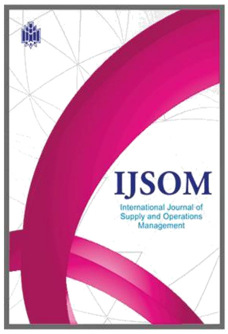
International Journal of Supply and Operations Management

IJSOM

May 2019, Volume 6, Issue 2, pp. 142-158
ISSN-Print: 2383-1359
ISSN-Online: 2383-2525
www.ijsom.com



Optimizing Total Delay and Average Queue Length Based on the Fuzzy Logic Controller in Urban Intersections

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Abstract
Currently, traffic congestion has become a serious problem in most developed cities. It is caused by an increasing number of vehicles and the delay on arterial roads resulting in negative consequences for air quality, travel time, and travel safety. To reduce the traffic volume and congestion, recent solutions offer optimization of operational characteristics including the total delay and average queue length in urban intersections. Optimizing such characteristics is considered as the major breakthrough concept of applying artificial intelligence to transportation engineering. Accordingly, the aim of this study was to develop and apply the fuzzy controller to reduce the total delay and average queue length in urban intersections. To this end, effective variables like the total delay and average queue length were simulated using the fuzzy logic controller. Then, the results were graphically simulated for the experts. Furthermore, the total delay and average queue length were compared employing the fixed-time control and fuzzy controller systems. The results indicated that in the fuzzy controller system rather than the fixed-time control system, the delay and average queue length were remarkably optimized. Statistical tests also approved the efficiency of the fuzzy controller as an optimum controller system as compared to the fixed controller system. The findings of this study may help the traffic engineers and urban managers to control the traffic congestion issues based on predicting and optimizing the delay and queue length and increasing the road safety in urban intersections in the future.

Keywords: Traffic congestion; Total delay; Average queue length; Fixed-time controller; Fuzzy logic controller; Optimum classification.

1. Introduction

Today, uncontrolled growth of the urban vehicles is one of the major problems causing traffic congestion on arterial roads in urban centers (Kermanian et al., 2013). Besides, urban traffic is a common issue in transportation systems. Especially, it increases the costs, travel time, travel delay, fuel consumption, and etc. in developing countries (Haregewoin, 2010). While implementing road and transportation projects, engineers and researchers have suggested creating the urban intersections as alternative ways to reduce negative traffic effects. Urban networks are classified as junctions, 3-leg and 4-leg intersections, and roundabouts in urban intersections. Recently, choosing roundabouts as a way to control the intersections has been a great concern for the urban engineers. Modern roundabouts have a significant role in decreasing severe injuries and fatality crashes and drivers are permitted to get through intersections more quickly. In addition, roundabouts are safe locations for pedestrians and bicyclists to pass throughout the traffic (Oketch et al., 2004).

According to Baldi et al. (2017), the urban traffic control method based on the fuzzy control theory, among many traffic intelligent control methods, has been a crucial method till present. Jin et al. (2017) expanded an intelligent control system for traffic signal applications. Accordingly, all the tested signal control strategies were compared in a real situation. As a result, their work showed that the control system was able to improve the traffic mobility and flexible phase structures. Moreover, Ge (2014) used the fuzzy logic controller as an adequate system to consider the urgency of the red phase. The

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results determined the max urgency degree of the red phase. Kim et al. (1997) also presented a classification model to control the intersection. The model was based on fuzzy control rules. However, the fuzzy classified controller had a coarser membership function and a fuzzy control rule. It also caused an improvement in fuzzy controllers for the intersections. According to this development, signal control methods of urban intersections and traffic networks were started.

There were significant studies conducted by different researchers which were fundamental and stratified hierarchical methods to adjust the phase difference or signal cycle among all the intersections. A number of researchers stated that the fuzzy controller model was developed for wider occasions (Soh et al., 2011; Lee & Lee-Kwang, 1999; Ponlathep, 2010; Hulea et al., 2011; Hawas, 2007). As mentioned by Azimirad et al. (2010), the fuzzy controller model (a new model to monitor the signalization of intersections) is used to facilitate the flow of traffic. Since humans cannot always control the events occurring around them carefully, it is necessary to use devices with artificial intelligence. Fuzzy logic is such an artificial intelligence application.

Many studies have provided basic information on the concept of fuzzy logic and its applications (Klir &Fogel, 1988; McNeill & Thro, 1994). Mandar et al. (2017), for instance, applied fuzzy modeling to assess the risk exposure indicator for improving the walking environment for the pedestrians while considering walking as an essential part of the overall transportation system. The simulation results of the study were confirmed by the first-order traffic flow theory. The fuzzy logic model was applied to simulate the complex behavior of the drivers regarding the dynamical modeling. To predict the crash severity, acceleration data were recorded by the kinetic energy and the jerk (Munyazikwiye et al., 2015).

Similarly, Niittymaki et al. (2001) focused on simulating and comparing the fuzzy control and traditional vehicle actuated control in urban intersections. They found that fuzzy control optimized the capacity of high-class arterial roads while increasing the traffic flow demands. In addition, Kulkarni and Waingankar (2007) used the fuzzy controller as a tool to minimize the delays. It was approved that the fuzzy controller was more effective than the fixed controller. In the same way, Hu et al. (2007) proposed a fuzzy control system for regulating the traffic flow approaching a single real intersection. They simulated real car flows in addition to new acceleration and deceleration movement models to ensure safe driving through avoiding the possible collision.

The fuzzy logic system has also been proved as an intelligent controlling tool for the expert knowledge in steering control of the autonomous vehicles inside the roundabout. Through using this system, speed profiles and lane change maneuvers inside the roundabout are taken into account for investigating the driver's behavior inside the roundabouts (Rastelli & Peñas, 2015). In ecological and environmental researches, Sulaiman et al. (2018) described modeling of CO_2 and NOx on signalized roundabout using a Modified Adaptive Neural Fuzzy Inference System (ANFIS) model. Their model was a function of traffic volume, average vehicle speed, traffic delay, mini trucks, heavy truck percentage, and a total of heavy and mini-trucks. The researchers stated that CO_2 modeling the triangular membership function was the best while for NOx, the membership function was two-sided Gaussian.

In another study, Martín et al. (2016) proposed a fuzzy model that indicated a new and reliable method for determining such a vehicle state on two-way, two-lane roads. They found that there was a close relationship between the level of service (LOS) and the driver's experience. Moreover, as stated by Corcoba and Muñoz (2014), LOS on two-lane roads and quality of traffic flow are estimated based on the delay and speed. Zaied and Al Othman (2011) also focused on the development of a fuzzy logic traffic controller for the isolated signalized intersections in the State of Kuwait. They found out that the proposed system could be used to accelerate the cycle time and to give other phases the chance to gain more benefit from the green time lost. Using fuzzy signal controller tackles traffic congestion during over-saturation flow traffic. In this respect, setting signal phases based on traffic conditions can be easy. An et al. (2014) introduced a method of using fuzzy logic to evaluate capacity, delay times, and LOS at roundabouts comparing normal metering and signal roundabouts. Surprisingly, they observed that the fuzzy logic improved the characteristics of roundabouts.

Based on the discussed studies, one can infer that the novelty of this research is to create a better delay and queue length model using fuzzy logic and Synchro 8 software for under-saturated and over-saturated traffic conditions. This is undertaken because the current methods are not adequate for over-saturated conditions. Another novelty of this paper is to improve operational characteristics including the total delay and average queue length and to reduce the traffic congestion in urban intersections. This paper, therefore, may be interesting for the traffic and urban managers in controlling the traffic issues. The results from this paper can solve traffic jams and complex problems caused by urbanization.

This paper aimed to model and simulate operational characteristics of the intersections by means of the fuzzy logic controller based on Matlab (matrix laboratory) software. Input and output variables such as speed, volume, total stop, total delay, and average queue lengths were first collected by Synchro 8 software which was set based on the fixed-time controller. After excluding the inputs and outputs, they were examined based on the fuzzy logic controller system. Such a system modeling can be used in computer simulations as compared to physical systems which are used in real applications. Using the fuzzy logic controller system, the above-mentioned operational variables can be decreased significantly. Another aim of this study was to classify the intersections according to the optimal amounts of the total delay and average queue lengths in comparison with fixed-time controllers. Following simulating the data in both mentioned systems, a comparison between both states in urban intersection determined the effect of the fuzzy controller as an optimum approach to control the traffic parameters.

To approve the accuracy and reliability of the fuzzy logic controller in comparison with the fixed-time controller, sensitivity analysis and data calibration were proposed and applied using SPSS (Statistical Package for the Social Sciences) software, version 17 and error percentage. Therefore, fuzzy logic was selected as an accurate and intelligent controller system to optimize and classify the optimum total delay and queue lengths in urban intersections.

2. Case study

Boroujerd is one of the most crowded cities in Lorestan Province and is located in the North-South corner of Iran with a population of over 240,654 people. It plays a strategic role in the economic and political areas of the country. Moreover, Boroujerd is rapidly developing, with an increasing number of traffic vehicles for transporting the goods to the neighboring cities. There are a variety of reasons for traffic problems in this city, for example, the increasing heavy vehicles as well as pedestrians which lead to delay and long queues behind the traffic lights making the vehicles at the intersections stop.

Geometric features of the selected intersections are demonstrated in Table 1. All the traffic volumes of each intersection were collected and reported from 7:30 A.M to 7:30 P.M. In all the intersections, pedestrians could pass across each path. Then, by simulating the traffic using the Synchro 8 software package, the total delay and queue length (unit: meter) were obtained as variables to be studied in the fixed-time control system. In order to achieve the objective of this study, geometric data were collected. A total of 16 lane groups were selected from five intersections in Boroujerd. The locations are illustrated in Figure 1.

Figure1. A Schema of Boroujerd Intersections.

Table1. Geometric Features of the Selected Intersections

Intersection name	Approach Street	Lane group	Movement	No. of Lanes	Lane width (m)	One Way or Two-way	Volume (Veh/hr)
Ghiam Roundabout	Jafari	1	LT+RT	3	5.5	Two Way	13,997
	Shohada	2	LT+RT	3	5.5	Two Way	26,018
	Rahnamai	3	LT+RT	2	3.2	Two Way	7,645
	Total			2	3.2	Two Way	47,660
Shohada Roundabout	Kashani	1	LT+RT	3	5.5	Two Way	17,503
	Shohada	2	LT+RT	3	5.5	Two Way	24,197
	Bahar	3	LT+RT	3	5.5	Two Way	14,153
	Takhti	4	LT+RT	3	5.5	Two Way	13,114
	Total						68,967
Baghmiri Junction	Seyed Mostafa	1	LT+RT	3	5.5	Two Way	9,025
	Gholesorkhi	2	LT+RT	3	5.5	Two Way	4,882
	Bahrololoum	3	LT+RT	3	5.5	Two Way	8,198
	Total						22,105
Hafez Junction	Northen Hafez	1	LT+RT	3	5.5	One Way	4,257
	Southen Hafez	2	LT+RT	3	5.5	One Way	5,204
	Razan	3	LT+RT	3	5.5	Two Way	7,123
	Shohada	4	LT+RT	3	5.5	Two Way	6,580
	Total						23,164
Safa Roundabout	Shariati	1	LT+RT	2	3.2	Two Way	9,286
	Safa	2	LT+RT	3	5.5	Two Way	8,978
	Bahrololoum	3	LT+RT	3	5.5	Two Way	11,861
	Jafari	4	LT+RT	3	5.5	Two Way	15,644
	Total						45,769

3. Research background

Intersections are complex infrastructures. According to their applications, intersections are made based on traffic flow, capacity, delay, and queue (Garber & Hoel, 2014). As traffic congestion is one of the most serious problems in the complex networks, it is crucial to investigate important components like capacity, delay, and queue length that have an effect on it. Therefore, the above-mentioned elements are particularly dealt with in the following sub-sections.

3.1. Capacity

There are a variety of methods to assess capacity at the controlled intersections. These methods are in accordance with Highway Capacity Manual standards (HCM, 2010). Van Aerde (1995) estimated location capacity based on the following parameters mentioned in equation 1. In addition, Webster (1958) calculated the capacity of intersections in accord with the average delay as follows:

$$C_i = \frac{U_i}{C_i + \frac{C_2}{u_{f,i} - u_i} + C_3 U_i}$$

(1)

Where C_i and u_i denote the estimated capacity and the space mean speed (km/h) for the location i, respectively. $u_{f,i}$ shows the free flow speed (km/h) for the location I and finally, c_1, c_2, and c_3 represent the headway constant coefficients.

3.2. Volume to capacity ratio

One of the performance characteristics of the intersections is the volume to the capacity ratio that can assess the LOS. A ratio of less than 0.85 means that vehicles could pass through the intersection since this ratio is below the maximum capacity. A ratio between 0.85 and 0.95 or 0.95 and 1 is close or equal to the maximum capacity, respectively. A ratio of more than 1 shows that the vehicles have a significant role in the contribution of increasing queues. Hence, LOS at the intersections is graded from A to F (HCM, 2010). Due to the fact that traffic flow is a nonlinear function, when an intersection reaches its maximum capacity, vehicles in queues lead to heavy traffic and delays which cause unstable traffic flows (Victoria Transport Policy Institute, 2013). As the delay and queue length can be predicted under different traffic conditions, a greater number of cycles is taken into account for timing traffic lights in order to prevent any extra delay and queue length in the intersections (FHWA publication, 2000).

3.3. Delay

In 1958, Webster studied uniform and random delay and offered a formula to calculate these two types of equations (i.e., Equations 2 & 3). He also indicated that random delay occurs when the volume to capacity ratio is increased and traffic flow becomes saturated. This means that intersections deal with a high volume of vehicles. The proposed formula is as follows:

$$UD = 0.5 \times RV \quad (2)$$

Where UD and R show the aggregate uniform delay of the vehicles (veh/secs) and red phase length (s), respectively. In addition, V is the total vehicles in the queue (veh). Variables such as light cycle length, effective green time, entry flow rate to the intersection, intersection capacity, and volume to the capacity ratio or saturation degree are also taken into account (Webster, 1958).

$$RD = 0.5 \times (X^2) \times (1 - X) \quad (3)$$

Where, X and RD are the volume per capacity (V/C) and average random delay per vehicle (s/veh).
Using equation 3, totally random and uniform delay of the vehicles are expressed as follows (Webster, 1958):

$$D = 0.9 \times (UD + RD) \quad (4)$$

Where, OD is the average overflow delay per vehicle (s/veh). X represents the v/c ratio or degree of saturation, C and V show cycle length (s) and arrival flow rate (veh/h), and T is the analysis period (s).
In addition to Webster's equation, Sofia et al. (2014) found a model to estimate the delay in signalized intersections. They showed the delay as a function of volume to capacity ratio, traffic lights cycle length, and width of the total exit paths to the intersection in equation 5 as follows:

$$d = 0.102 \times C + 30.19\frac{v}{c} + 19.59(1 - \frac{W_e}{W_s}) \quad (5)$$

In this equation, d and v are the delay for the lane group (vehicle/second) and volume rate of the vehicles (veh/hr), respectively. c and C show the lane group capacity (veh/hr) and cycle length (sec). In addition, W_s denotes the total width of the lane groups departing to the same exit roadway in the phase at the stop line (m) and W_c represents the total width of the exit roadway of intersection for the traffic departing straight forward (m).

Overflow delay:
It is the additional delay that occurs when the capacity of an individual phase is less than the demand or arrival flow rate which is described in equations 6 and 7 as follows (Webster, 1958):

$$OD = \frac{1}{2}T(X - 1) \quad (6)$$

$$OD_a = \frac{1}{2}T(vT - cT) = \frac{T^2}{2}(v - c) \quad (7)$$

where OD_a and OD show the aggregate overflow delay (veh-secs) and average overflow delay per vehicle (s/veh). X is the volume per capacity (v/c) or the degree of saturation. In addition, C, v, and T represent cycle length (s), arrival flow rate (veh/h), and analysis period (s), respectively.

3.4. Queue length

Kyte and Marek (1989) proposed a model for estimating the queue length at the intersections according to both variables of volume and queue length of the vehicles, which is shown in equation 8.

$$L = \frac{V}{3600} \times d \quad (8)$$

Where, L, v, and d show the average queue (veh), the volume of the vehicles (veh/s), and the delay (s), respectively.
In addition, Kyte and Marek (1989) showed 95th percent of the queue length based on queue length as follows:

$$L_{95} = 2.3L + 2.1\sqrt{L} + \frac{L}{L+4.6} \quad (9)$$

Where L is the 95th percentile of the queue length (veh).

4. Research method

4.1 Application of fuzzy logic

In 1965, Zadeh introduced the fuzzy logic theory with certainty and uncertainty perception. Fuzzy logic has many applications in science and technology. It is used in the assessment of uncertain problems in engineering aspects and fields (Hoogendoorn et al., 1999; Zadeh, 2003). In addition, Shirmohammadi and Hadadi (2017) used fuzzy logic in their study to carry out an evaluation of drowsy drivers. It was based on the multinomial regression by the fuzzy intelligent system to control the drivers' behaviors under different conditions like rainy and dry conditions.

In another study which was based on a monitoring controller, they evaluated the resilient modulus performance of the stone mastic asphalt in the pavement engineering. Similarly, Salman et al. (2018) used the fuzzy logic control method with vehicle-to everything (V2X) to solve the traffic congestion problem. The results indicated that logical problem was more accurate than the optimization problem. As stated by Isik and Arslan (2011), fuzzy logic has been significantly used in washing machines, microwave ovens, industrial process controls, and decision-supportive systems in recent years.

According to Kusan et al. (2010), a fuzzy logic system is composed of the fuzzy inference system (FIS), membership functions (MF), rule base, a ruler viewer, a surface viewer, and defuzzification for the assessment of all the input and output variables. Qiao et al. (2002) also proposed a methodological work based on fuzzy logic for the real-time traffic operational characteristics of the intersections to improve the delay estimation. The results showed that both the HCM and Webster models produced large errors. Nonetheless, the Webster model slightly outperformed the HCM model. Clearly, the fuzzy delay model provided a closer delay estimate for the field data than the other two models. In addition, Fazio et al. (2016) mentioned a new algorithm to characterize the driving behaviors based on the fuzzy logic approach. They classified the driving styles according to the environmental conditions and a set of Gaussian curves related to the average speed of the vehicles. From the above-discussed studies it can be concluded that fuzzy logic has been intensively used in different areas of engineering sciences and industrial works.

Accordingly, the fuzzy controller was designed and applied to improve the traffic characteristics (i.e., delay and queue) in urban intersections at the condition of the fuzzy rule and membership function parameters. Two controller systems which were called fixed time and fuzzy controller based on Synchro 8 and Matlab software were also proposed. The fuzzy controller system considered the effect of traffic flow, speed, total stop on the total delay, and average queue length. Finally, the significance of this paper was to optimize the total delay and average queue length. It determined optimized values of the total delay and average queue length through making a comparison between the two proposed controllers.

4.2 Selection of the fuzzy inference system

The process of fuzzy inference consists of membership functions, fuzzy logic operators, and if–then rules. Generally, fuzzy inference systems are classified as Mamdani and Sugenotypes. In this study, a Mamdani fuzzy inference system was used to optimize and model the total delay and average queue length in urban intersections (Mamdani & Assilian, 1975).

Meanwhile, such an inference system was also employed to simulate the impact of speed, volume, total stop on total delay, and queue length of the vehicles. Input and output data were processed in two ways, namely, multi-input and multi-output (MIMO) and multi-input and single-output (MISO). The diagram for the fuzzy inference system is shown in Figure 2.

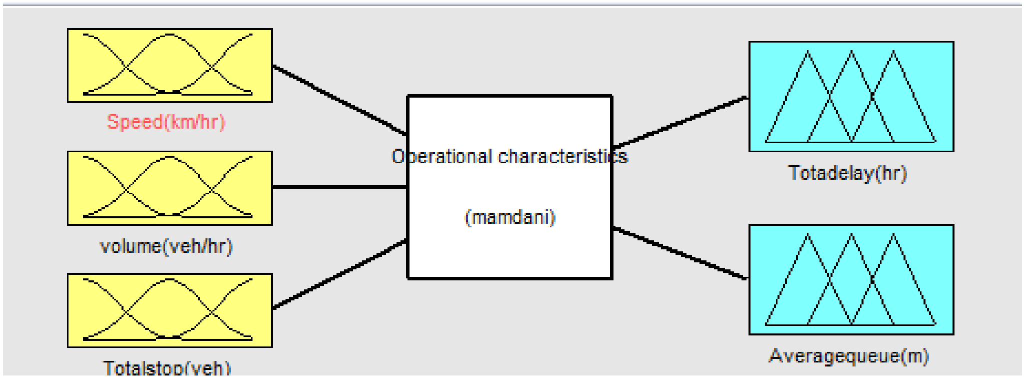
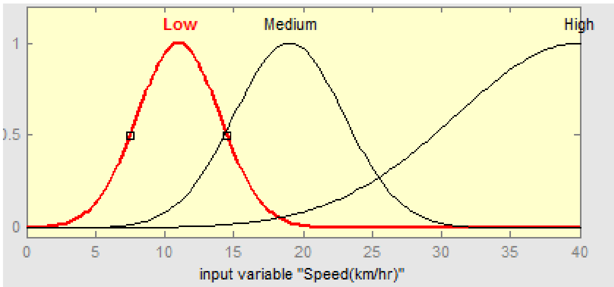


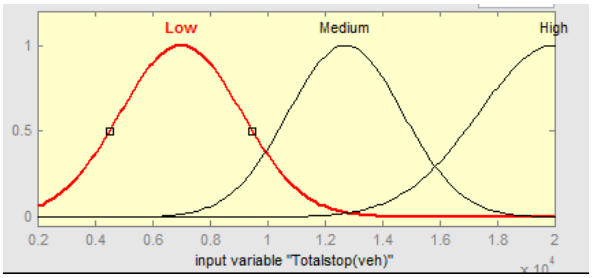
Figure 2. The Mamdani fuzzy inference system.

4.3 Implementation of the fuzzy system

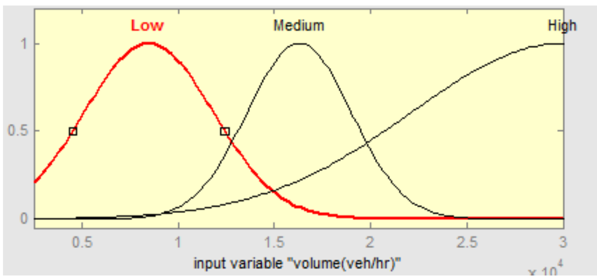
Input and output variables which were created for the fuzzy system to evaluate the operational characteristics at the intersections are shown in Figures 3 and 4. Using the input and output data obtained applying the Synchro 8 software (as shown in Table 2), the output results were considered as variables of the fuzzy logic system. Among the variables included in Table 2, only volume, total stop, and speed (as the input variables), and total delay and average queue length (as the output variables) were placed in the fuzzy system.



(A) Speed (km/hr)



(B) Total stop (vehicle)



(C) Volume (veh/hr)

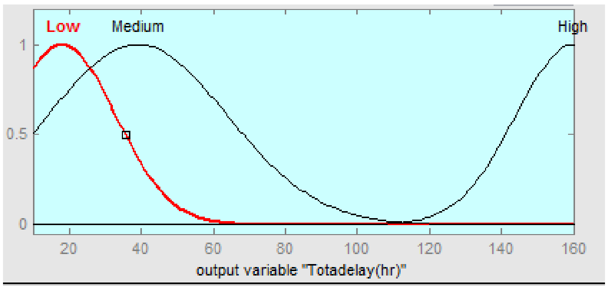
Figure 3. Input variables: (A) Speed; (B) Total stop; (C) Volume.

4.3.1. Input variables

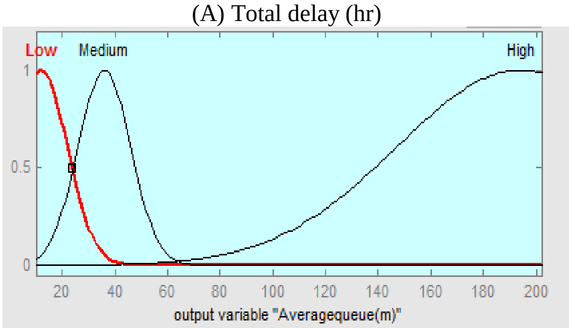
Since the main aim of this study was to evaluate and optimize the delay and average queue length of the vehicles in intersections, input variables like speed, total stop, and volume of the vehicles were valued and classified into the intervals based on the principles of fuzzy logic as shown in Figure 3.

4.3.2. Output variables

Output variables such as the total delay and average queue length were categorized as low, medium, and high based on linguistic and qualitative values according to Figure 4.



(A) Total delay (hr)



(B) Average queue length (m)

Figure 4. Output variables: (A) Total delay; (B) Average queue length.

4.3.3. Fuzzy rules

The fuzzy approach considers cases where linguistic uncertainties play a role in the control mechanism of the phenomena concerned. Fuzzy logic also consists of IF and THEN rules which are used to explain the truth values of the events as measures of their crisp values (Klir & Fogel, 1988; Kosko, 1992; Zadeh & Kacprzyk, 1992). Based on the expert experiences, the fuzzy rules were used to simulate the fuzzy logic for evaluating and optimizing the delay and queue length of the vehicles in intersections into the optimum classes.

Therefore, in this study, 24 rules were applied among which three rules have been expressed as examples. The rules applied in the present study are listed in Table 2. Since all the variables were independent of each other, there was no need for more rules and only a set of fuzzy rules could affect the output variables as follows:

- Rule 1: If the speed, volume, and total stop of the vehicles were low, so were the total delay and average queue length.
- Rule 2: If the speed and volume of vehicles were low and the total stop was medium, then the total delay and average queue lengths were medium.
- Rule 3: If the speed, volume, and total stop of the vehicles were medium, low, and medium, respectively, then the total delay and average queue length were low.

Based on the above-mentioned rules, membership degrees of the inputs were computed and multiplied in order to assign the weight W_k to the output variables according to Equation 6. Hence, the weighted average of the outputs from 24 rules gave a single output Y as follows:

$$Y = \frac{\sum_{k=1}^{24} W_k Y_k}{\sum_{k=1}^{24} W_k} \quad (10)$$

Table2. Fuzzy Rules for Input and Output Variables of the Total Delay and Average Queue Length

No.	Speed	Volume	Total stop	Total delay	Average Queue Length
1	Low	Low	Low	Low	**Low**
2	Low	Low	Medium	Medium	**Medium**
3	Medium	Low	Medium	Low	**Low**
4	Medium	Medium	Medium	Low	**Medium**

Table2. Continued

No.	Speed	Volume	Total stop	Total delay	Average Queue Length
5	High	Medium	High	Low	**Low**
6	High	Medium	Medium	Low	**Low**
7	Medium	Low	Low	Low	**Low**
8	Medium	Low	Low	Medium	**Low**
9	Low	High	High	Medium	**Medium**
10	Medium	High	Medium	Medium	**Medium**
11	High	High	Medium	Medium	**High**
12	High	High	Low	Low	**Medium**
13	Medium	Medium	Medium	High	**High**
14	High	Medium	Medium	Medium	**High**
15	High	Low	Low	Low	**Medium**
16	High	Medium	Medium	Medium	**Medium**
17	High	High	High	Medium	**Medium**
18	High	High	High	High	**Medium**
19	Medium	High	High	High	**High**
20	Low	High	High	Medium	**High**
21	Low	High	High	High	**High**
22	High	Medium	High	Medium	**Medium**
23	High	High	Low	Low	**Low**
24	Medium	High	Low	Medium	**Medium**

5. Results and discussion

To understand the traffic congestion and to find possible solutions to it, the present study sought to present the main causes of traffic congestion with real simulation by the fuzzy controller system. It was revealed that the speed, volume, and total stop of the vehicles had a great impact on increasing or decreasing the total delay. Based on the proposed method, input and output variables were classified in accord with the linguistic variables after running the fuzzy system. Then, using the fuzzy logic controller, the effect of input on output variables was observed. In Figure 5 the fuzzy rule viewer for the peak and non-peak hour operations is illustrated. The controller made a decision in order to control the impact of increasing or decreasing input variables on output variables. This controller allowed the experts to select the most optimal conditions for the total delay and average queue length under peak and non-peak our traffic flows.

Figure 6 shows the relationship between volume and total delay. As evident from the figure, the total delay grew when the volume slowly started to grow. This means that volume was a predominant factor in increasing the total delay in urban intersections. However, Figure 7 indicates that with increasing the speed of the vehicles, the total delay decreased. In fact, speed had a reverse relationship with the volume.

As shown in Figure 8, the total stop had a significant impact on the total delay. The total delay grew when the total stop slowly started to grow. In other words, reducing the speed, total delay significantly increased leading to traffic congestion. Furthermore, there was a close relationship between the volume and average queue length (Figure 9). It is clear that the average queue length grew when the volume significantly increased.

According to Figure 10, the total stop had a direct effect on average queue length in the intersection. Clearly, an increase in the total stop resulted in high average queue lengths at the intersections. Based on this proposed method, evaluation of the delay and queue length was carried out by the fuzzy controller system and finally, the results were compared with the fixed-time control system.

According to Figures 11 and 12, the optimum classifications were selected for each intersection based on the lowest total delay. Besides, the average queue length was also selected based on the fixed-time and fuzzy controller systems. A comparison between the fixed-time and fuzzy controller systems indicated that the fuzzy controller system was the only way to reduce the queue length in the intersections. Additionally, Figures 13 and 14 indicate the effectiveness of the fuzzy controller system in comparison with the fixed-time controller based on the optimized percent amounts of the total delay and average queue length in the intersections. As a result, it can be perceived that using the fuzzy controller was an optimal tool for controlling the operational characteristics of the urban intersections.

Generally speaking, the results provided in the figures and tables illustrate that employing the fuzzy controller system, all variables including the total delay and average queue length were evaluated under and over-saturation traffic flows. In addition, effective parameters such as volume, speed, and total stop were used to examine the total delay and average queue length through different trends. Thus, intersections based on the optimum delay and average queue length were compared and the results revealed that the fuzzy logic controller indicated a better performance, delay, and average queue length as compared to the fixed-time controller.

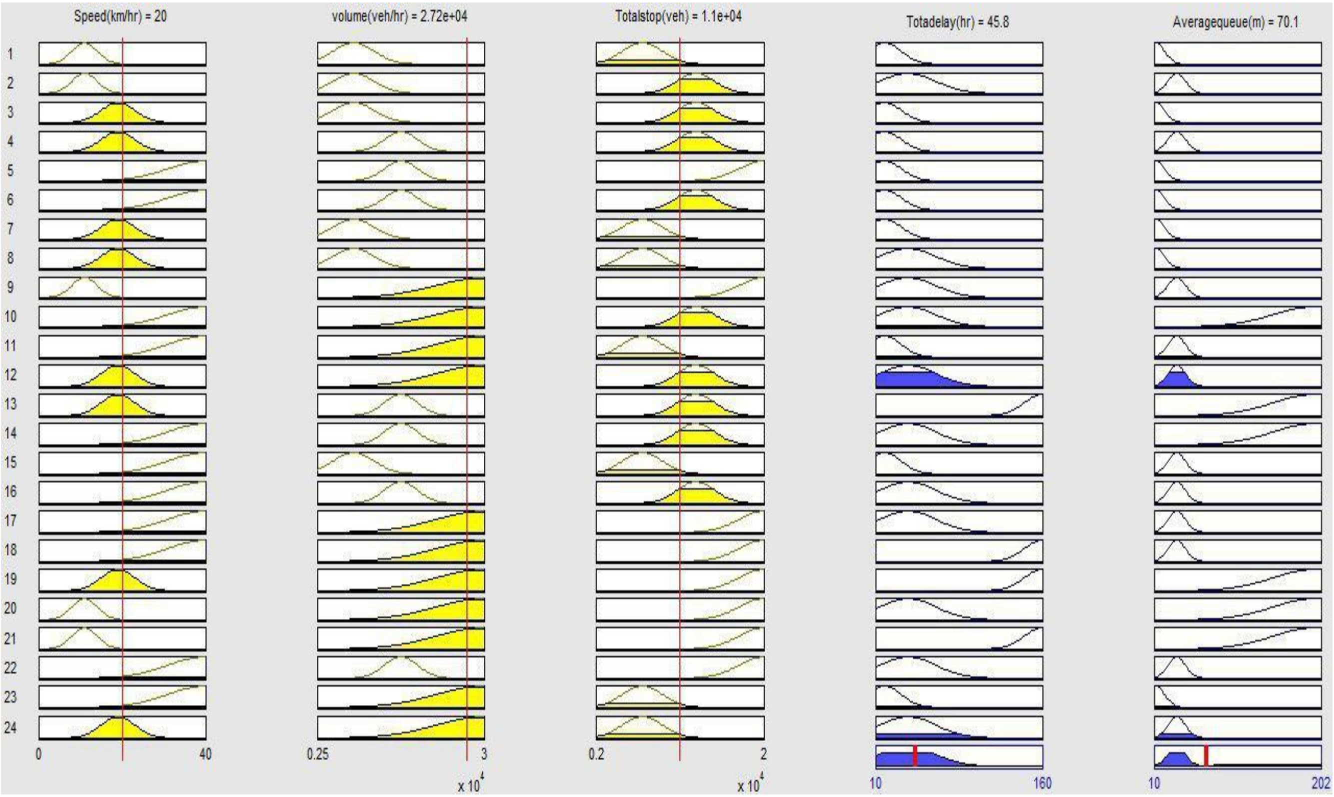


Figure 5. Fuzzy rule reviewer.

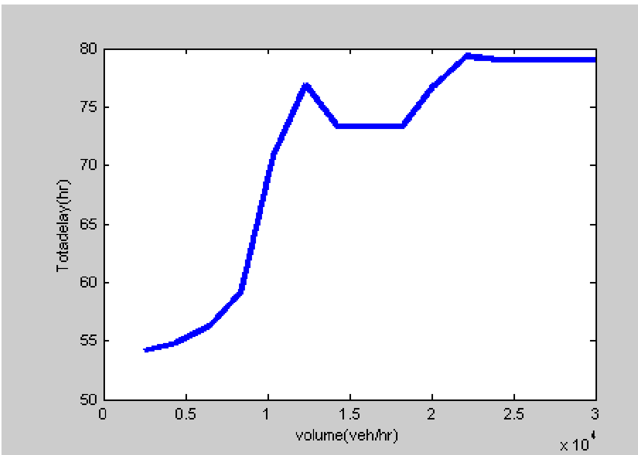


Figure 6. The relationship between the volume and total delay.

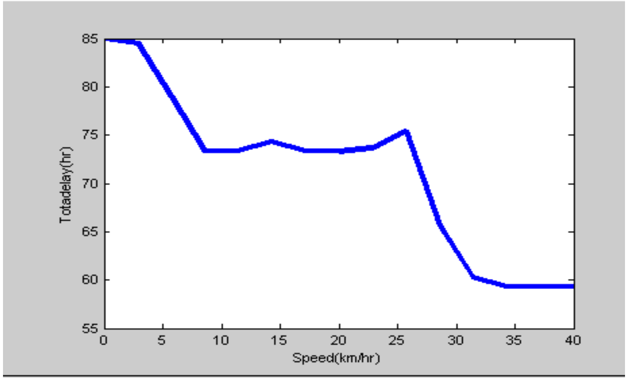


Figure 7. The relationship between the speed and total delay

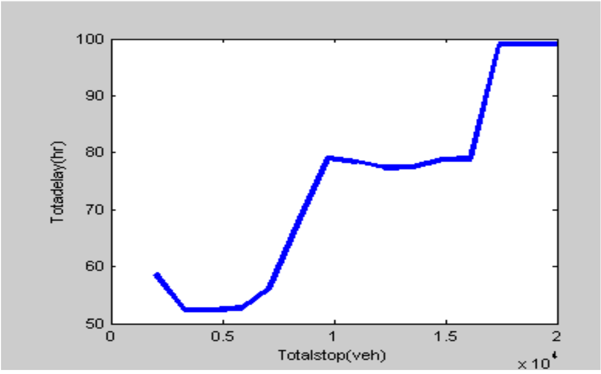


Figure 8. The relationship between the total stop and total delay

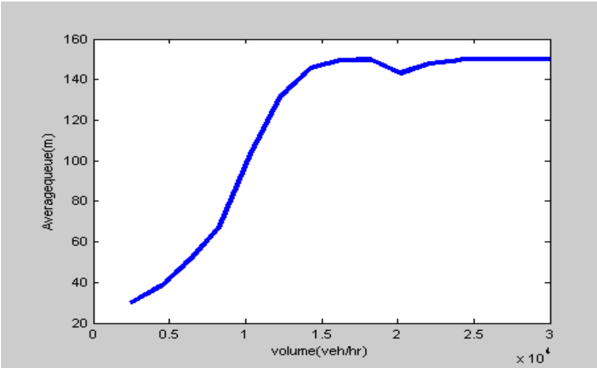


Figure 9. The relationship between the volume and average queue length

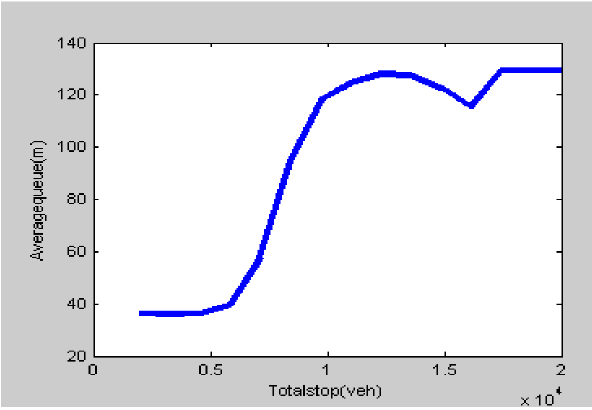


Figure 10. The relationship between the total stop and average queue length

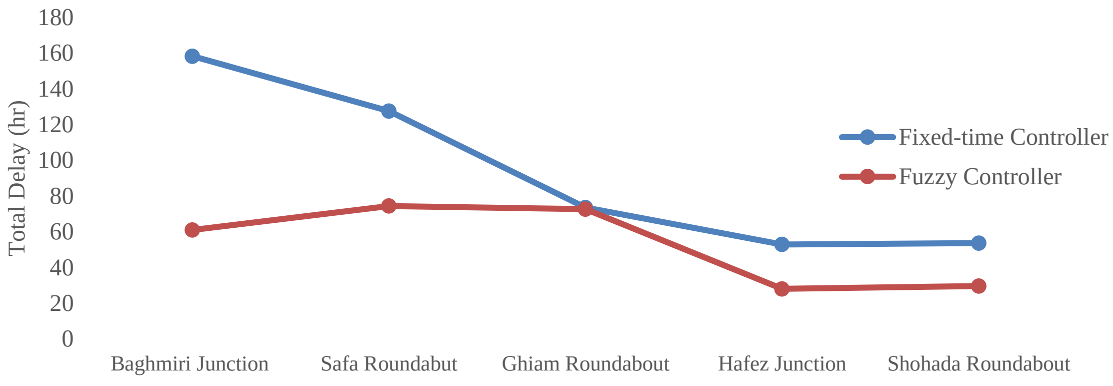


Figure 11. Classification of the optimum total delay at intersections based on fixed-time and fuzzy controller systems.

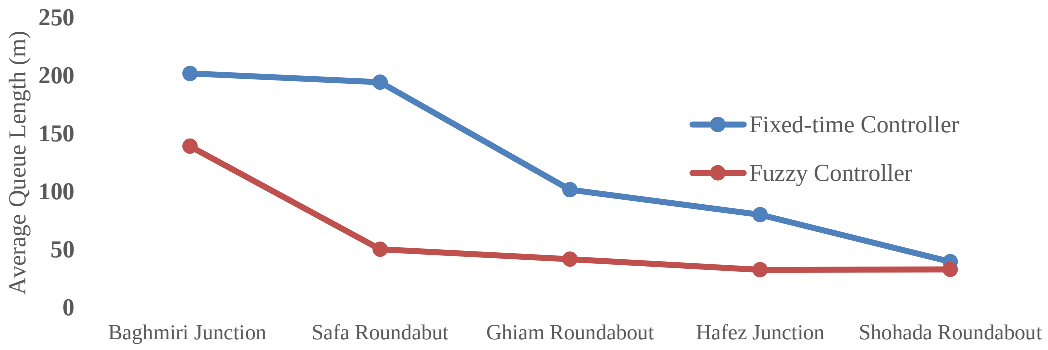


Figure 12. Classification of the optimum average queue length at intersections based on fixed-time and fuzzy controller systems.

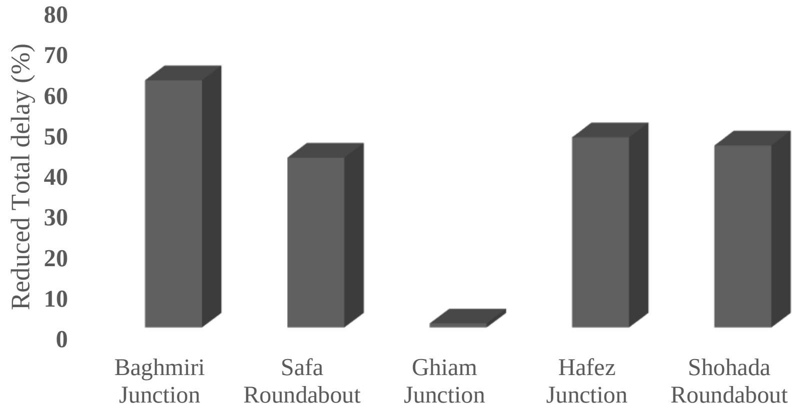


Figure 13. Optimized and reduced total delay at intersections based on the fuzzy controller in comparison with the fixed-time controller system (%).

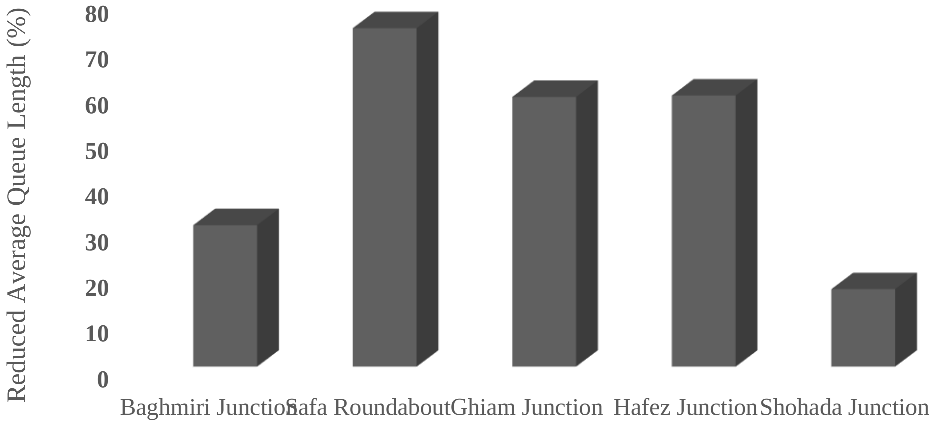


Figure 14. Optimized average queue length at intersections based on the fuzzy controller in comparison with the fixed-time controller system (%).

6. Sensitivity analysis

Based on the method proposed in this study, evaluation of the total delay and average queue length were completed using the fuzzy controller system. The results of this system were compared with those of the fixed-time control system. Tables 3 and 4 display a comparison between the fuzzy logic and fixed-time controller systems based on the prediction error percentage. According to the tables, using the fuzzy logic controller had a lower error percentage in comparison with the fixed-time controller. It can be concluded that the fuzzy controller had a significant performance in the optimization of the total delay and average queue length. Thus, the fuzzy controller model was introduced as a certain and optimized tool to control the delay and queue in urban intersections.

Table 3. Error Percentage of Average Queue Length Based on Fixed Time and Fuzzy Controller Systems

Urban Intersections	Error Percentage (Fixed-time controller)	Error Percentage (Fuzzy logic controller)
Baghmiri Junction	63	20
Safa Roundabout	61	45
Ghiam Roundabout	32	17
Hafez Junction	25	15
Shohada Roundabout	12	10

Table 4. Error Percentage of Total Delay Based on Fixed Time and Fuzzy Controller Systems

Urban Intersections	Error Percentage (Fixed-time controller)	Error Percentage (Fuzzy logic controller)
Baghmiri Junction	79	49
Safa Roundabout	64	27
Ghiam Roundabout	37	36
Hafez Junction	26	12
Shohada Roundabout	27	12

To determine the accuracy and reliability of the fuzzy controller system for operational characteristics at the intersections, several tests were performed to determine the model efficiency as compared to the outputs of the fixed-time control system in Synchro 8 software. First, based on Kolmogorov–Smirnov test, the normality of the data was confirmed (Table 5). Furthermore, following the data normality verification, a *t*-test was run for the sample pairs. Statistical indices like mean, number of samples, standard deviation, and average error deviation were also examined before and after variable pairs of the total delay and average queue length (Table 6).

According to Table 7, sample pairs of before and after the total delay and average queue length were correlated with each other and a significant correlation was observed between before and after variables in each sample. This deduction was due to the high correlation coefficients of these pairs which were 0.64 and 0.84, respectively. This means that before and after variables had significant differences using fixed-time and fuzzy controller systems.

The fuzzy logic controller method was verified by the *t*-test of the sample pairs in the SPSS software, version 17. The results provided in Table 8 approved the fact that pairs 1 and 2 had a low significance, that is, each significant coefficient was less than .05. Consequently, the total delay (after) and total average queue (after) had significant reductions after using the fuzzy logic. Based on the data in Table 8, it can be understood that employing the fuzzy intelligent control system surprisingly optimized the total delay and average queue length. Thus, the fuzzy logic controller method was found to be an effective tool for reducing the two pairs of after variables values in comparison with before variables of the fixed-time control in Synchro 8 software.

Table 5. Kolmogorov–Smirnov One-sided Test to Normalize the Data Using the One-Sample Kolmogorov-Smirnov Test

N		**Total delay (before)**	**Average queue length (before)**	**Total delay (after)**	**Average queue length (after)**
		10.00	10.00	10.00	10.00
Normal Parameters[a,b]	Mean	93.70	129.09	48.55	72.64
	Std. Deviation	35.16	56.93	19.84	44.86
Most Extreme Differences	Absolute	0.17	0.20	0.20	0.26
	Positive	0.17	0.19	0.20	0.26
	Negative	-0.13	-0.20	-0.19	-0.20
Kolmogorov-Smirnov Z		0.55	0.62	0.64	0.83
Asymp. Sig. (2-tailed)		0.93	0.84	0.82	0.50
a. Test distribution is Normal.					
b. Calculated from data.					

Table 6. Paired Samples Statistics

		Mean	**N**	**Std. Deviation**	**Std. Error Mean**
Pair 1	Total delay(before)	93.70	10	35.16	11.12
	Total delay(after)	48.55	10	19.84	6.27
Pair 2	Average Queue length(before)	129.09	10	56.93	18.00
	Average Queue length(after)	72.64	10	44.86	14.19

Table 7. Correlation Test of the Sample Pairs

		N	**Correlation**	**Sig. (2-tailed)**
Pair 1	Total delay (before) & Total delay (after)	10.00	0.64	0.04
Pair 2	Average queue lengths (before) & Average queue length (after)	10.00	0.80	0.01

Table 8. The T-test of the Sample Pairs

		Paired Differences					**t**	**df**	**Sig. (2-tailed)**
					95% Confidence Interval of the Difference				
		Mean	Std. Deviation	Std. Error Mean	Lower	Upper			
Pair 1	Total delay (before) – Total delay (after)	45.15	27.08	8.56	25.78	64.52	5.27	9.00	0.001
Pair 2	Average queue length (before) – Average queue length (after)	56.45	34.29	10.83	31.96	80.94	5.21	9.00	0.001

7. Conclusion

Through development in daily works of humans, artificial intelligence has successfully been presented to be used in industries, computer sciences, and transportation systems. From this perspective, experts proposed fuzzy logic to improve traffic congestion in urban areas. According to previous studies, there are many uncertain and vague variables with uncertain mathematical analysis. Hence, a system was needed to predict and control the problems of uncertainty. The fuzzy inference system which simulates the human experience with the use of membership functions and fuzzy rules was then applied from input to output variable space.

At the beginning of the study, delay and average queues of the vehicles at intersections were discussed based on the recent methods. After proposing the fuzzy controller system, effective variables of total delay and average queue length including speed, volume, and total stop were evaluated using Matlab software. Finally, the results indicated that the fuzzy logic controller could be an appropriate tool for classifying the intersections based on the optimum total delay and the average queue with high accuracy. Additionally, by a comparison between the fuzzy controller and fixed-time systems, it was revealed that this actuated system obtained optimized amounts of the total delay and average queue permanently in local intersections by significantly reduced percentage.

Therefore, according to the sensitivity analysis, it was inferred that the fuzzy logic controller was apparently more effective than the fixed-time controller in optimizing and improving the operational characteristics of the urban intersections.

8. Limitations of the study and suggestions for further research

The variability of human knowledge and common sense is considered as a limitation of this study. Increasing the data size, the design process of fuzzy logic controller becomes more complex and variability of the data enlarges fuzzy rules in a large space, as well. In addition, fuzzy rule and membership function cannot be rewritten according to the large data. Therefore, the accuracy and reliability cannot be determined. Other studies may modify the fuzzy controller by applying a combination of artificial neural networks and evolutionary algorithms in the future. It is believed that the dynamic and static performance of the fuzzy controller system can be improved using such networks and algorithms.

Due to the important roles of the intersections in urban transportation, it is perceived important to detect the problems at their performance characteristics. Fuzzy logic would help experts and engineers to design and control urban intersections. In the future, it is possible to use fuzzy logic in all the transportation systems and control parameters which affect the urban infrastructures and in doing so, to construct a smart city with the most optimal costs such as monitoring behavior of the drivers, automatic timing buses in stations and selecting the optimum signals for the light traffics. Future studies may also investigate the functional variables of the intersections on pollution emission and fuel consumption in the form of linear or nonlinear analytical equations.

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