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Improving Fuzzy Traffic Controller for Multilane-Multiple Intersection

Azura Che Soh, Marzuki Khalid, Mohammad Hamiruce Marhaban, Rubiyah Yusuf, *Member, IEEE*

Abstract—**This paper presents a fuzzy traffic controller for controlling a multilane-multiple traffic intersection in urban city environment. The developed controller applied to the model is based on the cooperation and distributed mechanisms with the neighbors' intersection. The phase sequence and phase length extension are used in decision making to provide efficient and more optimal traffic control. The input variables are normalized and the proposed fuzzy traffic controller is suitable to be used to any case study without modification to the controller modules. The simulation illustrates that the fuzzy traffic controller proposed in this study show a remarkable improvement over the existing fuzzy traffic controller without input normalization.**

I. Introduction

TRAFFIC control in urban networks is a nonlinear process varying dynamic characteristics throughout the day. The fundamental principle of urban traffic control is to respond to dynamic changes of the traffic demand and synchronizing traffic signal with the neighbor intersections. As the junctions in a road network are interconnected, the decisions made at one junction inevitably affect those made at the adjacent junctions.

In multilane-multiple intersection, the traffic signal control operates dependently to neighbor intersection. This means that the control algorithm can be much complicated than algorithms for isolated intersection. The system controlling the intersection has a lowest degree of freedom to choose a control strategy for multilane-multiple intersection. In this case, a control strategy is choosing must be considering the traffic from upstream intersection and congestion occur in the downstream intersection. Traffic control system is nonlinear, fuzzy and nondeterministic, and traditional methods of modeling and control can't work very well. As a perfect urban area traffic signals control system, it is supposed to respond to traffic demand and online-optimize timing plans in time, and then implement real-time control. Thus, the traffic system must have adaptive characteristic and automatic control strategy.

Fuzzy controllers have proven effective in controlling a single traffic intersection [1]-[3], even when the intersection is somewhat complex. In certain instances, however, even if local controllers perform well, there is clearly no guarantee that they will continue to do so when the intersections are coupled with irregular traffic flow.

Research on controlling a set of traffic intersections can be found in [4]-[6]. Jee-Hyong *et. al.* [4] applied the fuzzy logic approach for dynamic multiple traffic intersection in urban areas. The controller changes not only the phase lengths but also the phase sequences adaptively based on the traffic situation. References [5] and [6] were based on the distributed fuzzy controller which is adaptive to the traffic conditions. However, they dealt with simple traffic conditions, such as, regularly located intersections. They did not change the sequence of phases in their research. Changing of the phases sequence may confuse drivers, but in the view point of the performance of traffic controllers, it is much sought. If the sequence of phases is fixed and traffic conditions are often changed, the traffic signal cannot effectively deal with the traffic conditions which may result in deterioration of the of the traffic controllers.

In the case above [4]-[6], the controller could easily handle changes in traffic flow, but required different parameter settings for each junction. The fuzzy membership functions of the input fuzzy variables of the controller are different for each lane depending on the lengths of the traffic. The ratio value for this input is required as the length of the lane is different. Using the ratio value not only decreases the complexity of the fuzzy logic system but also improves computation time.

This paper presents the development of intelligent traffic light system based on the fuzzy logic approach applied to multiple-multilane intersection in an urban area. The controller is developed based on the cooperation mechanism and synchronizing mechanism with the neighboring intersections. The phase sequence and phase length extension are used in the decision making of the fuzzy controller. In this controller, the modification of input variables in the ratio values was purposely done to include all the related variables to one specific variable.

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Azura Che Soh, is currently doing PhD in Centre for Artificial Intelligence and Robotics (CAIRO) of Universiti Teknologi Malaysia, Jalan Semarak, 54100 Kuala Lumpur.(e-mail:azura@eng.upm.edu.my).
Marzuki Khalid, is a professor and Deputy Vice Chancellor (Research & Innovation) of Universiti Teknologi Malaysia, Skudai, Johor. (e-mail:marzuki@utmkl.utm.my).
Mohammad Hamiruce Marhaban is an associate professor with the Department of Electrical and Electronics Engineering, Universiti Putra Malaysia,43400, Serdang, Selangor.(e-mail:hamiruce@eng.upm.edu.my).
Rubiyah Yusuf, is a professor and director of CAIRO, Universiti Teknologi Malaysia, Jalan Semarak, 54100 Kuala Lumpur. (e-mail:rubiyah@utmkl.utm.my).

The paper is organized as follows. In the next section, an overview of the multiple-multilane traffic model is described. Section 3 briefly discusses the details of the proposed fuzzy traffic controller. Section 4 discusses the simulation results of the fuzzy traffic controller with comparison to the traditional controller on the multiple-multilane intersections. The conclusion of this paper is summarized in the last section.

II. Multilane-multiple intersection model

The network structure used in this model is the M/M/1 arbitrarily-linked topology and standard approach techniques. Figure 1 shows the schematic layout of the real case study in one of the busiest intersection in the capital city of Malaysia, Kuala Lumpur.

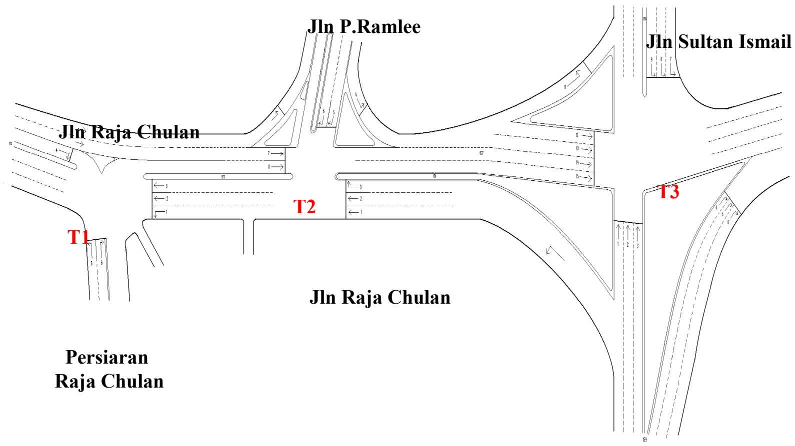

Figure 1: A schematic layout of Case Study.

The M/M/1 queue follows the FIFO principle and has one server serving its customers. For this queue to be used, the system is assumed to have the Markov property (memoryless), where the inter-arrival time and service time of the system is distributed exponentially [7].

In this study, the virtual server is introduced for multilane traffic light systems. The job of the virtual server is similar to a server, however, it gives a service to its own lane. When the traffic light system is activated (green), the entire virtual server for the same signal phase will be activated simultaneously and vehicles can move to the downstream intersection. One lane in the upstream intersection is linked to one lane or more in any downstream intersection.

Vehicles traveling in the intersection follow a routing probability which is controlled according to its signal phase. The signal phase is an important element in this model as it provides signal flow from one intersection to another. All the lanes which are facing the external intersections are defined as the infinite buffer. For an immediate intersection, the link which is connected between intersections is called the finite buffer.

The decomposition method used in this study is the stochastic analysis of the queuing stations in terms of arrivals and departures. The three key input parameters used in the analysis are (i) Arrival rates (λ), expected number of vehicles arriving at each intersection per unit of time, (ii) Mean service time (*$1/\mu$),* expected length of times that a vehicles spends at each intersection and (iii) Number of Servers (Intersection/Station and virtual server at each lane).

The relevant performance measures in the network queuing model, using the assumptions of Poisson arrivals (with λ_i=arrival rate) and exponential service times, (with μ_i=service rate) can be applied for the model as follows:

(a) Distribution of the queue length

- probability of n vehicles in the system

$$P_i(n) = (1-\rho_i)\rho_i^n \tag{1}$$

- the average number of vehicles in the system

$$L_i = \rho_i/(1-\rho_i) = \lambda_i/(\mu_i - \lambda_i) \tag{2}$$

- the average number of vehicles in the queue

$$L_{qi} = \rho_i^2/(1-\rho_i) = \lambda_i^2/\{\mu_i(\mu_i-\lambda_i)\} \tag{3}$$

- the expected total number of vehicles in the network

$$L_{total} = \sum_{i=1}^{K} L_i = \sum_{i=1}^{K} \frac{\rho_i}{1-\rho_i} \tag{4}$$

(b)Distribution of the waiting time

- the average time a vehicle spends in the system

$$W_i = 1/(\mu_i - \lambda_i) \tag{5}$$

- the average time a vehicle spends waiting in queue

$$W_{qi} = \lambda_i/\{\mu_i(\mu_i-\lambda_i)\} = \rho_i\{\mu_i(1-\rho_i)\} \tag{6}$$

- the expected total waiting time in the network

$$W_{total} = L_{total}/\lambda_{total} \tag{7}$$

where L_{total} from Equation (4) and λ_{total} is the number of vehicles enter to intersection.

The details analysis of the multilane-multiple intersection model is discussed by author in this reference [8].

III. FUZZY TRAFFIC CONTROLLER

The principles and rules for the fuzzy control system are modeled based on the cooperation mechanism and distributed mechanism within the neighboring intersections. For the strategy of fuzzy control, the dependencies all the intersection among them and influences from neighbor intersection cause the distributed mechanism is adopted. Each intersection has its own controller. For intersection cooperation mechanism, the controllers of an intersection control its own traffic and synchronize with its neighbors. Using the information from its traffic detectors and its neighbors, the fuzzy rule-based system gives optimal signals. The phase sequence and phase length extension are used in the decision making. It manages the phase sequences and phase lengths adaptively for its neighbors as well as its own traffic conditions.

The fuzzy traffic controller has three modules which are referred to as the NextPhase Module, the GreenPhase Module, and the Decision Module. Figure 2 shows the schematic diagram of the controller.

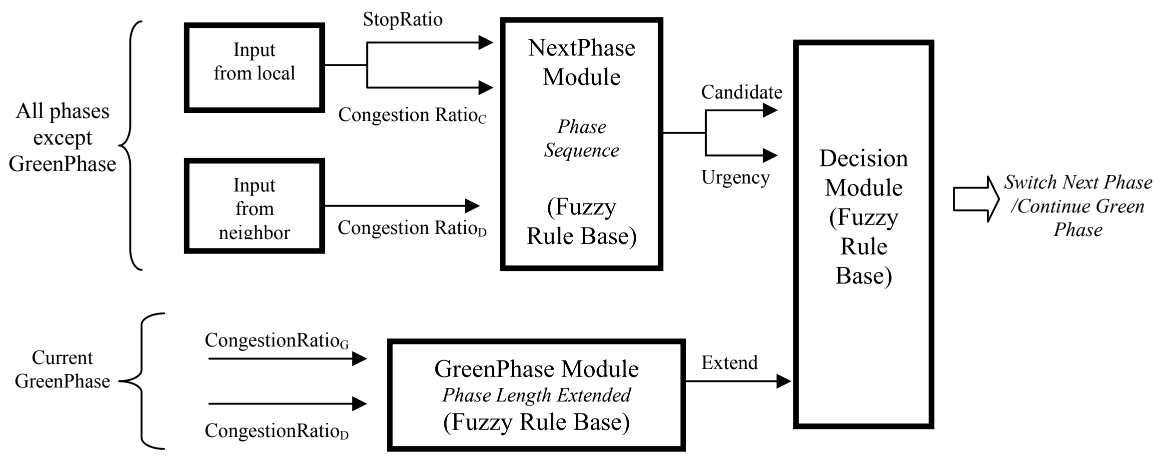

Figure 2: A schematic diagram of the proposed fuzzy traffic lights controller.

In the development of the fuzzy traffic controller, a multilane-multiple intersection traffic model in urban area is considered. The key features of the intersection, controller and the associated constraints are noted as follows:

- For any approach, the green signals give the left-turn, forward-going, and right-turn traffic the right of way to cross the intersection.
- The arrival of vehicles is independent on each lane. The inter-arrival of vehicles is also independent and Poisson distribution is used to generate arrivals.
- The vehicle arrivals are considered in the traffic volume which is the number of vehicles per hour. So the type of vehicles is not considered.
- For each of the approaches, the vehicle detectors are assumed to have been installed at appropriate locations to register the number of vehicles queuing up to cross the intersection.
- The external arrival rate at each station, where is define as the arrival from intersection with the length of link between neighbor intersections over 500m. So, the maximum number of vehicles can stay in the lane between external neighbor intersection is 78 vehicles.
- Pedestrian crossing is not considered.

A. NextPhase Module

In this module, phase sequence technique is applied as a decision making. The module selects one candidate for the green phase. It observes the traffic conditions of all phases except the green phase and selects the phase that is the most urgent among them. This module compares the urgency degree of all the input phases and selects the one that has the maximum of the urgency degree of a phase.

To obtain the urgency degree of a phase, the module assesses the urgency degrees of all traffic flows related to the Phase. The urgency degree of a traffic flow represents its traffic condition. The urgency degree of a phase is the average of that of the traffic flows related to the phase. In order to evaluate the urgency degree of the traffic flow shall have three inputs:

- CongestionRatio$_C$: the ratio number of vehicles waiting between the current lanes over the capacity.
- CongestionRatio$_D$: the ratio number of vehicles waiting between the next lanes in the downstream intersection over the capacity.
- StopRatio: the ratio time of vehicles stop for the time duration that a traffic flow stays on red signal since the end of the last green over cycle length.

In this research, all of the input membership functions are normalized. Figure 2 show the membership functions of input fuzzy of CongestionRatio_C, CongestionRatio_D and StopRatio, respectively. The CongestionRatio and StopRatio in this research are expressed by following relationship:

$$\text{CongestionRatio} = n_i/C \quad (8)$$
$$\text{StopRatio} = t_s/c \quad (9)$$

where C is the capacity of vehicles in the lane; n_i is defined as actual number of vehicles in the current lane or next lane in downstream intersection; t_s is the time of vehicles stop for the time duration that a traffic flow stays on red signal; c is the cycle length.

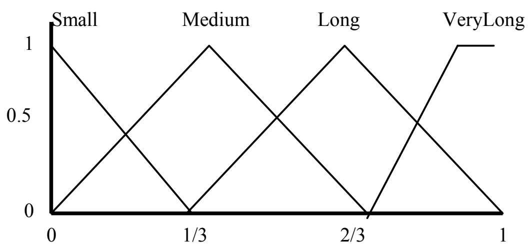

Figure 3: The membership functions of the input variables

The output variable referred to as Urgency, is the urgency degree of the phase corresponding to the given traffic flow. Figure 4 shows the membership functions of output variable.

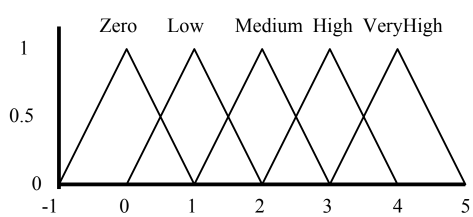

Figure 4: The membership functions of output variable Urgency

The fuzzy rules of the NextPhase module are generated such that the urgency of the phase increases proportionally to CongestionRatio_C, CongestionRatio_D and StopRatio. As the ratio of the waiting vehicles over the capacity increases and/or the red signal lasts longer, the traffic condition is considered to become more urgent. For signal synchronizations, when the vehicles departed from the neighboring intersections arrive, the urgency degree of a traffic flow of the arriving traffic flow will increase. However, if CongestionRatio_D becomes large, the urgency degree of the traffic flow should decrease due to a larger value of the CongestionRatio_D which means that there are too many vehicles in the next intersection. Thus the number of vehicles entering the next intersection should be reduced. Table I shows some examples of rules of the NextPhase module.

TABLE I: SOME EXAMPLES OF RULES THE NEXTPHASE MODULE

Rules	Congestion Ratio_C	Congestion Ratio_D	Stop Ratio	Urgency
1		VeryLarge		**Zero**
2	Long	Small	Long	**VeryHigh**
3	Long	Medium	Medium	**High**
4	Medium	Small	High	**High**
…	...	**…**	**…**	**…**

B. GreenPhase Module

The GreenPhase Module observes the traffic conditions of the green phase. According to the condition of traffic flow of the observation, it produces the Extend degree, which indicates the possibility whether the controller should extend the green phase. The technique used in this module is called Phase length extended.

The fuzzy rules of this module take the CongestionRatio_C and CongestionRatio_D as its antecedents and generate Extend as an output. In order to evaluate the possibility that the green phase should extend, the traffic flow has two inputs:

- CongestionRatio_G: the ratio number of vehicles remaining between the front and the rear detector over the capacity during the green time.
- CongestionRatio_D: the ratio number of vehicles waiting between the next lanes in the downstream intersection over the capacity. CongestionRatio_D is the same as CongestionRatio_D of the NextPhase Module.

If the green phase involves more than one traffic flow, the maximum CongestionRatio_G and CongestionRatio_D of the traffic flows will be applied. CongestionRatio_G and CongestionRatio_D are normalized and similar to the CongestionRatio_C and CongestionRatio_D of the NextPhase Module as shown in Figure 3. Figure 5 show the fuzzy membership functions of Extend output variable.

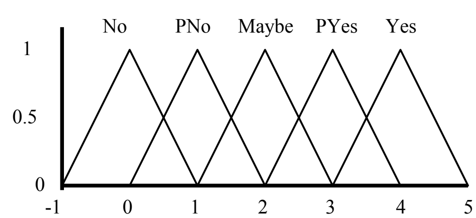

Figure 5: The membership functions of output variable Extend

This module has ten rules. Table II shows some rules of the NextPhase Module. If a ratio number of vehicles waiting in the traffic flow have remained long enough on the green signal, the number of remaining vehicles

(CongestionRatio$_G$) will become small. Thus, if CongestionRatio$_G$ is small, the Extend degree will be reduced. If there are many vehicles at the next intersection, the Extend degree is lowered to reduce the vehicles from entering the next intersection.

TABLE II. SOME EXAMPLES OF RULES THE GREENPHASE MODULE

Rules	Congestion Ratio$_C$	Congestion Ratio$_D$	Extend
1		VeryLarge	**No**
2	Small	Small	**PNo**
3	Long	Small	**Yes**
4	Medium	Long	**No**
…	…	…	…

C. Decision Module

The Decision Module makes decision whether to switch the green phase or not. The inputs of the module include Candidate, Urgency, and Extend while the output shall be the Decision. The Candidate variable is the phase selected by the NextPhase Module and the Urgency variable is its urgency degree phase. Extend is the extension of the green phase from the GreenPhase Module. Decision is the decision on phase switching to the Candidate variable.

The module switches the current green phase to the Candidate variable if this value exceeds the specified threshold. The module will stop the green phase and gives a green signal to the Candidate variable if the urgency degree of Candidate or the extend degree of current green phase is low. Table III shows some rules selected from the 15 rules of this module. The fuzzy sets of Urgency and Extend are the same as Urgency of the NextPhase Module and Extend of the GreenPhase Module respectively (see Figure 4 and Figure 5). Figure 6 shows the fuzzy membership functions of the Decision variable.

TABLE III. SOME EXAMPLES OF RULES THE DECISION MODULE

Rules	Urgency	Extend	Decision
1	PNo	VeryHigh	**Yes**
2	Maybe	Zero	**No**
3	Yes	Medium	**Maybe**
4	Yes	Small	**No**
…	…	…	…

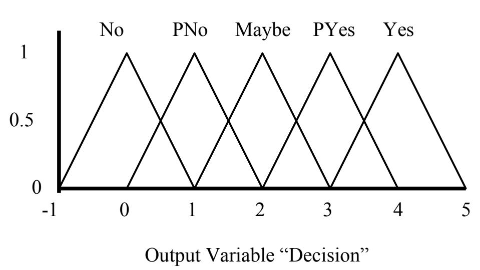

Figure 6: The membership functions of the output variable Decision.

IV. EXISTING FUZZY TRAFFIC CONTROLLER

To perform the intersection control task, the controller must be provided with the information from detector in current intersection and also the neighbor intersections. The information provided by detector is the traffic condition on the approach currently in the green phase, the vehicle queue that has formed in the remaining approaches and the traffic condition on the next downstream intersection. Based on this information, it decides whether to extend the current green time. If it decides not to do so, the traffic controller state must change to allow traffic from another approach to flow. Therefore, the fuzzy controller must have the following inputs:

- Number of vehicles for the approach in the green phase: defined over a universe of discourse Q_C, whose generic element is $q_C \in Q_C$.
- Length of queue of vehicles for the approaches in the red phase: defined on the universe of discourse R, with element $r \in R$.
- Number of vehicles for the approach in the downstream intersection: defined over a universe of discourse Q_D, whose generic element is $q_D \in Q_D$.

In the case of existing fuzzy traffic controller, the membership functions of input variables are used directly from the data provided by detector as mentioned above. But in the urban area, the topology for each intersection in an urban area is not the same and usually arbitrarily structured. The traffic fuzzy controller could easily handle changes in traffic flow, but required different parameter settings for each junction. The fuzzy membership functions of the input fuzzy variables of the controller are different for each lane depending on the lengths of the traffic.

To resolve this problem, the input variables of modules are normalized. The ratio value for this input is required as the length of the lane is different. Using the ratio value not only decreases the complexity of the fuzzy logic system but also improves computation time. The normalization of input variables is because the controller suitable to be used to any case studies without modification to the controller modules.

V. SIMULATION RESULTS AND DISCUSSIONS

The performance of the developed controller is evaluated by simulation. The performance of the developed controller is evaluated by simulation. The simulation is done in the peak-hour situation, so we assumed that the blocking effect occurs in the immediate intersection. The proposed fuzzy controller and existing fuzzy controller method are simulated under the same condition.

The external arrival vehicle from an upstream intersection entering the network model is used as the input parameters which are taken from Integrated Transport Information System (ITIS) data [9]. The data from ITIS is the traffic volume data, which is the number of vehicles per hour. From the real traffic data, the routing probability of the vehicles distributed in each lane can be calculated based on the total number of vehicles per direction.

The average waiting time, average queue length and the number of vehicles departure from each intersection is used as an index of performance. The simulation results are summarized as in Table IV and Table V.

The proposed method shows improvement in average waiting time for intersection 1 is 29.85% and intersection 3 is 33.16% over the existing fuzzy controller. But for intersection 2, the existing controller is better than proposed method with only small improvement (0.10%).

During peak hour condition, the intersection was faced with heavy traffic conditions where there are too many vehicles entering the intersection from external upstream intersection. The lane facing the external upstream intersection is assumed to have an infinite capacity and thus the system is driven into saturation. An intersection 2 is the immediate intersection, so the blocking occurs and increasing the waiting time. In intersection 2 for proposed fuzzy controller allows more vehicles to pass an intersection than the existing fuzzy controller shows in Figure 7. All the intersection allows more vehicles to pass an intersection by using proposed method.

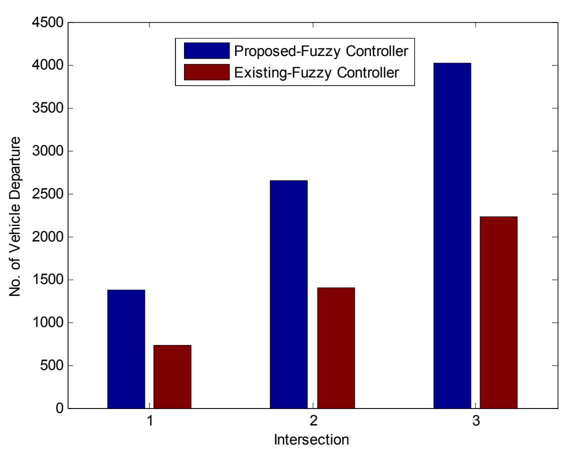

Figure 7: The number of vehicle exit intersection

Table V shows the proposed fuzzy controller outperforms existing fuzzy controller in terms of the average queue length. The proposed method shows improvements from 2.96% to 40.18% over the existing method.

TABLE IV. AVERAGE WAITING TIME

Intersection	Average Waiting Time		Comparison
	Proposed Controller	Existing Controller	Improvement (%)
1	0.0698	0.0995	29.85
2	0.2102	0.2100	-0.10
3	0.1536	0.2298	33.16

TABLE V. AVERAGE QUEUE LENGTH

Intersection	Average Queue Length		Comparison
	Proposed Controller	Existing Controller	Improvement (%)
1	0.0064	0.0075	14.67
2	0.0295	0.0304	2.96
3	0.0134	0.0224	40.18

VI. CONCLUSIONS

In the urban area, the different topology in each intersection and traffic congestion is a main problem in traffic management. To deal with this problem, it is important that the traffic signal controller is realizable. In order to design a more practical controller, we constructed a simulation environment that meets the characteristic of intersection and traffic situations more than ever. To reduce complexity of the controller and also to improve computation time, the input variables of modules are normalized.

Overall, the proposed method shows good performance during peak hours. The effectiveness of the proposed fuzzy traffic controller is superior to the existing fuzzy controller due to the former's ability to adapt to different traffic conditions. The time extendibility is not fixed and it can freely determine the length of the green phase according to traffic conditions at the intersection, which does improve the efficiency of the controller. The proposed fuzzy controller can be applied to any multiple-multilane intersection without modification to the controller modules.

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