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Fuzzy logic based smart traffic light simulator design and hardware implementation

Cihan Karakuzu [a,*], Osman Demirci [b]

[a] Kocaeli University, Engineering Faculty, Electronics & Tell. Eng. Department, 41070 Veziroglu Yerleskesi, Izmit-Kocaeli, Turkey
[b] Turkish General Directorate of Highways, Directorate of the 1th Region, 14th Branch Chieftaincy, Izmit-Kocaeli, Turkey

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ABSTRACT

The objective of this study is to develop fuzzy logic based traffic junction light simulator system for design and smart traffic junction light controller purposes and also to observe its performance. Traffic junction simulator hardware is developed to overcome difficulties of working in a real environment and to easily test the performance of the controller. By using the traffic light simulator developed in this study, results of constant duration (conventional) traffic light controller and fuzzy logic based traffic light controller are compared where the vehicle inputs are supplied by the simulator. Statistical experimental results obtained from the implemented simulator show that the fuzzy logic traffic light controller dramatically reduced the waiting time at red lights since the controller adapts itself according to traffic density. It is obvious that the intelligent light controller is going to provide important advantages in terms of economics and environment.

1. Introduction

Most of the traffic junction signal controllers are fixed-cycle type (conventional), i.e., constant green/red phase for each traffic signal cycle. Although this operation style is simple, its performance is generally poor for heavy traffic. One reasonable alternative is to design an intelligent controller instead of a fixed-cycle traffic light control system. Since they have many advantages, smart traffic lights cannot be ignored especially in metropolitan areas. After Zadeh defined the fuzzy sets theory in 1965, this technique has been widely used in engineering applications. Some studies applying fuzzy set theory to traffic signal control have been done [1–6]. The most popular of these was put forth by Pappis and Mamdani [1]. They built a good model for a two way traffic junction where each way has a single lane of traffic flow [1]. Following this Nakatsuyama realized the fuzzy logic based traffic light control of cascaded two way traffic junctions in 1984 [2]. In 1993 Favilla et al. introduced traffic light controller for a traffic junction with multiple lanes [4]. Recently, Trabia et al. [6] simulated a single junction with four lanes which also took the left-turning traffic flow into account. Current studies [7–14] have considered traffic signal control from the standpoint of different aspects. The objective of these studies is obtaining optimal traffic flow to reach minimal waiting time. These studies are based on software simulation model. The most important aspects of these studies can be summarized as below.

In Ref. [7], Ella Bingham used the same intersection configuration as in the Pappis and Mamdani simulation [1]. In her study, the parameters of a Mamdani type fuzzy traffic signal controller were determined by reinforcement learning algorithm based on simulation environment. The objective was to minimize vehicular delay. She reported that the proposed fuzzy controller exhibited successful performance at constant traffic volumes. Chou and Teng [8] extended the traffic signal controller to solve problems of consecutive junctions and lanes. Their controller could deal with queue lengths of up to 700 m or longer. They set up detectors at certain distances to obtain traffic data. In order to simulate flow rate of vehicles, they used a parabolic equation due to its simplicity. They constructed a simulative environment to model a case in the real world. They considered two scenarios for a traffic junction: single traffic junction with multiple lanes and a main line multiple traffic junction with multiple lanes. Their controller uses maximum queue length for the related direction/lane as inputs of the fuzzy controller for both cases. They assumed the lengths of vehicles to be different than [1,2,4]. Niittmaki and Turunen achieved better results when applying Lucasiewicz's many-valued control instead of using artificial defuzzyfication [9]. Murat and Gedizlioglu [10] presented Mamdani structured fuzzy signal control model comprised of a fuzzy phase green duration model

* Corresponding author.
E-mail addresses: cihankk@kocaeli.edu.tr (C. Karakuzu), osdemirci1971@yahoo.com (O. Demirci).

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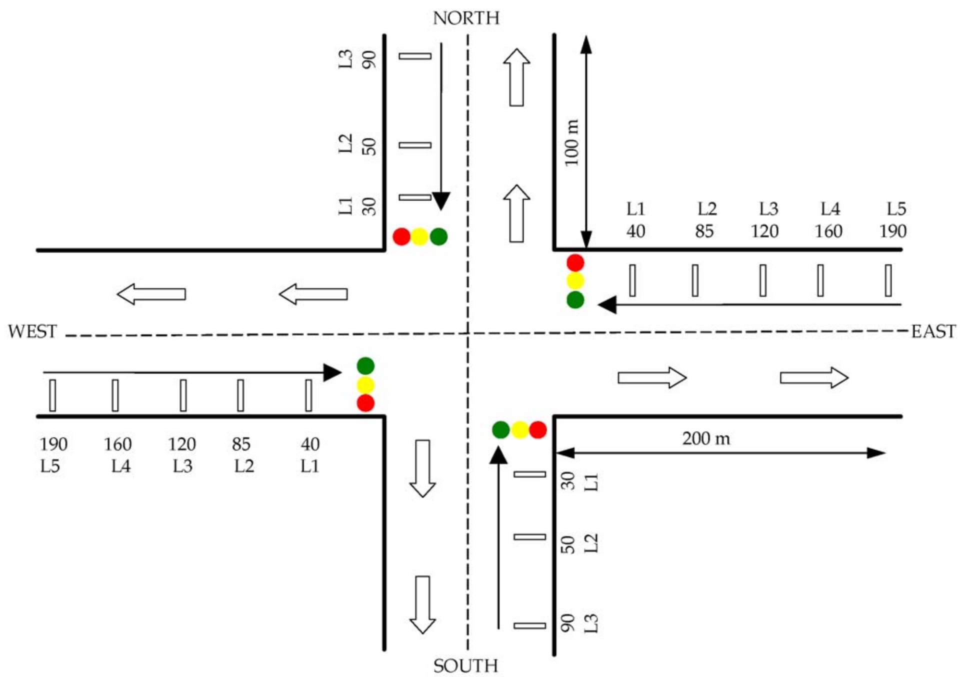

Fig. 1. Traffic junction with four directions and single lanes.

and fuzzy phase sequence model. They compared their models using simulations for an isolated four-armed intersection. They used triangular memberships function for inputs and output in Refs. [7–10]. Fan and Liu [11] presented a fifth layered neuro-fuzzy phase sequence-changeable controller for a single intersection. They used back-propagation to train the controller with pre-determined training samples. They concluded that their control method could significantly reduce the average delay of vehicles based on simulation results they obtained. Chong et al. investigated performances of four different neuro-fuzzy architectures for traffic lights control at an isolated four-arm simple traffic intersection based on Green Light District (GLD) traffic light simulation software in Ref. [12]. Training of the neuro-fuzzy networks was done with data sets collected from the traffic simulator controlled by a human operator. They reported that all architectures performed very well. Schmöcker et al. gave particular attention to pedestrian delays at a four directional traffic junction in Ref. [13]. They presented multi-objective signal control using fuzzy logic. The memberships of the fuzzy logic were optimized by GA coupled to the VISSM microscopic traffic simulator with a case study intersection in London in which pedestrians as well as vehicle flows are high. Dimitriou et al. [14] developed a fuzzy Mamdani model estimating traffic flows at a point from previous traffic flow measurements at this and other points using GA for offline tuning of fuzzy model parameters. This model was developed for prediction of traffic flow rate within 3 min time intervals.

As can be seen from the studies depicted in the previous paragraph traffic lights control has been developed by software simulation models. In this paper traffic simulator system and the fuzzy controller for traffic lights are implemented based on hardware for a four directional junction. From this point of view, this study differs from those depicted above and makes a contribution to the literature. In this study, a four directional single traffic junction is used as shown in Fig. 1. The implemented traffic simulator system is embedded in the microcontroller hardware. Key points that should be considered for the control of the traffic junction traffic lights are as follows. The average speed of vehicles moving from west to east at green light is 12 m/s. The time needed to reach the lights on the 200 m length lane where the detectors are placed is calculated using Eq. (1), assuming that there is no vehicle in queue.

$$v = \frac{200\,\text{m}}{12\,\text{m/s}} = 16.66\,\text{s} \tag{1}$$

Using a similar approximation, the vehicle moving from north to south lane with 100 m length, at an average speed of 12 m/s will need 8.33 s. The length of traffic junction is an important parameter in determining the lower limit of the green light duration for the traffic light controller considered in the above calculation. The green and red light durations should be changed with respect to the number of vehicles in the queue at each cycle in order to keep the number of the vehicles in the queue at a minimum. For example, a 20–120 s phase duration limit may be selected for green light. Then the duration of green light can be increased step by step up to a maximum level starting from the minimum considering the length of queue at the beginning of each phase. When there is no vehicle in the queue the phase cycle should immediately be terminated to let the vehicles pass through in the other direction. Amount of the increment is determined at the end of each phase cycle that can be adjusted depending on the length of queue. However, the total phase duration with the extra increments cannot exceed the maximum level.

In conventional traffic lights, length of vehicles was not taken into account for the duration of lights. However the real length of vehicles such as 4, 4.2, 4.6 and 8 m has been used for simulation in a recent study in Ref. [8]. In recent studies, sensors are used to determine the number of vehicles at each lane and the length of vehicles approximately in order to calculate proper durations and phase cycles of the lights. In this paper, Fuzzy Logic Controlled Smart Traffic Lights simulator application, the block structure of which is given in Fig. 2 is presented. This system considers the real length of vehicles and uses loop detector to determine the number of vehicles at each lane. The objective of this study is to control traffic flow adaptively and to minimize the waiting time at traffic junctions. Since this study is a hardware implementation, it should have been done in a real traffic environment. However, it was

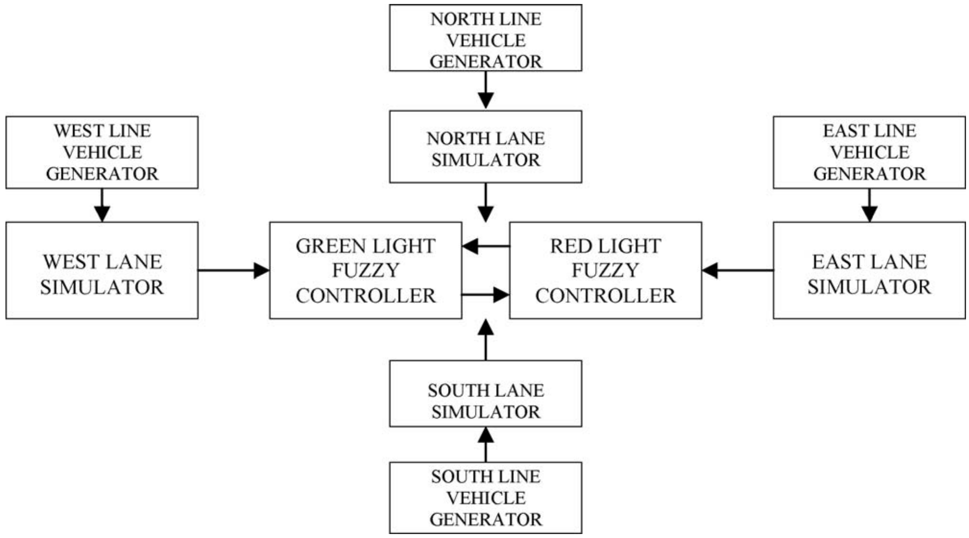

Fig. 2. Block structure of the implemented traffic junction light control system.

decided to work in a hardware simulation environment, since working in real traffic contains high risks and has many difficulties such as the need for online observation and measurement diversity for exact conclusions.

2. Traffic junction hardware simulator design

In order to design the fuzzy logic based smart traffic light simulator that can simulate any traffic junction, conditions of the real environment and simulation should be identical for the best approximation of real traffic. Real environmental data can be acquired by placing detectors on traffic junction lanes at proper intervals and signals from the detectors are recorded for long periods of time to reach a better approximation. If information collection system is impossible to set up for the traffic junction under consideration, a realistic traffic model should be obtained from traffic flow observations. There are two alternatives for this solution; using traffic flow simulation software or hardware simulators for generating traffic data. The second one is chosen for this study. The most common traffic junction is the four directional one that can be seen in Fig. 1. One of the directions is considered as the main artery which has heavier traffic load than the other directions. In our simulator system east–west direction is selected as the main artery. North–south direction is the secondary artery which has a slightly lighter traffic flow.

In our hardware simulator, two microcontrollers are used for each of the four directional traffic flows. One of them is used to generate vehicles with pre-described properties and the other is used to simulate vehicles for purposes of either moving ahead or waiting on the lane. Additional two microcontrollers are used for fuzzy logic/conventional control of red and green traffic lights. In our implementation, a total of ten microcontrollers are used for the purposes described above. The hardware implemented fuzzy logic controller has four input variables as the queue lengths of each direction Nq, Sq, Wq and Eq. The output of the fuzzy logic controller is the duration of red/green lights (t_r, t_y). Separate fuzzy logic controllers are used for red and green lights. The outputs of the controller are determined in a fuzzy sense by using the input variables.

Fuzzy logic controller design process is started with the determination of fuzzy sets for input variables that are queue lengths in conjunction. Traffic junction queue lengths have limited values such as 200 m. It is difficult to precisely determine the length of the queue in real applications since the number of detectors that can be placed at each lane is limited. Detectors can be placed in 20 or 50 m intervals at each lane depending on the requirements of the application. In this work detectors of the hardware simulator are placed at the 40th, 85th, 120th, 160th and 190th m in east and west direction lanes which have a length of 200 m according to the software of the related lane vehicle simulators. In the same way, detectors are placed at the 30th, 50th and 90th m of the north and south direction lane. In this system, the lengths of the queues are determined via the software using these detectors. The locations of detectors are shown in detail in Fig. 1. The circuit, the schematic of which is given in Fig. 3, is the common hardware for generating and simulating vehicles on the lane in each direction. In this vehicle simulator circuit, the microcontroller on the left is used for generation of vehicles, time and type of vehicle such as car, minibus, bus or lorry which have lengths 5, 7, 9 and 13 m respectively. The lengths include the gaps between the vehicles.

The vehicle generator generates vehicles according to a plan described below. If the queue is not completely full, the microcontroller on the right side produces a trigger signal to the micro controller on the left side informing that it can generate a vehicle. If the micro controller on the left side generates a vehicle, then the microcontroller on the right side releases the vehicle to the lane. This process goes on continuously in a similar manner. The vehicle generation program sends vehicles one by one into the lane according to a pre-described plan. The types of vehicles and time intervals between them have been designed in three different types depending on the time of day and have been adapted to the statistical properties of the period of day. Three different traffic densities are evaluated in this study: morning, noon and evening. Vehicle patterns in each direction of traffic flow are generated independently. For instance, vehicle generation pattern in the west direction in the morning is completely different than that of the north direction in the evening. In Table 1, sample vehicle generation pattern in the east direction for evening traffic flow is shown.

Vehicle generation program continuously generates 30 vehicles according to a predetermined order for each generation cycle. The vehicle generation sequence is the same for conventional and fuzzy logic based traffic light controller. That is, sequences of the vehicle are exactly the same for both types of controllers in order to be able to compare the results. In this way the results of control techniques can be compared with each other. Related works in the literature have been investigated and it was observed that the vehicles

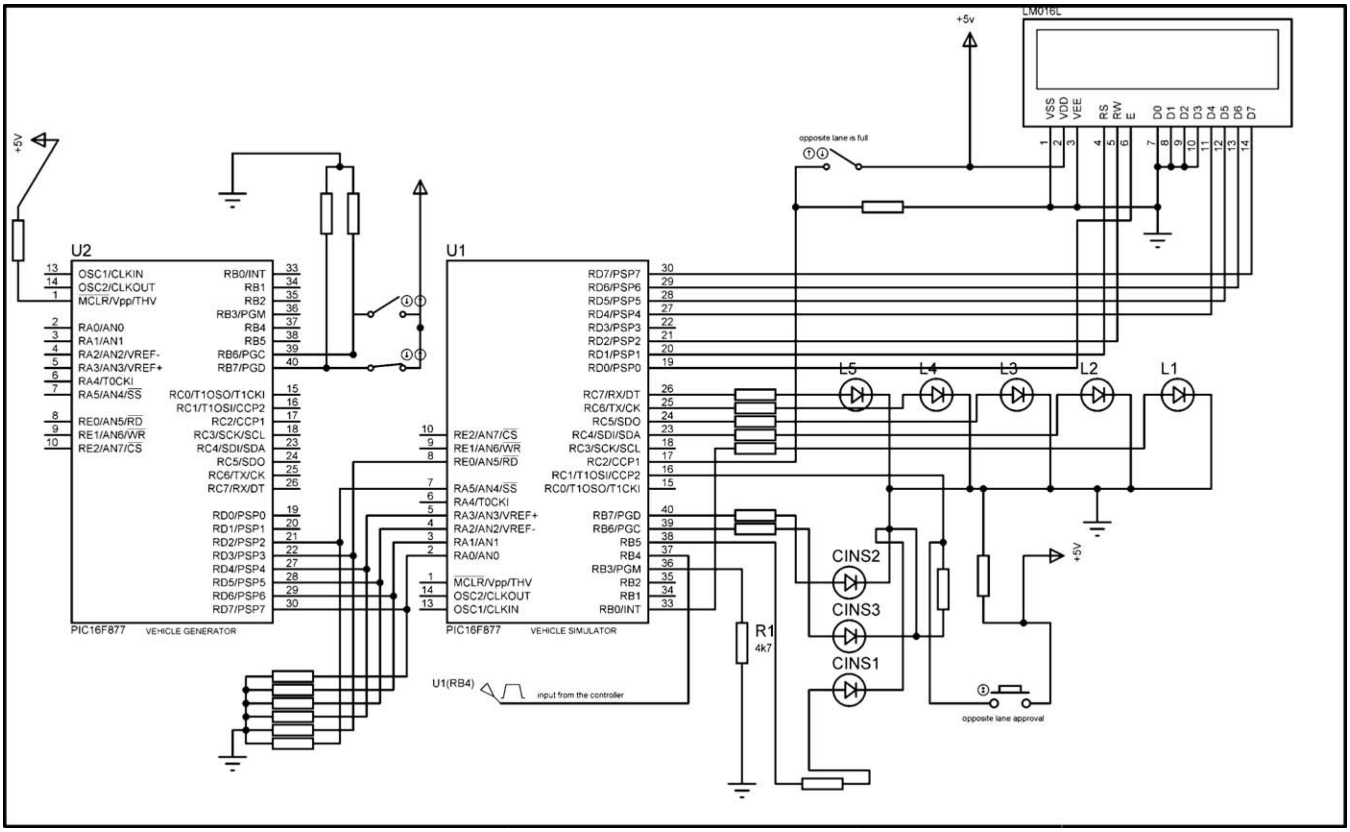

Fig. 3. Vehicle simulator hardware schematic for each direction.

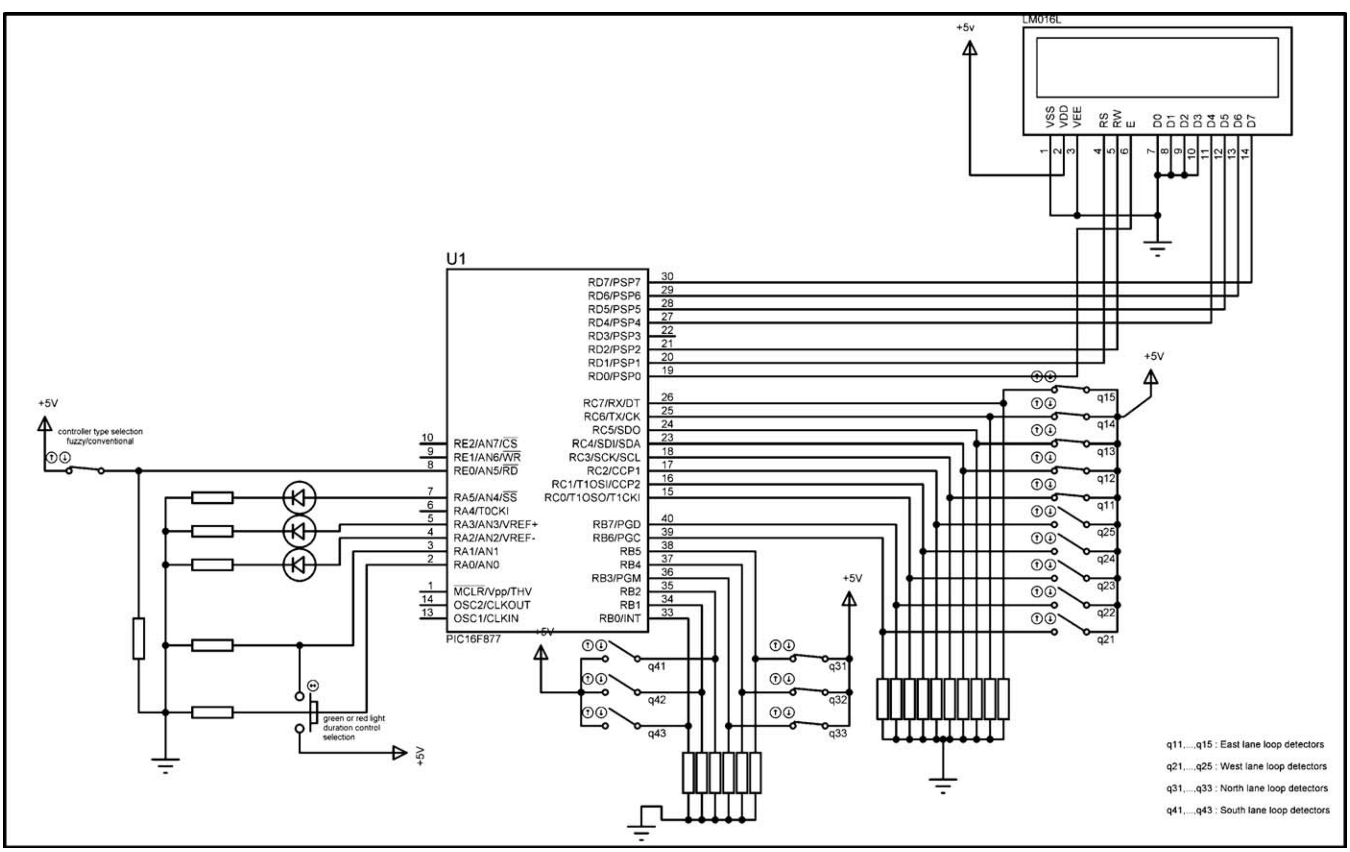

Fig. 4. Traffic lights duration controller circuit diagram.

Table 1
A sample vehicle generation pattern.

```
void evening(void) {
    bus();
    delay_ms(2250);
   bus();
    delay_ms(2750);
    minibus();
    delay_ms(1850);
    taxi();
    delay_ms(15 00);
    minibus();
    delay_ms(1850);
    minibus();
    delay_ms(1650);
    bus();
    delay_ms(2250);
    bus()    ;
    delay_ms(2250);
    taxi();
    delay_ms(1500);
    taxsi();
    delay_ms(1500);
   lorry();
    delay_ms(3100);
                          }
```

entering the traffic junction are not completely the same because the traffic flow changes cycle by cycle, thus making the results incomparable. In the comparison process for real traffic flows, vehicle models do not match even if the traffic is observed at the same time of day, since the vehicles are neither in the same order nor of the same type. Furthermore, some performance criteria may not be obtained exactly since waiting times of vehicles at red light cannot be precisely measured. In this study, the disadvantages of previous works mentioned above are eliminated by software for vehicle generation on the hardware, thus conventional and fuzzy logic based traffic light controllers are evaluated under the exact same conditions.

The microcontroller on the right hand side in Fig. 3 places the vehicles produced by the vehicle generator to the lane and moves them ahead to the queue depending on the queue status. Furthermore, it controls the speed of vehicles in the queue. If the green light is on, the vehicle in front of the queue goes across the traffic junction. If not, the vehicle waits and queue formation starts. If there is a vehicle in front of it, it enters the queue and waits until the vehicle in front moves. Vehicles in the queue start to move when the light turns green and when a vehicle goes across the traffic junction, the vehicle counter is increased by one. If there is no queue in front of the vehicle, its speed is selected to be 12 m/s as a nominal speed value for inner city traffic flow. An integer value is selected for ease of calculation purposes. The vehicle speed in the queue is selected as 8 m/s when the vehicles are moving. If there is no queue, a vehicle passes through the 200 m lane in 16 s and 100 m lane in 8 s. If there is a queue or the light is red, the vehicles in the queue start to slow down and wait until the light turns green, this means they wait more than the nominal duration of the lane. For instance if a vehicle passes through the lane in 70 s, it means that it has waited for 54 s. Longer waiting times are not preferable. When the number of vehicles in the queue increases, the importance of waiting time becomes more important. The main goal of the traffic light controller is to minimize waiting time in the lane and maximize the number of vehicles passing through the traffic junction. The main performance measures are average waiting time per vehicle and the number of vehicles passing through the main artery line.

3. Fuzzy logic controller design

Fuzzy logic controller is designed to control red and green light durations for traffic lights in the system. The controller basically determines the durations of red and green light for the main artery using fuzzy logic. The red and green light durations for the secondary artery are the exact opposites of those for the main artery. If the green light duration is 50 s for main artery, then the red light duration is 50 s for the secondary artery and so on. A fuzzy logic controller with two inputs and two outputs is designed for the control of traffic lights. Two separate microcontrollers are used for the calculation of green and red light durations due to limited program memory of the available microcontroller. Fuzzy logic controller circuit diagram is shown in Fig. 4, where q1*i*, q2*i*, q3*j*, q4*j* correspond to loop detectors on east, west, north and south lanes respectively. In principle, the main artery green light duration controller is identical to that of the secondary artery. The inputs of the fuzzy logic controller are the queue lengths in east–west direction and north–south direction. In the traffic junction simulated in this study there are two queues for each direction opposite to each other and the longest one is selected as the input for fuzzy logic controller. These inputs are fuzzified via fuzzy sets characterized by three membership functions namely "SHORT/short", "MIDDLE/middle" and "LONG/long" as defined in Table 2. Among the many various types of membership functions, the one that can be best applied for solution with fuzzy mathematical programming is the linear one. In this context, detailed comparisons of important types of membership functions (MFs) used in the literature have been given as a table by Liang in Ref. [16]. He

Table 2
Membership function definitions for west–east (left side) and north–south (right side) directions.

W–E queue length (m)	W–E lane membership functions			N–S queue length (m)	N–S lane membership functions		
	SHORT	MIDDLE	LONG		short	middle	long
0	1.000	0	0	0	1.000	0	0
10	0.875	0	0	5	0.875	0	0
20	0.750	0	0	10	0.750	0	0
30	0.625	0.125	0	15	0.625	0.125	0
40	0.500	0.250	0	20	0.500	0.250	0
50	0.375	0.375	0	25	0.375	0.375	0
60	0.250	0.500	0	30	0.250	0.500	0
70	0.125	0.625	0	35	0.125	0.625	0
80	0	0.750	0	40	0	0.750	0
90	0	0.875	0	45	0	0.875	0
100	0	1.000	0	50	0	1.000	0
110	0	0.875	0	55	0	0.875	0
120	0	0.750	0	60	0	0.750	0
130	0	0.625	0.125	65	0	0.625	0.125
140	0	0.500	0.250	70	0	0.500	0.250
150	0	0.375	0.375	75	0	0.375	0.375
160	0	0.250	0.500	80	0	0.250	0.500
170	0	0.125	0.625	85	0	0.125	0.625
180	0	0	0.750	90	0	0	0.750
190	0	0	0.875	95	0	0	0.875
200	0	0	1.000	100	0	0	1.000

Table 3
The fuzzy rules table for green light extra duration.

Green light rules		Length of North-South Queue		
		short	middle	long
East-West Queue	SHORT	10	5	0
	MIDDLE	15	10	15
	LONG	20	20	20

Table 4
The fuzzy rules table for red light extra duration.

Red light rules		Length of North-South Queue		
		short	middle	long
East-West Queue	SHORT	0	15	20
	MIDDLE	0	10	15
	LONG	0	0	5

also emphasized that using linear or piecewise linear MFs give higher computational efficiency. For this reason, all input MFs are selected as triangular MFs considering their easy implementation on the microcontroller in this study. Parameters of the MFs have been determined by taking into consideration the location of loop detectors on the lanes. These MFs are mathematically defined in the software program (Microchip PIC C) used for programming the microcontroller.

The controller has two outputs as duration extension of red and green lights. The outputs of the controller are fuzzified via five singleton membership functions. The mapping between the input and output space of the fuzzy logic controller is realized by zero order Sugeno type inference system. The fuzzy inference is realized using the nine fuzzy rules as shown in Table 3 for the green light phase and Table 4 for the red light phase. The output is determined by means of weighted averages [15].

Initially, the red and green light durations are 20 s. The output levels of the fuzzy logic controller change between 0 and 20 s. The maximum extension determined by the rule base depending on queue length is 20 s. The fuzzy logic software of the simulator is triggered in the last 3 s of the current light cycle; if duration extension is required, the duration can be extended up to 5 times in a phase. Maximum duration for green light then can be calculated as in Eq. (2). In the case when the extension repeats for 5 times, the minimum duration of green light for the main artery is 35 s as can be seen from Eq. (3). The 3 s in Eq. (3) is the minimum value obtained from the output of the fuzzy controller. This value is selected in order to allow maximum vehicles to go across the traffic junction for the main artery. Maximum duration for red light then can be calculated as in Eq. (4). Minimum extension for red light can be calculated by using Eq. (5). Minimum value for red light duration is kept at 20 s in order to turn the light to red on the secondary artery as fast as possible when there is no queue in the north–south direction. Consequently if there is no vehicle in the north–south direction, the green light phase is ended and red light phase is started.

$$Tg_{\max} = 20 + 5.20 = 120 \tag{2}$$

$$Tg_{\min} = 20 + 5.3 = 35 \tag{3}$$

$$Tr_{\max} = 20 + 5.3 = 35 \tag{4}$$

$$Tr_{\min} = 20 + 0 = 20 \tag{5}$$

The main reason for the minimum red light duration of 20 s is to attain that the number of vehicles passing from main artery is at its maximum. The light at the east–west line is turned green and the light of the north–south line is turned red if there is any vehicle moving in the north–south direction. Microcontrollers used in the implemented simulator system have been programmed by using C Language with Microchip PIC C. The codes of the programs have not been given in the paper since they are too long.

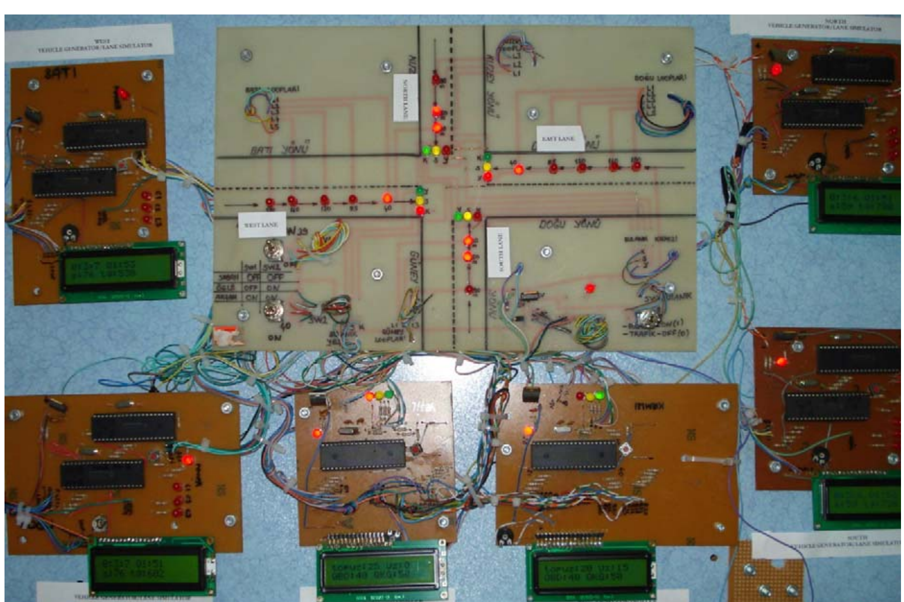

Fig. 5. A photo of the smart traffic simulator system while it is running.

Table 5
Switch positions to select three time intervals of a day.

	SW1	SW2
Morning	OFF(0)	OFF
Noon	OFF	ON
Evening	ON(1)	ON

4. Results and conclusions

In Fig. 5, the photo of the simulator system is shown while it is running. The simulator system is designed and implemented to select controller type (conventional or fuzzy) by a switch SW3. Hence it is possible to make comparisons. The system can select three kinds of time intervals of a day via SW1 and SW2 switches according to their position given in Table 5.

In the experimental studies performed on the implemented system based on hardware; the waiting time of vehicles, the number of vehicles that passed through in unit time, the response of the traffic light controller with respect to the length of queue have been investigated and the obtained results have been evaluated in detail. Performance of the fuzzy light controller has been statically compared with the conventional ones using vehicle data which is constituted by the software located in the hardware. In these tests, three kinds of time intervals of a day with different vehicle densities have been considered as described above. The results of the tests are listed in Table 6 according to controller type and time interval of a day with different vehicle density. The table includes comparative results for an hour. It can be seen from these

Table 6
The comparative statistical results between smart fuzzy logic and conventional traffic conjunction lights controller for an hour.

Light control type and time of day	Direction	The number of Passing Vehicles	Total waiting time on the lane (s)	Difference in the number of passing vehicles	% Superiority of the smart light controller for passing vehicle	Difference in the waiting time	% Superiority of the smart light controller for waiting time
Smart Fuzzy Logic/ Morning	West	2367	15762	410	20,95%	9714	38,13%
	East	1723	5701	20	1,17%	11229	66,33%
	North	690	17417	-4	-0,58%	-2795	-19,12%
	South	689	17636	-4	-0,58%	-2695	-18,04%
Conventional / Morning	West	1957	25476	Comparisons for the morning traffic			
	East	1703	16930				
	North	694	14622				
	South	693	14941				
Smart Fuzzy Logic/ Noon	West	1709	9752	12	0,71%	7092	42,10%
	East	1717	10714	47	2,81%	6429	37,50%
	North	1218	17112	363	42,46%	4315	20,14%
	South	1217	15566	398	48,60%	5177	24,96%
Conventional / Noon	West	1697	16844	Comparisons for the noon traffic			
	East	1670	17143				
	North	855	21427				
	South	819	20743				
Smart Fuzzy Logic/ Evening	West	1704	8990	15	0,89%	7848	46,61%
	East	1711	9620	40	2,39%	7522	43,88%
	North	1188	18242	334	39,11%	3129	14,64%
	South	1187	16928	369	45,11%	3942	18,89%
Conventional / Evening	West	1689	16838	Comparisons for the evening traffic			
	East	1671	17142				
	North	854	21371				
	South	818	20870				

results that conventional traffic signalization in the mornings have 19% superiority for only the total waiting time, but for the other time intervals and categories, its performance is worse when compared to fuzzy traffic signalization. In some cases, traffic signalization with fuzzy controller has 48% superiority according to conventional traffic signalization for the number of passing vehicles. It exhibits % 66 superior performance than conventional method for waiting duration when the traffic is the densest. The results given in Table 6 are obtained for only an hour. For all day, especially if there are two or more traffic lanes, superiority of smart traffic light controller becomes more apparent. As a result, it is clear that smart traffic signalization presented in this paper will provide environmental and economical positive contributions to people's lives from the point of view of fuel and time consumption in traffic.

5. Comments and future work prospects

In this study, the main objective was to implement fuzzy light duration control based on hardware and to compare its performance with the conventional ones for four directional traffic junction. We can summarize major contributions of this research study as follows:

- Smart traffic light simulator system is implemented based on hardware.
- System hardware structure is suitable for comparison between fuzzy light and fixed (conventional) control.
- In recent studies, vehicles entering the traffic junction are not completely the same because traffic flow changes from cycle to cycle. Thus, some performance criteria are not obtained accurately since waiting times of the vehicles at red light cannot be precisely measured. In this study, we used the same vehicle array for both types of controllers in order to be able to make an exact comparison of the results. In this manner conventional and fuzzy logic traffic light controllers are evaluated under exactly the same conditions.
- In our experimental studies on the system, the waiting time of vehicles and the number of vehicles passing through in unit time are evaluated in detail.
- The most simple fuzzy controller model is used since its implementation is easy on the hardware used.

On the other hand, a major drawback of the intelligent light controller implemented in this study is that parameters of the fuzzy controller are determined beforehand by our expertise. These parameters were not optimized offline/online by GA as in Refs. [13,14], by supervised learning as in Refs. [11,12], by reinforcement learning as in Ref. [7], etc. since we studied and implemented the systems based on hardware and running these algorithms is not possible on hardware used in this study due to limited program memory capacity.

The future works prospects for smart traffic light systems can be stated as follows: A possible problem is wiring while adapting the system to real traffic conditions. This problem can be solved by using a wireless communication facility between related points. In case the location and cost of loop detectors cause a problem, the queue lengths may be determined by image processing using a camera for each direction. However these approximations described above will require additional or different hardware.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.asoc.2009.06.002.

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