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Ultimately Bounded Takagi-Sugeno Fuzzy Management in Urban Traffic Stream Mechanism: Multi-Agent Modeling Approach

Reza Ghasemi, Negin Amiri Hazaveh

Abstract**—**In this paper, control methodology based on the selection of the type of traffic light and the period of the green phase to accomplish an optimum balance at intersections is proposed. This balance should be flexible to the static behavior of time, and randomness in a traffic situation; the goal of the proposed method is to reduce traffic volume in transportation, the average delay for each vehicle, and control over the crash of cars. The proposed method was specifically investigated at the intersection through an appropriate timing of traffic lights by sampling a multi-agent system. It consists of a large number of intersections, each of which is considered as an independent agent that exchanges information with each other, and the stability of each agent is provided separately. The robustness against uncertainties, scalability, and stability of the closed-loop overall system are the main merits of the proposed methodology. The simulation results show that the fuzzy intelligent controller in this multi-factor system which is a Takagi-Sugeno (TS) fuzzy is more useful than scheduling in the fixed-time method and it reduces the lengths of vehicles queuing.

Keywords**—**Fuzzy intelligent controller, traffic-light control, multi-agent systems, state space equations, stability.

I. Introduction

TRAFFIC congestion is a significant issue in big cities. It is typically caused by an inappropriate control of traffic lights which is not corresponding to the ongoing traffic situation surrounding the road intersection [1]. Traffic control is a challenging problem when it comes to the application of computational intelligence in the real world. The development of an effective approach to control traffic light is indispensable when the number of vehicles in the urban network increases fast [2].

In the last few years, the number of papers devoted to applications of multi-agent systems (MASs) technologies in traffic and transportation because of its physically spread landscape and its flashing busy-idle effective features has grown hugely [3], [4]. The reason of the increasing achievement of this approach is that there is a developing discussion over how to model and enhance traffic flow and transportation systems at both micro and macro level. From the traffic and transportation point of view, the most interesting characteristics of agents are independence, partnership, and reactivity. These structures are valuable for applying intelligent traffic mechanism and management systems. Moreover, agent-based traffic management systems let spread subsystems collaborating with one another with the aim of controlling traffic based on simultaneous situations [3]-[6].

A distributed vehicle monitoring test-bed proposed is a primary example of the distributed problem-solving network. The idea of agent and activity-based demand generation coupled to traffic simulation was also transferred to the simulation of commercial vehicles delivering goods in an urban environment [7], [8]. Garcia-Serrano et al. [9], Tomas and Garcia [10] and Chen et al. [11], [12] focus on MASs to design, detect and manage roadway traffic and also are compliant with the IEEE Foundation for Intelligent Physical Agents (FIPA) standards. In [9], numerous knowledge-based recommendation (TRACK-R) traffic agents are planned to offer traffic method commendation for humans. Authors in [10] propose MASs to assistance traffic operators elect the best traffic policies for dealing with nonurban roadway climatological happenings.

The agents in these two systems are applied by the Java Agent Development Framework (JADE) [13]. Supreme issued agent-based requests in traffic and transportation systems focus on developing MASs that contain of multiple distributed static agents. Mobile agent apparatus has not been widely applied on this region. To validate the great value of mobile agents to intelligent transportation systems (ITSs), authors in [11] and [12] joins portable agent information with MASs to advance the flexibility of large-scale traffic control and society systems. Wang [3], [4] advanced an agent-based networked traffic-management system to attain flexible and intelligent control of traffic and transportation systems. The agent-based mechanism decomposes a complicated control algorithm into simple task-oriented agents which are distributed over a network. In this study, a fuzzy intelligent controller to achieve an optimal balance at 9 intersections is proposed. Recently, fuzzy logic has been applied by several investigators in the field of traffic management.

Reference [14] attempts to apply fuzzy logic on traffic mechanism. They employed an insulated signalized intersection that contains two one-way streets with two paths without rotating circulation. Moreover, [15] imitates a simple two-phase signal control of an isolated intersection with one path on each approach. The fuzzy logic performed better than both pre-timed and actuated organization, especially when the traffic flow between different directions was highly unbalanced.

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Reference [16] planned a fuzzy logic approach for a signalized intersection with left-turning traffic. Traffic capacities and lengths of line counted by detectors were used in a two-stage fuzzy system to lengthen or terminate the current signal phase. In [17] a fuzzy logic controller (FLC) pretends the expert human traffic controllers who replace signal controls at over-saturated intersections during special events to choose the green phase based on predefined fuzzy rules.

Compared to the recent researches that concentrate on fuzzy controller and multi-agent approaches for traffic management regardless of stability of the overall system, the proposed approach deals with fuzzy traffic super vision based on MAS with guaranteed stability.

The rest of this paper is categorized as follows: In Section II mathematical models of intersection are described. The stability analysis is mentioned in Section III. In Section IV designation of fuzzy intelligent controller is described in detail. Simulation results are mentioned in Section V. Finally, Section VI concludes this paper.

II. Mathematical Models in Intersection

A. Mathematical Model of an Intersection

Fig. 1 shows an intersection that has four paths. Leg1, leg3 are the first phase, and leg2, leg4 are the second phase.

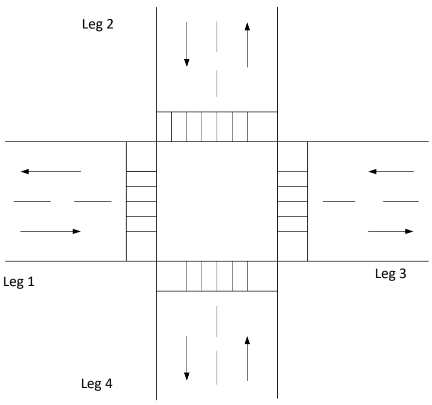

Fig. 1 Two phases signalized intersection

At an intersection, the length of the vehicle's queue is one of the main parameters in the flow of traffic, which is as (1) [18]:

$$Q_i(n+1) = Q_i(n) + q_i(n) - d_i(n)s_i(n) \tag{1}$$

where $i = 1,2,3,4,...,n$ is the index of the leg that enters the intersection. Moreover, $n = 0,1,...,N-1$ is the index of discrete time intervals. N is the horizons of simulation, $Q_i(n)$ is the length of the queue of vehicles, $d_i(n)$ is the number of vehicles leaving the queue, $q_i(n)$ is the number of vehicles entering the queue, and S_i is a control signal that depicts the status of the traffic light in the legs. Furthermore, $d_i(n)$ and $q_i(n)$ are distributed normal random signals. The state $S=1$ refers to green light and vehicle movement and $S=0$ refers to the red light and the stop in the vehicle. Fig. 1 shows two phases signalized intersection in which $s_1 = s_3 = 0$ and $s_2 = s_4 = 1$ refer to the red light in the first and third leg and green one in the second and fourth leg. Consequently, the state $s_1 = s_3 = 1$ and $s_2 = s_4 = 0$ refer to the red light in the second and fourth leg and it is green in the first and third leg. If T is considered as the discretized time interval and is short enough, then the vehicle arrivals can be assumed uniform in every time interval and as a result, the overall waiting time of vehicles is achieved as (2) [19]:

$$\begin{aligned} W_i(n+1) = {} & w_i(n) + T\,Q_i(n) - 1/2T\,d_i(n)s_i(n) \\ & + 1/2T\,q_i(n) \end{aligned} \tag{2}$$

For further details, the intersection state-space equations can be written as (3):

$$\begin{cases} X(n+1) = AX(n) + B(n)S + C(n) \\ Y(n) = CX(n) \end{cases} \tag{3}$$

where $X(n) = [Q_1(n)Q_2(n)....Q_M(n)W_1(n)W_2(n)..W_M(n)]^T$ is the vector of variables of mode and $S(n) = [S_1(n)\,S_2(n)....S_M(n)]^T$ are control variables.

Other matrices of coefficients and vectors are as follows:

$$C = \begin{bmatrix} I_M & 0 \\ 0 & I_M \end{bmatrix}$$
$$A = \begin{bmatrix} I_M & 0 \\ TI_M & I_M \end{bmatrix}$$
$$B(n) = -\begin{bmatrix} d_1(n) & 0....................0 \\ 0 & d_2(n)....................0 \\ \vdots & \vdots \\ 0 & 0.....................d_M(n) \\ 1/2Td_1(n) & 0............0 \\ 0 & 1/2Td_2(n)............0 \\ \vdots & \vdots \quad \vdots \\ 0.......0 & ....1/2Td_M(n) \end{bmatrix} \tag{4}$$
$$C_n = [q_1(n)q_2(n)...q_M(n)1/2Tq_1(n)1/2Tq_2(n)....1/2Tq_M(n)]^T$$

B. Mathematical Model of Multi-Agent Intersections

Fig. 2 shows multi-agent intersections linked to each other.

When the intersections are connected, all the parameters of $Q_i(n), W_i(n)$ and all the matrices of the coefficients are similar to the intersection and their only difference is in the state-space equations, which is based on the Kronecker product as (5):

$$\begin{cases} X(n+1) = (I_M \otimes A_i)X(n) + (I_M \otimes B_i)S(n) + \underline{1}.C_i \\ Y(n) = CX(n) \end{cases} \tag{5}$$

III. Designing Stable TS Fuzzy Controller for Multi-Agent Intersections

The fuzzy controller can take the number of different inputs with different outputs. The control system utilized in this study is the TS fuzzy system, which has three inputs and one output. The inputs of the controller include the length of the queue and the number of input and output vehicles to the leg. In the first phases (legs 1 and 3) we will have $\left(Q_1(n)+Q_3(n)\right., Q_2(n)+Q_4(n), d_1+d_3, \left.q_1+q_3\right)$ and in the second phases (legs 2 and 4) we will have $\left(Q_1(n)+Q_3(n)\right., Q_2(n)+Q_4(n), d_2+d_4, \left.q_2+q_4\right)$.

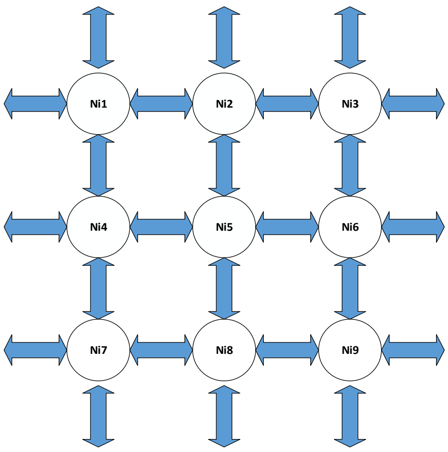

Fig. 2 Multi-agent two-phase signaled intersection

Q_1, Q_2, Q_3 and Q_4 are buffers that represent the relationship between intersections and the output of each controller respectively is S_1 and S_2 (green phase renewal time). The general format of the fuzzy rules is as follows:

If $\{\left(Q_1(n)+Q_3(n)\right)$ is x_1, $\left(Q_2(n)+Q_4(n)\right)$ is x_2, $\left(d_i+d_j\right)$ is x_3, $\left(q_i+q_j\right)$ is x_4, $Q_i(n)$ is x_5, and $Q_j(n)$ is x_6 then $\left(S_i \text{ is } y\right)$ where $y=f(u)$ is a constant function that gets the value of 0 or 1. Zero indicates that the traffic lights are red and the vehicles will stop and one indicates that the vehicle is moving. So low (L), high (H) and medium (M) stand for fuzzy membership function for input and output number of the vehicles in each intersection. It is assumed that the number of the vehicle in each leg is bounded and consequently, each leg contains bounded buffer.

The number of rules used in each Controller is 37. Input membership functions for the length of the queue are considered as triangular in the interval [0 100] and the number of input and output machines are in the form of triangles [0 5] and open for buffers used [0 200] is selected. The parameters $Q_i(n)$ and $S_i(n)$ for i = 1,2,3,4 represent four legs in each set. A sample of the rules of the fuzzy controller in leg 1,3 is as follows:

If $\left(Q_1(n)+Q_3(n) \text{ is } H\right)$, $\left(Q_2(n)+Q_4(n) \text{ is } H\right)$, $\left(d_1+d_3 \text{is } H\right)$, $\left(q_1+q_3 \text{is } L\right)$, $\left(Q_1(n) \text{ is } L\right)$ and $\left(Q_3(n) \text{ is } L\right)$ then $(S_1 \text{is } 1)$ (6)

A sample of the rules of the fuzzy controller in leg 1,3 is as follows:

If $\left(Q_1(n)+Q_3(n) \text{ is } M\right)$, $\left(Q_2(n)+Q_4(n) \text{ is } M\right)$, $\left(d_2+d_4 \text{is } H\right)$, $\left(q_2+q_4 \text{is } L\right)$, $\left(Q_2(n) \text{ is } L\right)$ and $\left(Q_4(n) \text{ is } L\right)$ then $(S_2 \text{is } 0)$ (7)

Similarly, at other intersections, all controllers are similar to the above conditions with suitable inputs and output.

Theorem. Consider the urban dynamical system given in (3), then the controller structure given in (6), (7) makes the states of the system be uniformly ultimately bounded and all signals involved the closed-loop system are bounded.

Proof. Typically, in urban intersections, the control signal is a traffic light that is green or red and if it is green vehicles can enter or leave and during the red phase, the vehicles only can enter the queue. For the green light, the length of the queue and delay are as (8):

$$\begin{cases} Q_i(n+1)=Q_i(n)+q_i(n)-d_i(n) \\ W_i(n+1)=W_i(n)+TQ_i+\frac{1}{2}Tq_i(n)-\frac{1}{2}Td_i \end{cases} \tag{8}$$

where $X_g=\begin{bmatrix} Q_g \\ W_g \end{bmatrix}$ and its state vector is as follows:

$$X_{g(n+1)}=(I_M \otimes A_g)X_{g(n)}+(I_M \otimes B_g)q_i+(I_M \otimes B_g^{'})d_i \tag{9}$$

For red lights, the queuing and delay of vehicle equations are derived in (10):

$$\begin{cases} Q_i(n+1)=Q_i(n)+q_i \\ W_i(n+1)=W_i(n)+TQ_i+\frac{1}{2}Tq_i(n) \end{cases} \tag{10}$$

where $X_r=\begin{bmatrix} Q_r \\ W_r \end{bmatrix}$ and its state vector is shown in (11):

$$X_{r(n+1)}=(I_M \otimes A_r)X_{r(n)}+(I_M \otimes B_r)q_i \tag{11}$$

Now, the suitable Lyapunov function to prove stability should be introduced in this theorem. Since the equations are discrete, then the Lyapunov function is a candidate as (12):

$$V(X)=\begin{bmatrix} X_g \\ X_r \end{bmatrix}^T \begin{bmatrix} P_1 & 0 \\ 0 & P_2 \end{bmatrix} \begin{bmatrix} X_g \\ X_r \end{bmatrix} \tag{12}$$

where P is positive and symmetric and also the difference of the Lyapunov function is as $\Delta V(n)=V(n+1)-V(n)$. Using $(AB)^T=B^TA^T$ and $(A\otimes B)^T=A^T\otimes B^T$ properties than ΔV can be rewritten in (13):

$$\begin{aligned}\Delta V(n) &= X_g^T(n)(I^T{}_M \otimes A_g^T)P_1(I_M \otimes A_g)X_g(n)\\ &+q_i^T(I^T{}_M \otimes B_g^T)P_1(I_M \otimes B_g)q_i\\ &+d_i^T(I^T{}_M \otimes B_g^{'T})P_1(I_M \otimes B_g^{'})d_i +\\ &X_r^T(n)(I^T{}_M \otimes A_r^T)P_2(I_M \otimes A_r)X_r(n)\\ &+q_i^T(I^T{}_M \otimes B_r^T)P_2(I_M \otimes B_r)q_i\\ &-X_g^T(n)P_1X_g(n) - X_r^T(n)P_2X_r(n)\end{aligned} \quad (13)$$

Using (3), the above equation can be rewritten as:

$$\begin{aligned}\Delta V(n) &= ((I_M \otimes A_g)X_g(n) + (I_M \otimes B_g)q_i\\ &+(I_M \otimes B_g^{'})d_i)^T P_1((I_M \otimes A_g)X_g(n) + (I_M \otimes B_g)q_i\\ &+(I_M \otimes B_g^{'})d_i) + ((I_M \otimes A_r)X_r(n)\\ &+(I_M \otimes B_r)q_i)^T P_2((I_M \otimes A_r)X_r(n)\\ &+(I_M \otimes B_r)q_i) - X_g^T(n)P_1X_g(n) - X_r^T(n)P_2X_r(n)\end{aligned} \quad (14)$$

After some mathematical manipulations, we get:

$$\begin{aligned}\Delta V(n) &= X_g^T(n)(I^T{}_M \otimes A_g^T)P_1(I_M \otimes A_g)X_g(n)\\ &+q_i^T(I^T{}_M \otimes B_g^T)P_1(I_M \otimes B_g)q_i\\ &+d_i^T(I^T{}_M \otimes B_g^{'T})P_1(I_M \otimes B_g^{'})d_i +\\ &X_r^T(n)(I^T{}_M \otimes A_r^T)P_2(I_M \otimes A_r)X_r(n)\\ &+q_i^T(I^T{}_M \otimes B_r^T)P_2(I_M \otimes B_r)q_i - X_g^T(n)P_1X_g(n)\\ &-X_r^T(n)P_2X_r(n)\end{aligned} \quad (15)$$

Because $A_i^T P_i A_i - I = -Q_i$ then the following features can be used to simplify the formulas:

$$\begin{aligned}\Delta V &= -X_g^T Q_1 X_g + q_i^T[(I^T{}_M \otimes B_g^T)P_1(I_M \otimes B_g)\\ &+(I^T{}_M \otimes B_r^T)P_2(I_M \otimes B_r)]q_i\\ &+d_i^T(I^T{}_M \otimes B_g^{'T})P_1(I_M \otimes B_g^{'})d_i - X_r^T Q_2 X_r\end{aligned} \quad (16)$$

Without loss of generality, the following inequalities are considered to simplify the stability proof.

$$\begin{aligned}&1)\ ((I_M \otimes B_g^{'})d_i)^T P_1((I_M \otimes B_g^{'})d_i) \le \lambda_{\max}(p_1)\left\|(I_M \otimes B_g^{'})d_i\right\|^2 \le\\ &\lambda_{\max}(p_1)\left\|(I_M \otimes B_g^{'})\right\|^2\left\|d_i\right\|^2 \le \beta\left\|d_i\right\|^2 \le \beta d^2{}_{\max}\\ &2)\ ((I_M \otimes B_g)q_i)^T P_1((I_M \otimes B_g)q_i)\\ &\quad + ((I_M \otimes B_r)q_i)^T P_2((I_M \otimes B_r)q_i) \le \lambda_{\max}(p_1)\left\|(I_M \otimes B_g)\right\|^2\left\|q_i\right\|^2\\ &\quad + \lambda_{\max}(p_2)\left\|(I_M \otimes B_r)\right\|^2\left\|q_i\right\|^2 \le \alpha\left\|q_i\right\|^2 \le \alpha q^2{}_{\max}\\ &3)\ -X_g^T Q_1 X_g - X_r^T Q_2 X_r \le -\lambda_{\min_1}(Q_1)\left\|X_g\right\|^2\\ &-\lambda_{\min_2}(Q_2)\left\|X_r\right\|^2 \le -\lambda_{\min_1}\left\|X_g\right\|^2 - \lambda_{\min_2}\left\|X_r\right\|^2\\ &4)\ \left\|q_i\right\| \le q_{\max}\\ &5)\ \left\|d_i\right\| \le d_{\max}\end{aligned} \quad (17)$$

Using inequalities mentioned in (17), (16) is rewritten as:

$$\begin{aligned}\Delta V &\le -\lambda_{\min_1}\left\|X_g\right\|^2 - \lambda_{\min_2}\left\|X_r\right\|^2 + \beta d^2{}_{\max} + \alpha q^2{}_{\max}\\ &\le -\lambda_{\min_1}\left\|X_g\right\|^2 - \lambda_{\min_2}\left\|X_r\right\|^2 + \xi_1 + \xi_2\end{aligned} \quad (18)$$

The difference of the Lyapunov function is uniformly ultimately in the compact set mentioned in (19):

$$\Omega = \left\{X_g, X_r \,\middle|\, \left\|X_g\right\| \ge \xi_1 / \lambda_{\min_1}, \left\|X_r\right\| \ge \xi_2 / \lambda_{\min_2}\right\} \quad (19)$$

It completes the proof.

IV. Simulation Results

In the simulation, the quadruple length reduction criterion is used in both fixed time and also the proposed fuzzy controller and sampling time T = 15 are utilized. Table I shows the values of β different traffic conditions.

The number of vehicles leaving the queue i[th] at the n[th] time step is updated by:

$$d_i(n) = \min(Q_i(n) + q_i(n), d_{si}(n)) \quad (22)$$

TABLE I
Values of β in Traffic Situation

The position of traffic	β
Unsaturation	$\beta \ge 0.7$
Saturation	$0.4 \le \beta \le 0.6$
Super-saturation	$0.1 \le \beta \le 0.3$
In stable	$\beta = 0$

As a result, the saturation flow rate is as follows:

$$d_{si}(n) = d_{cons}(n) + \beta q_i(n) \quad (23)$$

For $i = 1,2,3$ and 4, we consider $d_{cons} \ge 50$ and the value of β between 0 and 1. The parameters q_i and d_i are random distributed parameters in the fuzzy model.

The results of this example are shown in visual form.

Case1: Fixed Time Controller

In fixed time approach, the results for the number of vehicles in the queue lacking controller actions are shown in Fig. 3. It demonstrates the length of queue in the first leg using fixed-time control, which improves using the fuzzy controller.

Fig. 3 demonstrates the length of queue in the first leg using fixed-time control, which improves using the fuzzy controller. Fig. 4 shows the length of a queue in the second leg using fixed time control. Fig. 5 depicts the number of vehicles in the third leg with constant time control. Fig. 6 shows the volume of traffic in the fourth leg is greater than the other legs, which has improved using the fuzzy controller. Fig. 7 shows control variables that indicate the green or red traffic lights. Similarly, the length of the vehicle's queue is shown at other intersections, which has ultimately improved using a fuzzy controller.

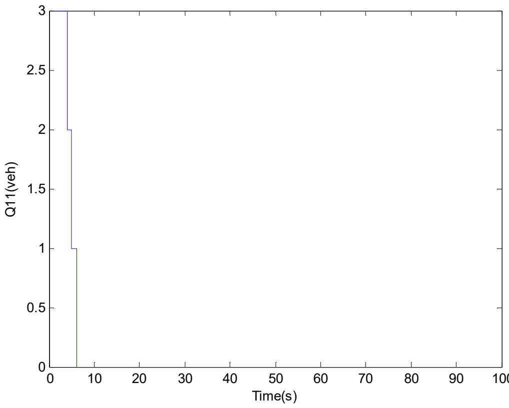

Fig. 3 The number of vehicles in the first leg of the first intersection

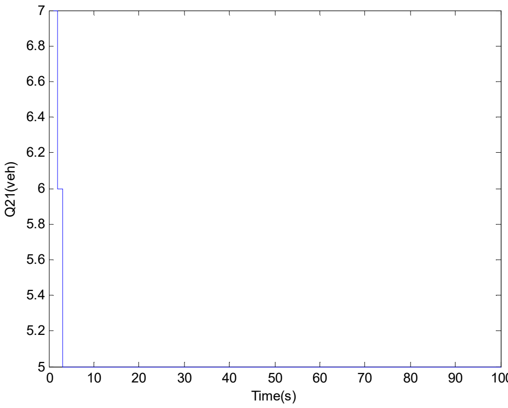

Fig. 4 The number vehicle in the second leg of the first intersection

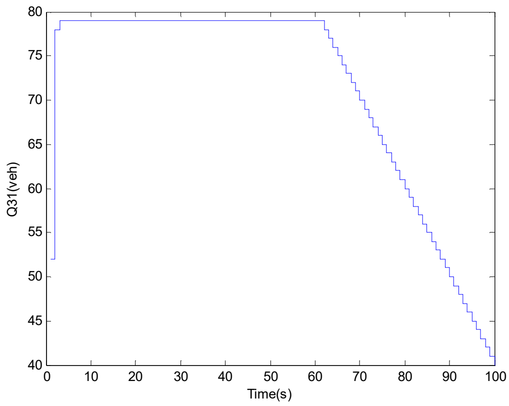

Fig. 5 The number of vehicles in the third leg of the first intersection

Case 2: Stable Fuzzy Controller Design

The controller variable output (S_i) is shown as Fig. 8. As we can see in Fig. 8, the length of the queue of cars in the first leg has not changed from the uncontrolled state. In Fig. 9, the length of the queue of the case has not changed much and stayed constant. In Fig. 10, the number of vehicles decreased significantly compared to the non-controlling mode. Fig. 11 depicts the length of the car's queue in the fourth leg. Fig. 12 exhibits control variables that are green or red indicator light in the presence of a fuzzy controller. In Figs. 9 and 10, the length of the vehicle's queue is shown at the intersections with the fuzzy controller. This result showed that using a fuzzy controller leads to reducing the length of queues in each leg compared with constant time control.

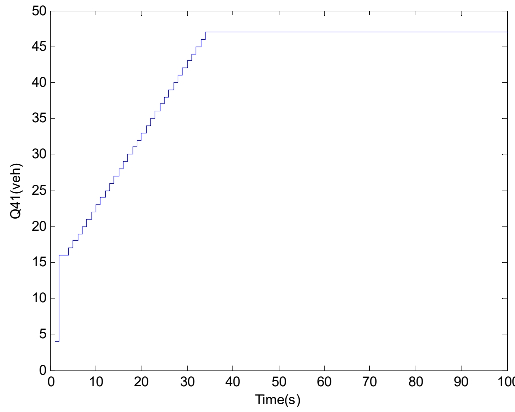

Fig. 6 The number of vehicles in the fourth leg of the first intersection

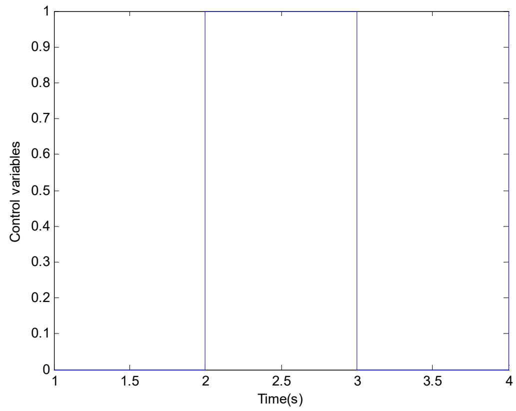

Fig. 7 Duration of Green or red traffic light

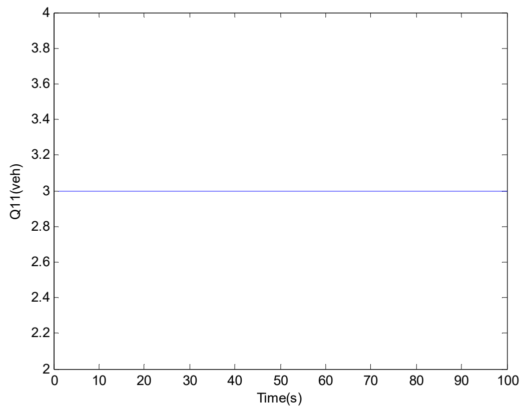

Fig. 8 The number of vehicles in the first leg of the first intersection

V. Conclusion

In this paper, a fuzzy model was first developed to produce and control traffic signals for multi-agent intersections linking to each other, and then their stability was proved. The fuzzy model is designed based on the theory of multi-functional systems and the effect of adjacent intersections on their behavior is considered. In each phase, two basic parameters are the length of the queue and the delay of the vehicle to reduce them. A fuzzy controller which is designed based on the state space equations showed that the queue of vehicles in each phase decreased in comparison with the constant time mode and maximizes the volume of traffic. The stability of closed loop system in presence of fuzzy approach, and using expert's knowledge are the main merits of the proposed methodology. Simulation results depicted the efficiency of the method proposed for the intersections.

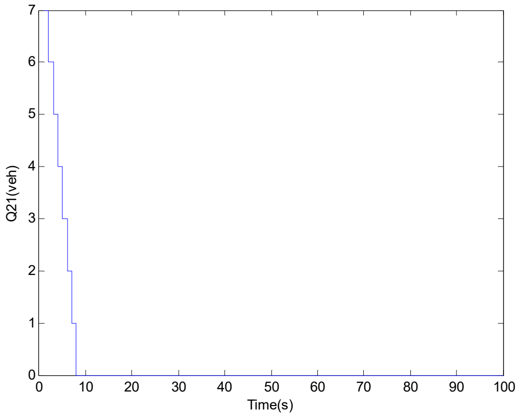

Fig. 9 The number of vehicle in the second leg of the first intersection

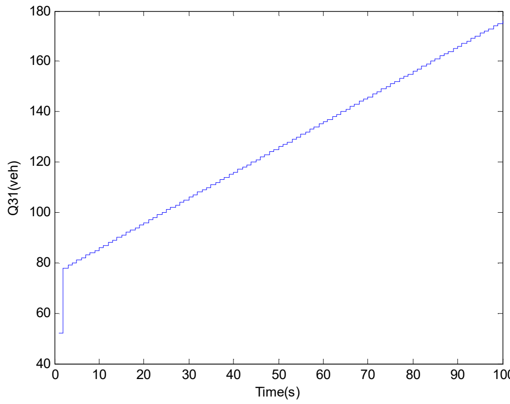

Fig. 10 The number of vehicles in the third leg of the intersection

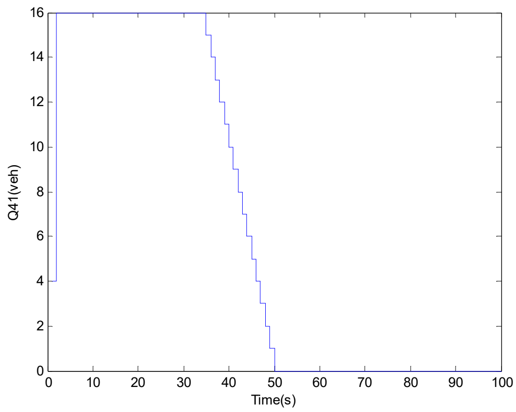

Fig. 11 The number of vehicles in the fourth leg of the first intersection

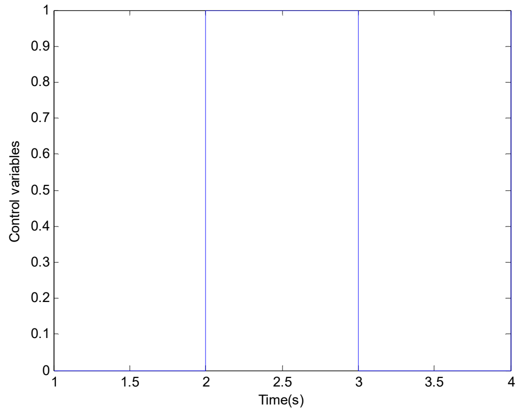

Fig. 12 Duration of Green or Red light in Fuzzy controller

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