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Coordinated signal control for arterial intersections using fuzzy logic

Research Article

Davood Kermanian[12]*, Assef Zare[12], Saeed Balochian[1]†

1 Department of Electrical Engineering, Islamic Azad University, Gonabad Branch

2 Gonabad / Khorasan-e-Razavi, 96916-29, Iran

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Abstract: Every day growth of the vehicles has become one of the biggest problems of urbanism especially in major cities. This can waste people's time, increase the fuel consumption, air pollution, and increase the density of cars and vehicles. Fuzzy controllers have been widely used in many consumer products and industrial applications with success over the past two decades. This article proposes a comprehensive model of urban traffic network using state space equations and then using Fuzzy Logic Tool Box and SIMULINK Program MATLAB a fuzzy controller in order to optimize and coordinate signal control at two intersections at an arterial road. The fuzzy controller decides to extend, early cut or terminate a signal phase and phase sequence to ensure smooth flow of traffic with minimal waiting time and length of queue. Results show that the performance of the proposed traffic controller at novel fuzzy model is better that of conventional controllers under normal and abnormal traffic conditions.

Keywords: Intelligent Transportation System (ITS) • State-space equation • Fuzzy logic controller • Preset time controller

1. Introduction

Traffic signal control has been one of the most active research areas in intelligent transportation systems (ITS), because such control directly affects the efficiency of urban transportation systems. For years many investigators have conducted research into optimal signal control algorithms. Many optimization algorithms have been researched for an isolated intersection, such as actuated control and fuzzy control, and they show successful improvement indeed. But do these methods still work well when putting several unstable intersections along an arterial? The answer is no, and traffic jam will happens. This is a common scenario in big cities. Current control methods typically cannot accommodate heavy or highly uneven traffic well. Traffic control system is a non-linear, fuzzy, uncertain system and this is why the old methods of modeling and controlling cannot work for solving the traffic control problems. By everyday development of computer technologies, dramatic progress took place in the case of artificial intelligence. These methods include: fuzzy logic, neural network, evolutionary algorithms, and reinforcement learning which used engineering sciences. There have been many studies done related to fuzzy logic controller for signalized intersection [?]. It seems that by changing the viewpoint on artificial intelligence, new ways could be taken for controlling the traffic [5]. First, Pappis

*E-mail: d.m.kermanian@gmail.com
†E-mail: Saeed.balochian@gmail.com

and Mamdani considered the control of an isolated intersection with simple one-way east-west/north-south traffic control with random vehicle arrivals and no turning movements. The macroscopic model is deployed in this fuzzy controller for modeling the queue length and estimating the delay time. The delay time of the vehicles using the above mentioned fuzzy controller, is reported satisfactorily in comparison with a fixed time controller (in the vast bounding of the input volume for each path) [6]. Fuzzy rules were developed for evaluating the suitability of extending a current green phase by different time durations based on a computed measure of "degree of confidence". Nakatsuyama used fuzzy logic to model the control of two adjacent intersections with one-way movements [7]. Fuzzy control rules were developed to select an option of extending the red signal or the green signal for the downstream intersection in anticipation of the upstream traffic. Chiu applied fuzzy logic for controlling multiple intersections in a network of two-way streets with no turning movements by adjusting cycle lengths, phase splits, and offset parameters based on local information alone [8]. A number of adaptive traffic control systems have been deployed all over the world, such as SCOOT [9], SCATS [10], OPAC [11], and RHODES [12]. In recent years, artificial intelligence techniques have been introduced into signal control using fuzzy logic controllers and genetic algorithms (GA) [13]. Qiao and Yang designed a fuzzy logic controller for a signalized intersection that has two-stages. At the first stage, a green phase selector has been developed to select the subsequent green phase. At the second stage, a green time adjustor has been proposed to determine the green time for the selected phase. An offline genetic algorithm (GA) has been developed to optimize the fuzzy rules and membership functions of the two controllers [14]. Studying the above mentioned article, we find out that the maximum green time is considered as a restricting factor. At the end of this time, despite servicing demands in the current green phase and controller decision based on green phase extension, due to the end of this maximum green time, current green phase comes to its end. The undemanding results in some of these articles represent these major problems [?]. The research reviewed above generally reported a better performance of fuzzy logic controllers compared to preset time and actuated controllers. However, most of the reviewed research studies control over isolated intersections and the fuzzy controllers are not designed to be used in crowded arterial. In this search, state-space equations are used to formulate the signal control problem for a single intersection in a simplified mathematical model, which can lead to designing better signal controller [18]. Modeling of systems is a very essential concept to develop an effective control system and for simulation of a physical process. Fuzzy logic is a distinct idea for developing models of physical processes. Fuzzy models are less externally complex; they can be understood easily and very much suitable for non-linear processes. Models with fewer rules are more advantageous. The main objective of this research is to design a novel fuzzy model based signal controller for two intersections that are close to each other with through and have left-turning movements along an arterial. Fuzzy logic uses the traffic conditions to decide whether to extend or terminate a current green phase. The model is developed using MATLAB 7.8 [19], [20].

2. Structure of arterial and model definition

This section presents a model for describing two intersections along an arterial. The typical structure of an arterial is like the one shown in Fig.1. Gray areas indicate congestion zone. Middle link connecting intersections A and B and every two intersections are considered as a group. Intersections under control of fuzzy logic controller connect one after another.

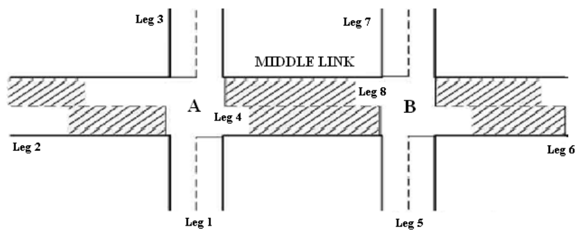

Figure 1. An arterial with two intersections

2.1. Over view

Fig.2 shows the typical case of a four-leg intersection, with lane and vehicle detector configuration. Each leg has through, right-turning and left-turning movements. Inductive loops for vehicle detection are installed on stop-lines and upstream-lines. Detectors can count the number of vehicles through the upstream-line and stop-line within a given time interval. To detect left-turning vehicles, vision detectors are placed on the side of left-turning bays. Using vision detectors the controller measures approach flows and estimates approach queues at regular time intervals. These detectors can detect the vehicle appearance and count the number of the vehicles driven in to left-turning bays, and also queue length estimation of lanes is given. As a simplification, right-turning vehicles are not taken into account, neither in detection nor calculation.

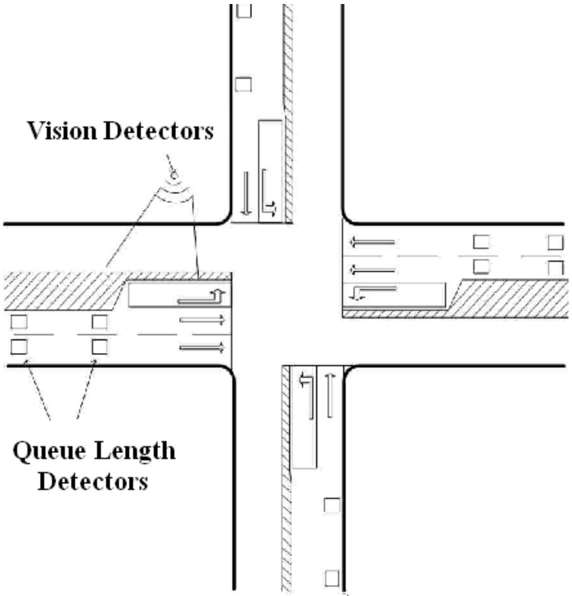

Figure 2. An intersection with typical detectors and lane configuration

For each intersection a two-phase signal is adopted. In a cycle, each leg goes through two time intervals, the green interval during which vehicles on this leg can proceed through the intersection, and the red interval. Fig.3 shows the diagram for a two-phase signal.

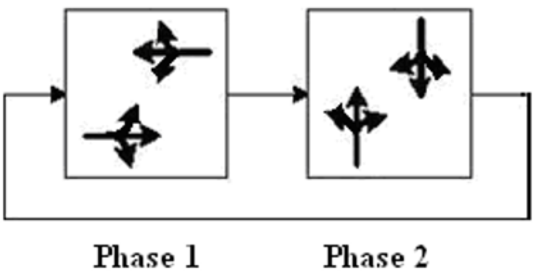

Figure 3. Phase diagram for two-phase signal

2.2. State-space equation

The queue length is an important variable that describes the traffic state of an intersection. The queue evolves as

$$Q_i(n+1) = Q_i(n) + q_i(n) - d_i(n)S_i(n) \quad (1)$$

Where $Q_i(n)$ in unit of number of vehicles, is the queue length of the i^{th} stream at the onset of the n^{th} time interval; $q_i(n)$ is the number of vehicles that join the i^{th} queue in the n^{th} time in-terval; $d_i(n)$ is the number of vehicles that depart from the i^{th} queue in the n^{th} time interval; and, $S_i(n)$ is the signal state of the i^{th} stream in the n^{th} time interval. q_i and d_i are normally distributed random signals. Integrating the length of queue with respect to time yields the average vehicle's waiting time in the queue. Let T denote the length of the discredited time interval. If T is short enough, the vehicles arrivals can be treated as being uniform in every time interval. Hence, integrating (1) yields

$$W_i(n+1) = W_i(n) + TQ_i(n) + \frac{1}{2}Ts_i(n) - \frac{1}{2}Td_i(n)S_i(n) \quad (2)$$

Where $W_i(n)$ is the average vehicle-wise waiting time of the i^{th} queue from the beginning of the period to the onset of the nth time interval. Equations (1) and (2) are the state-space equations describing the dynamic evolution of the traffic state at a single intersection. Performance measurement should be chosen according to control policy, which is different with different traffic situation. The waiting time and the number of vehicles are popular performance indices for signal controls. Therefore, the optimization objective is

$$min\{W(n) = \sum_{i=1}^{M} W_i(N)\} \quad (3)$$

$$min\{Q(n) = \sum_{i=1}^{M} Q_i(N)\} \quad (4)$$

where $i = 1,2,Ě,M$ is the index of the traffic streams; $n = 0,1,..., N-1$ is the index of the discredited time intervals; To facilitate the formulation, the state-space equations and the optimization objective can be rewritten in matrix form as

$$X(n+1) = AX(n) + B(n)S(n) + C(n) \quad (5)$$

$$y(n) = XC(n) \quad (6)$$

Where $X(n) = [Q_1(n)Q_2(n)...Q_M(n)W_1(n)W_2(n)...W_M(n)]^T$ are the state variables, $y(n)$ is call the output matrix and $S(n) = [S_1(n)S_2(n)...S_M(n)]^T$ are the control variable. The various coefficient matrices and vectors are [18].

$$A = \begin{bmatrix} I_M & 0 \\ TI_M & I_M \end{bmatrix},$$

$$B(n) = -\begin{bmatrix} d_1(n) & 0 & \cdots & 0 \\ 0 & d_2(n) & \cdots 0 & \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & d_M(n) \\ \frac{1}{2}Td_1(n) & 0 & \cdots & 0 \\ 0 & \frac{1}{2}Td_2(n) & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \frac{1}{2}Td_M(n) \end{bmatrix},$$

$$C = \begin{bmatrix} I_M & 0 \\ 0 & I_M \end{bmatrix},$$

$$C(n) = [q_1(n)q_2(n)...q_M(n)\frac{1}{2}Tq_1(n)\frac{1}{2}Tq_2(n)...\frac{1}{2}Tq_M(n)] \tag{7}$$

where I_M is the unit matrix of size M and T is sampling time. The number of vehicles that depart from the i^{th} queue in the n^{th} time interval is adapted by equation [21].

$$d_1(n) = mkin(Q_i(n) + q_i(n), d_{si}(n)) \tag{8}$$

Such that saturation flow rate is

$$d_{si}(n) = d_{cos}(n) + \beta q_i(n) \tag{9}$$

For *i=1,2,...,8*. The d_{cons}. parameter is greater than or equal to ten, ($d_{cons} \geq 10$). The parameter β is between 0 and 1; such that its variations are related to follows Table2.2. The qi and di variables are normally distributed random signals in this fuzzy model.

Table 1. The position of traffic by variable of β [21]

Position of Traffic	β
Normal	$\beta \geq 0.7$
Saturation	$0.4 \leq \beta \leq 0.6$
Unstavle (Jam)	$\beta = 0$

3. Novel fuzzy model using adjacent information

Interaction of intersections on arterial is achieved by taking adjacent information into calculation when applying fuzzy logic control on one intersection, and this optimization is applied in every intersection on arterial. The arterial is linked up by intersections and their adjacent. Existent traffic prevention approaches can be categorized as follows [22]:

- Global Strategies: the considered global strategies are a "synchronized strategies", a "green wave strategies". In the case of synchronized strategy all traffic lights switch synchronously to green (red) for the east (north) bound vehicles and vice versa. In the case of green wave strategy adjacent traffic lights switch with defined offset. Additionally, an appropriate offset has to be determined for the green wave strategy; this is equal to the free flow travel time for the depicted case.
- Adaptive Strategies: In the following three different adaptive strategies are presented. The first investigated adaptive strategy is the "switching based on the queue length". Here a traffic signal switches if the length of a vehicle queue in front of a red light trespasses a certain value. Further investigated adaptive strategy is the "switching based on waiting time". In this case a traffic light switches to red if the green phase is not used by a vehicle for a certain time [23, 24].

In the proposed controller, traffic flow data of intersection and its adjacent are collected and evaluated every refresh cycle to decide whether to extend the current phase or make an early cut or terminate. Using two-phase signal control, evaluation of each phase is carried out sequentially.

3.1. Input and output parameters

The first stage of fuzzy modeling is the selection of performance variables. The aim of this part is to optimize the signal timings considering traffic flows and allocated green times. So, firstly the decision variables are determined, and observations about these parameters are carried out in signalized junctions. Input and output parameters of fuzzy logic signal time controller are explained below. (1) LQRS: The longest of the queues in red signal in A and B intersections. This parameter determines the leg of an intersection which has the longest queues. Membership functions of this parameter are determined using trapezoidal fuzzy membership functions exhibit in Fig.4. Membership functions of this parameter are represented with three sub-sets: "Normal", "Saturation", and "Jam".
(2) AJGS: Arrivals to junction during green signal in each intersection. Arriving vehicles during green signal is selected as the second input parameter of the fuzzy logic

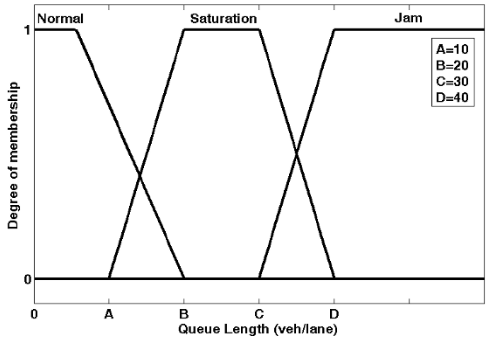

Figure 4. Fuzzy membership functions for LQRS

signal time controller. The membership functions of this parameter are represented with three sub-sets: "Few", "Many", and "Too many" (Fig.5).

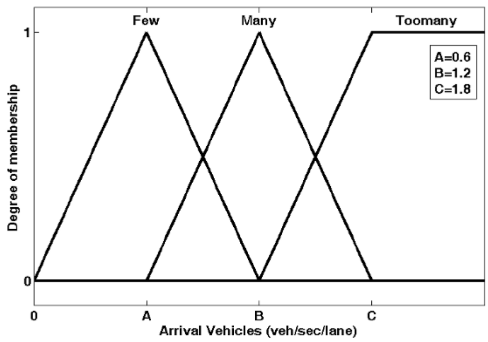

Figure 5. Fuzzy membership functions for AJGS

(3) AVWT: Average vehicles-wise waiting time in A and B intersections. This parameter is selected as the third input parameter of the fuzzy logic signal time controller and represented with three sub-sets: "Low", "Medium" and "High". The graphical representation of this variable is shown in Fig.6.

(4) SSI: State signal indicator in each intersection considered output parameter. Membership functions of this parameter are determined using theoretical structure of signal control membership functions of the parameter are shown in Fig.7.

The configuration of these membership functions is done according to expert observation of the system and environment. Also width and center of the membership functions of these fuzzy subsets can be easily changed and configured according to different traffic environment and conditions. The structures of these memberships are not fixed and can be changed by depending on the traffic state

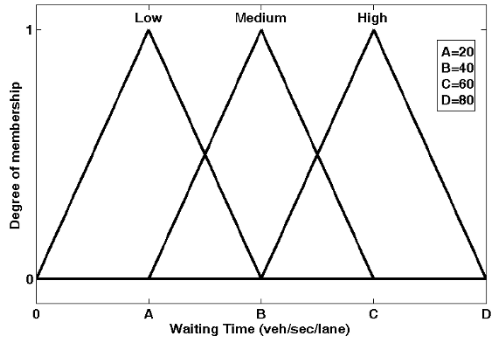

Figure 6. Fuzzy membership functions for AVWT

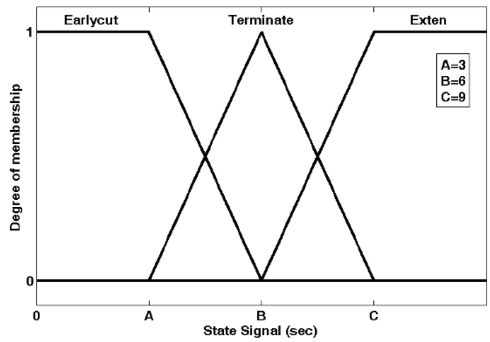

Figure 7. Fuzzy membership function for SSI

for this congestion. Also we can add other memberships which affect the traffic flow, for example we can take the weather state as another membership which is one of the important factors that causes traffic problem. Each intersection can be positioned in different traffic situation such as: normal, saturation, or jam. If the waiting vehicles almost cover the surface of road, and new vehicles join the queue incessantly, a traffic jam is very possible to happen. Fuzzy logic is used to make the inferences with similar reasoning with arrival rate and queue length. Therefore in this study, control strategy is identified based on traffic condition of the two intersections. Fig.8. shows the intended fuzzy model of the traffic network.

3.2. Fuzzy rules

Fuzzy rules work like humans intelligence to decide the optimal choice for the problem which try to solve it. The rules are formed from the available inputs-outputs data sequences of the urban traffic network, based on if-then statement. The general format of the fuzzy rules of controller is as follows:

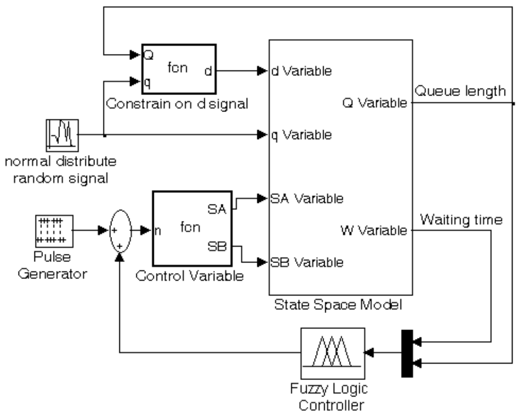

Figure 8. Block diagram proposed fuzzy model

$$
if \begin{bmatrix} Q_A is & x_1 \\ Q_B is & x_2 \end{bmatrix}, and \begin{bmatrix} AR_A is & y_1 \\ AR_B is & y_2 \end{bmatrix},
if \begin{bmatrix} W_A is & z_1 \\ W_B is & z_2 \end{bmatrix}, if \begin{bmatrix} S_A is & h_1 \\ S_B is & h_2 \end{bmatrix}. \quad (10)
$$

Where x_i, y_i, z_i and $h_i (i = 1, 2)$ are linguistic variables that were described in pervious section. The number of fuzzy rules depends on the combination of the fuzzy sets for input data. In this study, for control strategy jam-normal (A intersection is in jam situation and B intersection is in normal), there are 81 rules for each state. Some fuzzy control rules are shown in table 2. These rules designed by rule editor also found in MATLAB toolbox and can be changed until reaching to the best solution for the problem. Also the basic operation options found in the editor (AND, OR, NOT). By using these options during making the rules we have the whole control to play with estimated result. This is an important point since different traffic have different structures and then the rules that set for one of them may not be appropriate for the other.

4. Simulation result

The results of all implemented simulations in this study are carried out using Fuzzy Logic Tool Box. The Fuzzy Logic Tool Box is useful to build quickly the required rules and changes are easily made. Also, the structure of controller membership functions can be easily changed so as to achieve the best answer to the problem. This significantly reduces the development time of the simulation model.

Table 2. Results for the determination of V in ten real samples and two reference materials

Row	Input						Output	
number	Q_A	Q_B	AR_A	AR_B	W_A	W_B	S_A	S_B
1	N	N	F	F	L	L	T	T
2	N	N	M	F	Me	L	T	Ea
3	S	N	M	M	Me	Me	Ex	T
4	S	S	M	M	Me	Me	Ex	Ex
5	J	N	M	F	H	L	Ex	Ea
6	J	N	To	M	H	Me	Ex	T
7	J	N	To	M	H	H	Ex	Ex

N: Normal, S: Saturation, J: Jam, F: Few, M: Many, To: Too many, L: Low, Me: Medium, H: High, Ea: Early cut, T: Terminate, Ex: Exten

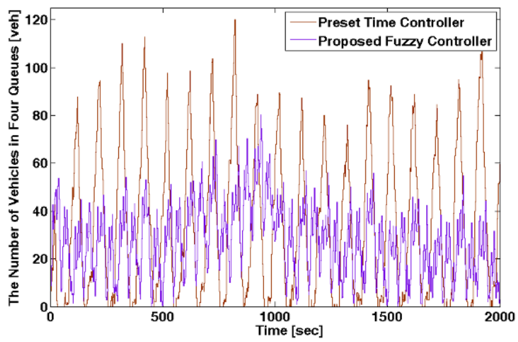

Figure 9. The number of vehicles in four legs in A intersection

4.1. Fuzzy intelligent controller

In this controller, the traffic light is sensitive to traffic movement and the green time scope of each phase (which is already determined) depends upon the volume of the traffic in the roads of that phase. Green time is set by

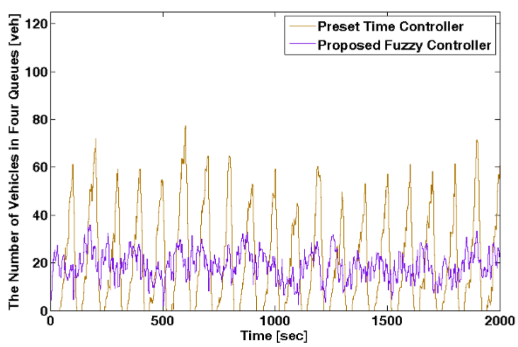

Figure 10. The number of vehicles in four legs in B intersection

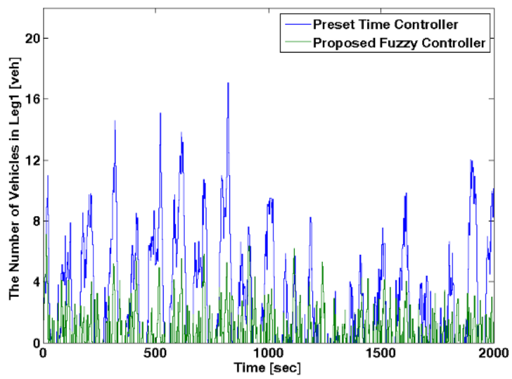

Figure 11. The number of vehicles in Leg1

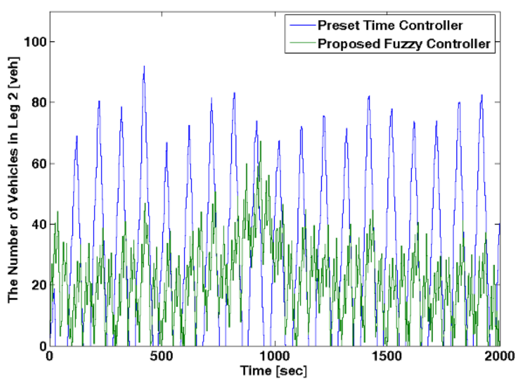

Figure 12. The number of vehicles in Leg2

placing detectors on the approaches which all lead to the intersection, and are placed in certain distance from the stop line. The designed intelligent controller is able to control and optimize the traffic flow in the intended network in different situations including jam-normal (A intersection is in jam situation and B intersection is in normal). If traffic state of B intersection is normal, decision making will allow more traffic enter the normal intersection if local traffic pressure is considerable. Consider A intersection is in a traffic jam, and then fuzzy rules should make some changes accordingly. In this case, if the intersection takes action without knowing the neighboring information, it may influx more vehicles into the congested links and brings a more serious congestion to it, and this congestion will finally spread to itself. So, if traffic jam is detected, fuzzy controller should act correspondingly to reduce the pressure of adjacent intersection. In the design of the fuzzy traffic lights controller, we consider 2 main features: first, to reduce the total delay time of waiting vehicles as well as to avoid heavy traffic congestion and second, to synchronize the local traffic controller with its neighbors, such as controlling the outgoing vehicles into neighboring traffic controllers. If the number of incoming vehicles overruns the capacity of the intersection, that congestion would then spread to its neighbors and eventually all nearby intersections will be jammed. The fuzzy traffic lights controller is designed with a number of useful features not found in existing traffic lights controller. One example is that if a large volume of vehicles are congested at a neighboring intersection, the number of vehicles coming into that intersection will be reduced. The following are the hypotheses in carrying out the designed simulation system:

1. All the simulations were carried out during 2000 seconds and the traffic information was also recorded every 2 second (sampling time) and was used in the simulation.

2. Regarding the received information from the detectors of the vehicles which were placed in certain distance (the maximum vehicle that can be detected queuing is 35 vehicles), the queue length, the arrival rate and the mean waiting time were measured in each intersection. Then the controller determines the minimum green time and phase sequent of intersection (this time is 10 seconds in A intersection and 8 seconds in B intersection).

3. When the minimum green time ends, based on the level of intersection crowdedness and whether demands for servicing continue, the time in the current green phase re-extends to certain duration (the duration is measured as a discrete quantity between 0-8 seconds in A and 0-6 seconds in B intersection).

4. After the end of the extended time, the controller evaluation the level of demands based on the received data from sensors, and if necessary, the green time of the current phase can be extended to its maximum. When this time ends (even if the traffic of the vehicles continue in approaches of that phase), the traffic light in the mentioned phase turns red and the green time is applied to the other approach and this cycle is repeated.

4.2. Preset time controller

This type of traffic control has preset time for green and red light for each phase, and the duration of each phase in one cycle is set according to its program. This preset time does not change according to the conditions of

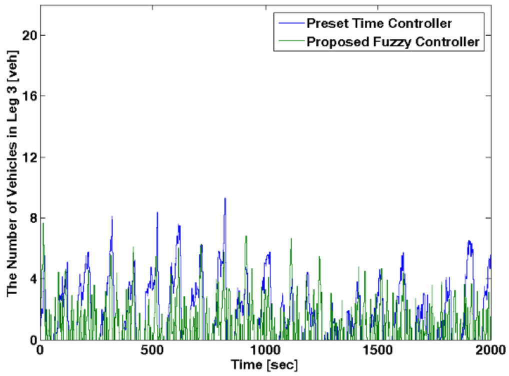

Figure 13. The number of vehicles in Leg3

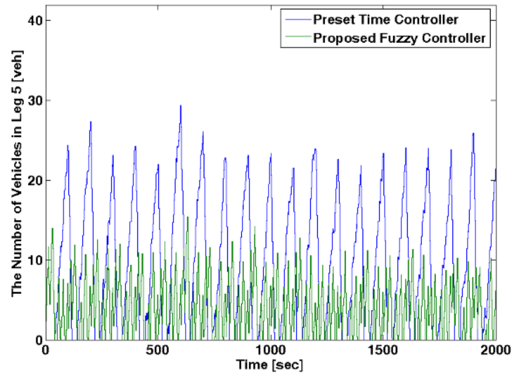

Figure 15. The number of vehicles in Leg5

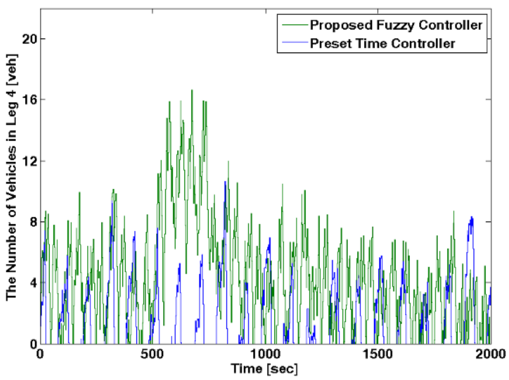

Figure 14. The number of vehicles in Leg4

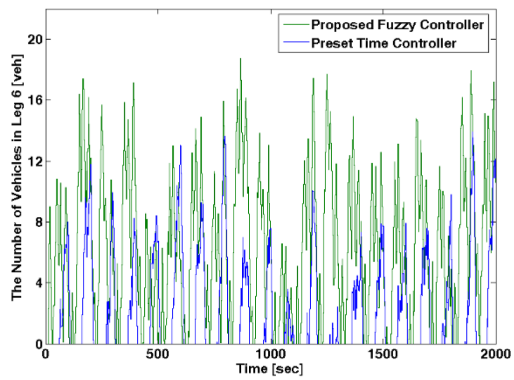

Figure 16. The number of vehicles in Leg6

the traffic flow. The disadvantage of this method is that if there is congestion in a particular road at a junction, the green lights will not be extended and the next phase is continued without considering the density of the cars at any of the junction. In open-loop model, in designing preset time controller with considering cycle length (100 sec); and offset (16 sec) between the two intersections in order to coordinate the traffic flow, in Leg1 and Leg3 the traffic light is set green in the first 40 seconds and red in the next 60 seconds. The traffic light in Leg2 and Leg4 is set green in the first 60 seconds and red in the next 40 seconds. In the adjacent intersection, in Leg5 and Leg7 the light is set green in the first 40 seconds and red in the next 60 seconds. In Leg6 and Leg8 the light is set green in 60 seconds and red in 40 seconds. The summation of number vehicles in queues in different situations including jam-normal (A intersection is in jam situation and B intersection is in normal) were demonstrated in Figs.9-10. Results show that in the mass the proposed fuzzy model performs the best. When traffic volume is low and no congestion happens, results show that neighboring information does not affect control action. Also, Figs 11-18 show what happened in each leg of the intersections.

Table 4.2 and Table 4.2 show the comparison of the results of implementing fixed-time controller and fuzzy logic controller in improving the queue length and the average waiting time of the vehicles in an urban traffic network during simulation time 2000 seconds.

5. Conclusion

The fuzzy model of urban traffic network was designed for two intersections on an arterial, with the length of queues and average waiting time vehicles in any lane as the state of variables. To demonstrate the percentage of improvement traffic, a Fuzzy signal controller was designed. Fuzzy logic signal controller using local and

Table 3. The Compare of Results Queues Length in Two Control Methods

Performance \ Index	Summation of Vehicles in A Intersection(veh)	Summation of Vehicles in B Intersection(veh)
Preset Time Control	17145	10705
Fuzzy Intelligent Control	11323	5948
Improvement Percentage	33.95%	44.43%

Table 4. The compare of Result Average Waiting Time in four Leg

Performance \ Index	Average Waiting Time in A Intersection(sec)	Average Waiting Time in B Intersection(sec)
Preset Time Control	8187.39	5148.29
Fuzzy Intelligent Control	5254.13	3384.99
Improvement Percentage	35.82%	34.25%

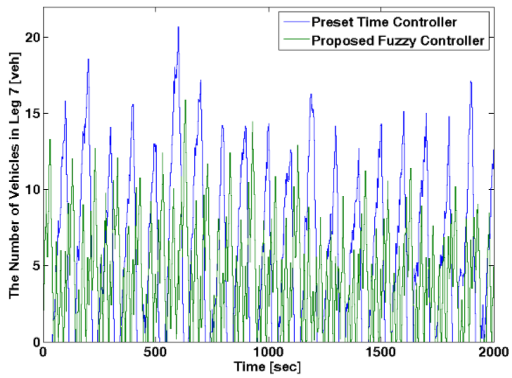

Figure 17. The number of vehicles in Leg7

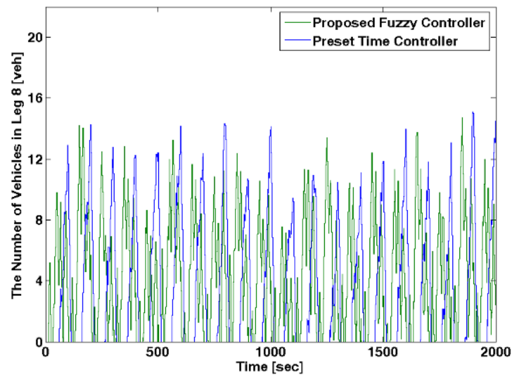

Figure 18. The number of vehicles in Leg8

neighboring intersections traffic information to achieve coordinated signal control for different traffic situation such as: normal, saturated, or jammed. The research demonstrates that taking the neighboring traffic information into account and applying the interactive control on the calculations has a positive effect once congestion occurs in an arterial intersection. Control action should change to prevent a more serious traffic jam. The controller was tested using Simulink program on MATLAB 7.8. Simulation results show that under congested situation, the fuzzy logic controller can improve the summation of number vehicles in queues and reduces the average waiting time vehicles in any lane both intersections compared to preset time control. It seems that investigation into heuristic methods of solving the developed optimal control problem based on the state-space equations should be done in the future.

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