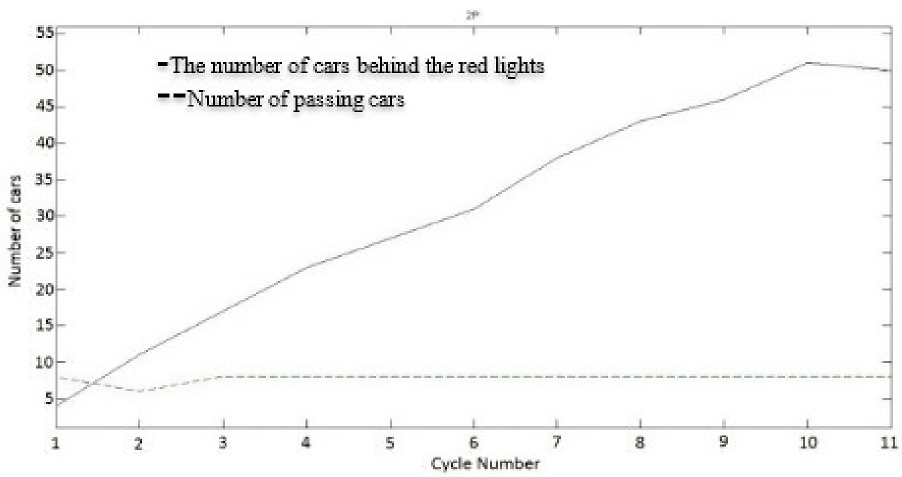

Diagram 1: Conventional two-phase system

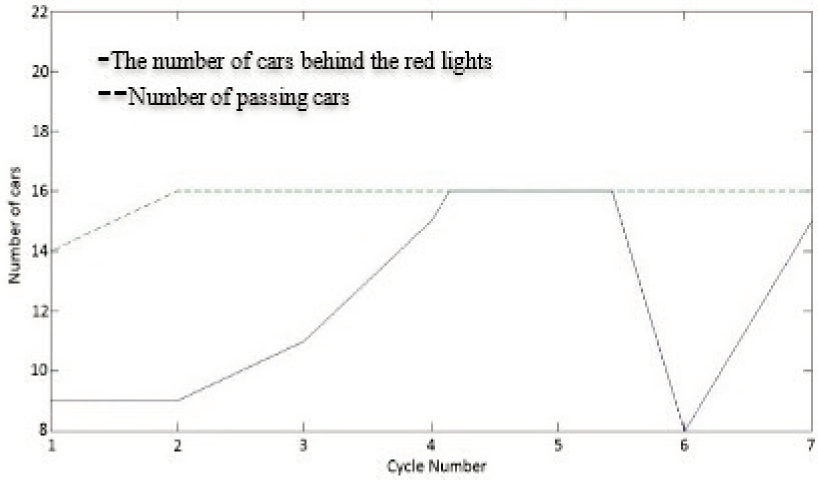

Diagram 2: Four-phase system

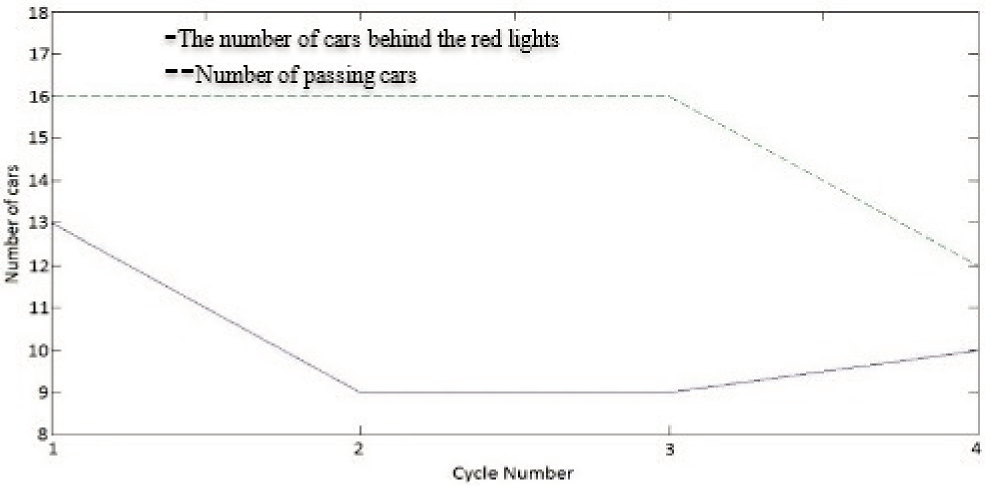

Diagram 3: The suggested eight-phase system

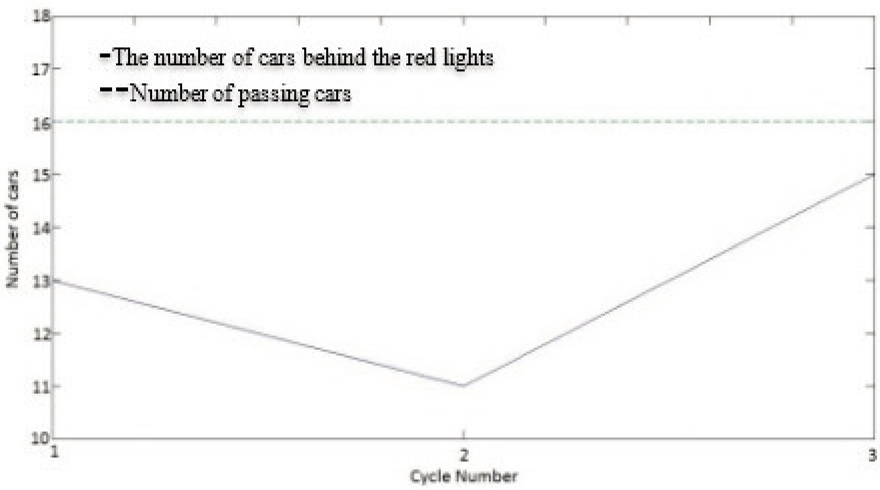

Diagram 4: The suggested emergency eight-phase system

In another part, the efficiency of the systems is examined using Equation 4 to make the assessments more precise. As shown in Diagram 5, the conventional two-phase system with the fixed-time cycle has the worst efficiency, the four-phase system proposed by researchers has acceptable efficiency, the suggested emergency eight-phase system has average efficiency, and the suggested eight-phase system has an excellent efficiency. Thus, we conclude that the proposed eight-phase system reduces the waiting time of cars in the intersection queue and traffic congestion under normal and emergency traffic situation. Dynamic scheduling and optimal phases adopted by the eight-phase system as compared to other systems allows more vehicles to pass and reduces the traffic density of the intersection.

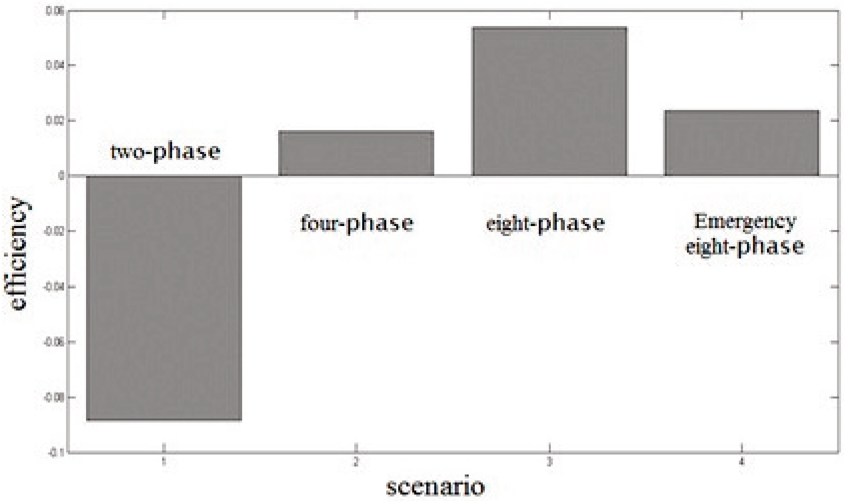

Diagram 5: The comparison of the efficiency of the systems

CONCLUSION AND RECOMMENDATION FOR FUTURE WORKS

The intersections are the most important traffic jams in cities, so that the solution of traffic jams with an expert systems approach is a key step in organizing traffic in the city-level road network. Assigning green light to roads based on the traffic density at any moment and coordinating the urban transport network is possible only by dynamic, smart central control systems of the traffic lights in intersections.

This paper introduced a dynamic, smart eight-phase traffic light control system using fuzzy controllers for normal and emergency situations in order to reduce vehicle waiting time at intersection queues and traffic congestion. To evaluate the performance of the system, it was simulated with the conventional two-phase system and the four-phase system proposed by Mario et al. (2015) using MATLAB Software Package (Matlab, 2013) and according to the traffic property and input rate of random data and the creation of the same initial conditions in an isolated intersection.

The results of the study and the diagrams derived from efficiency index and traffic density of the intersection revealed that the conventional two-phase system with constant scheduling has low efficiency and aggravates the traffic of the intersection. Mario et al. (2015)'s four-phase system with four output phases in which fuzzy system is used exhibited a fairly acceptable efficiency. This system is unbalanced, so that it reduces the traffic in normal traffic conditions, but when traffic congestion occurs, not only does it do nothing to control the traffic, but it also aggravates the traffic of the intersection. The proposed eight-phase system shows significantly higher efficiency than the traditional two-phase system and four-phase system suggested by other research, thanks to its dynamic scheduling and optimization of the green light durations, as well as the management of the sequence of phases at the intersection in which more cars pass through each cycle. This system reduces the traffic of the intersection under normal traffic conditions and traffic congestions. In emergency situation, the eight-phase system prioritizes emergency vehicles by a slight change in the normal eight-phase system which has lower performance but still better than the conventional two-phase systems and four-phase systems. As a result, the proposed system is expected to be effective in improving traffic control systems of an intersection in normal and emergency conditions.

Future research can work on integrating the proposed system with neural networks that can predict traffic conditions and improve the efficiency of the systems. Also, temperature and humidity sensors can be used to estimate snow and ice on roads and inform drivers. As another approach, fuzzy systems and wireless sensor networks can be used to integrate traffic lights with vehicle-to-vehicle (v2v) or vehicle-to-infrastructure (v2i) communications in advanced transportation systems of the smart city. Another possible field of study is the connection of all crossings on one or more streets and their connection to each other to create an integrated automatic fuzzy control system in the city.

REFERENCE

Kelsey, R L., & Bisset, K R. (1993). Simulation of traffic flow and control using fuzzy and ¬ conventional methods. Fuzzy Logic and Control: Software and Hardware Applications, Prentice-Hall, M. Jamshidi (Ed.), Englewood Cliffs, NJ, p. 262– 278.

Kulkarni, G., & Waingankar, P. (2007). Fuzzy logic based traffic light controller. In Industrial and information systems. ICIIS 2007. International conference on (pp. 107–10).

Mario, Collotta, & Lucia, Lo Bello, & Giovanni, Pau (2015). A novel approach for dynamic traffic lights management based on Wireless Sensor Networks and multiple fuzzy logic controllers Elsevier Ltd. All rights reserved.

Murat, Y. S., & Gedizlioglu, E. (2005). A fuzzy logic multi-phased signal control model for isolated junctions. Transportation Research Part C: Emerging Technologies, 13, 19–36.

Niittymaki, J., & Pursula, M. (2000). Signal control using fuzzy logic. Fuzzy Sets and Systems, 116(1), 11–22.

Pappis, C., & Mamdani, E. H. (1977). A fuzzy logic controller for a trafc junction. IEEE Transactions on Systems, Man and Cybernetics, 7, 707–717. http://dx.doi.org/10.1109/TSMC.1977.4309605.

Shahraki, A., Shahraki, M., & Mosavi, M. (2013). Design and simulation of a fuzzy controller for a busy intersection. In Computer applications technology (ICCAT), 2013 international conference on,1–6.

Trabia, M. B., Kaseko, M. S., & Ande, M. (1999). A two-stage fuzzy logic ontroller for traffic signals. Transportation Research Part C: Emerging Technologies, 7, 353–367. URL: www.sciencedirect.com.

Wilamowski, B. (2012). Suitability of fuzzy systems and neural networks for industrial applications. In Optimization of electrical and electronic equipment (OPTIM), 13th international conference on,1–7.

Zaied, A. N. H., & Othman, W. A. (2011). Development of a fuzzy logic traffic system for isolated signalized intersections in the state of kuwait. Expert Systems with Applications, 38, 9434– 9441. www.sciencedirect.com

Zou, F., Yang, B., & Cao, Y. (2009). Traffic light control for a single intersection based on wireless sensor network. In Electronic measurement instruments, 2009. ICEMI'09. 9th international conference on, 1-1040–1-1044.