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A Fuzzy Signal Controller for Isolated Intersections

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Abstract

Fuzzy reasoning has become an important intelligent control method for traffic operation. This paper proposes a new fuzzy control system for signal control of an isolated intersection. This new fuzzy signal control system (FSCS) contains fuzzy phase selector and fuzzy green phase extender functions, which located in different levels of this multi-level signal control system. The phase selector is working on the phasing, while the green extender belongs to the green extension level of this multi-level signal control system. The phase selector function determines the next green phase and green extender controller function makes the decision whether to extend or terminate the current green phase. Simulation is used to evaluate the performance of the proposed FSCS system. The FSCS system is compared with pre timed control system and shows significant improvement over pre timed control strategy.

Keywords: isolated intersection, fuzzy control system, fuzzy reasoning

1 Introduction

With the rapid increasing of global vehicle numbers, the problems such as congestion and accidents happen more frequently. So the signal control of traffic intersection is becoming more important.

Intersections are common bottlenecks in roadway systems. Intelligent traffic signal control makes the current roadway system operate more efficiently without building new roadways or widening existing roadways which are often impossible due to scarce land availability and public opposition to roadway expansion in many locations. It has been recognized that signal improvement is one of the most useful and cost-effective methods to reduce congestion [8]. The traffic signal control had been studied in early time such as [4].

Most signal controls are implemented with either pre timed controls or actuated controls. A pre timed controller repeats presetting signal timings derived from historical traffic patterns. An actuated controller computes phase durations based on real-time traffic demand obtained from the detection of passing and stopping traffic on all lanes leading into an intersection. Actuated control has a simple operating principle of phase extension until a preset maximum is reached. Thus, a single vehicle arrival prolongs the green and cycle length for the whole intersection without regarding for the traffic conditions on all other approaches with a red signal.

Adaptive control is designed to take account of the traffic conditions for the whole intersection. It has the ability to adjust signal phasing and timing settings in response to real-time traffic demands at all approaches. Several methods have been developed for designing adaptive control systems and Li [6] and Li and Prevedouros [7] categorized them as optimization-based, rule-based, and optimization and rule-based control strategies. The current research focuses for intersection control is on the application of artificial intelligence techniques such as expert systems, neural networks, and fuzzy logic. Fuzzy controllers simulate the control logic of experienced human traffic controller such as police officers who take the place of signal controls at over saturated intersections.

The first attempt to use fuzzy logic in traffic control was made by Pappis and Mamdani [13]. They simulated an isolated signalized intersection composed of two one-way streets without turning traffic. Chen and Chen [2] made deeper research based on them, but their researches were mainly fixed-phases signal control. Kelsey and Bisset [5] also simulated a simple two-phase signal control of an isolated intersection with one lane on each approach. The fuzzy logic control performed better than both pre timed and actuated control especially when the traffic flow between different directions was uneven.

Niittymaki and Pursula [12] simulated an isolated intersection. They found that fuzzy logic controller lead to shorter vehicle delay and lower stops percent. Trabia *et al.* [14] designed a fuzzy logic controller for a signalized

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intersection with left-turning traffic. Traffic volumes and queue lengths counted by detectors were used in a two-stage fuzzy logic algorithm to determine whether to extend or terminate the current signal phase. Niittymaki and Kikuchi [11] developed a fuzzy logic algorithm for controlling a pedestrian crossing signal. Through simulation they found that their fuzzy logic algorithm provided better performance than conventional actuated signal control.

Chen *et al.* [1] studied a fuzzy logic controller for freeway ramp metering. The fuzzy logic controller was able to reduce congestion as well as efficiency losses due to incidents.

Nakatsuyama *et al.* [9] used fuzzy reasoning to control vehicle moving of two adjacent intersections; Chiu [3] used fuzzy reasoning to control multi-intersections, in which vehicles have no turning behavior. Fuzzy rules were used to adjust cycle time, phase split and offset parameters, and Niittymaki [10] presented a simple two-phase fuzzy signal controller. The results showed that the fuzzy logic controller performed better than vehicle-actuated control.

The research reviewed above generally reported a better performance of fuzzy logic controllers compared to pre timed and actuated controllers. However, most of the researches involved either one-way streets or intersections without turning movements. In addition, fuzzy rules were determined mostly by traffic conditions on the subject approaches without taking into account the traffic conditions on competing approaches and the phase sequence they chose are fixed. If we know the current phase, then we could know what the next phase is. In this paper, fuzzy traffic signal control with phase selector and green extender functions is presented and its performance is evaluated by simulation. We propose a newly changeable phase-sequences signal control method.

The rest of this paper is organized as follows: In Section 2, two functions of FSCS, fuzzy phase selector function and fuzzy green extender function are presented. In Section 3, the performance of this new controller is evaluated by simulations. Section 4 gives our conclusions.

2 Description of the Proposed Fuzzy Control System

In the proposed FSCS, fuzzy phase selector function and fuzzy green phase extender function are located in different levels of the multi-level signal control system as presented in Fig.1. The phase selector function is working on the sequence level, while the green extender function belongs to the green extension of the multi-level signal control system.

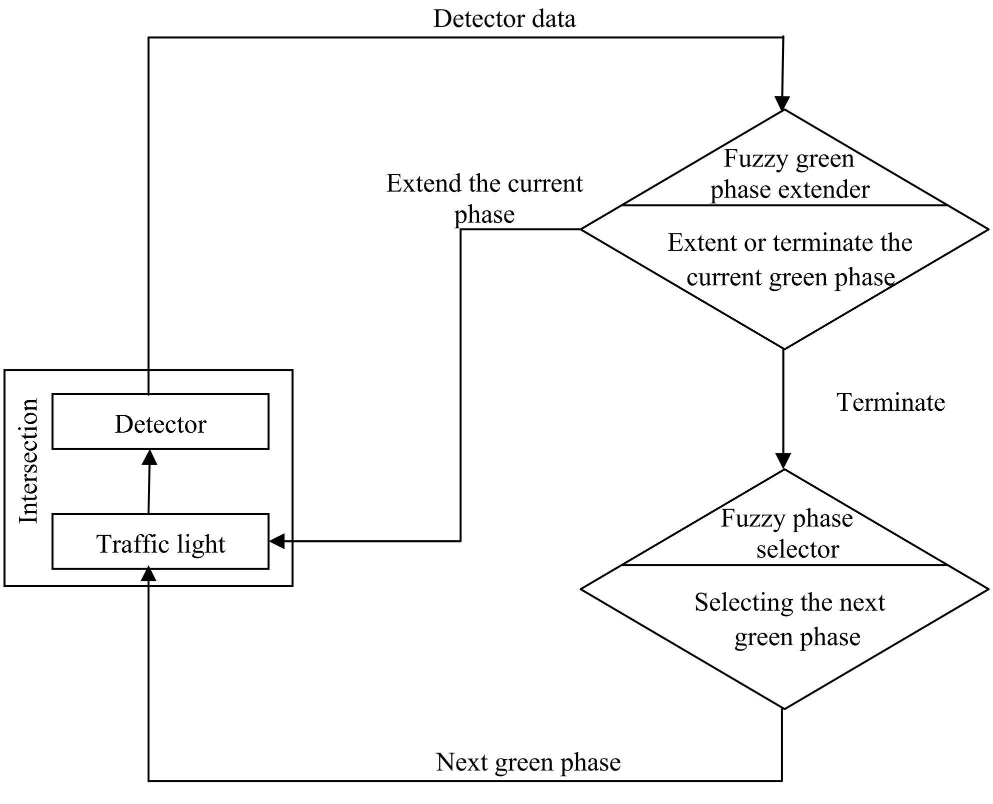

Figure 1: Fuzzy traffic signal control in different levels

The performance of this signal control system is as follows:

Step 1: System receives the necessary data from the detectors of intersection.

Step 2: Determines if current green phase should extend or terminate (fuzzy green phase extender function).
  Step 2.1: If current green phase should extend, then goes to Step 1.
  Step 2.2: If current green phase should terminate, then goes to Step 3.
Step 3: Determines the next green phase (phase selector function) and goes to Step 1.

2.1 Fuzzy Phase Selector Function

The phase selector determines the most suitable phase order for the traffic conditions. This is accomplished by selecting the next green phase. The traffic situation is monitored continuously and when the green phase is terminated, the decision of the next phase is updated. Fig.2 presents the phases and the basic phase order of the intersection model, in which the control function is tested. The geometry of this intersection is illustrated in Fig.3. If the current green phase *A* is to be terminated, the phase selector decides whether to launch next the phase *B* or the phase *C*.

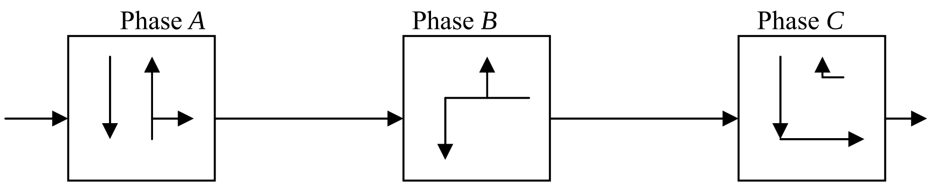

Figure 2: Basic phase sequence of the signal control at the test intersection

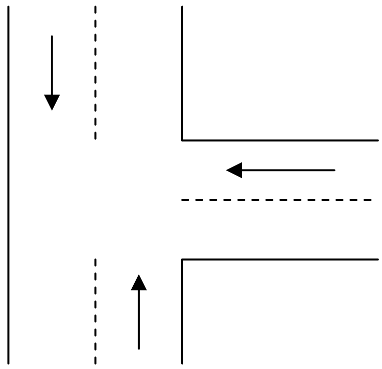

Figure 3: Layout of simulated intersection

Table1: Phase selector *B* or *C*

	Length of queue		Length of queue		Chosen phase
IF	QN_B = very long	AND	QN_C = very long	THEN	C
IF	QN_B = very long	AND	QN_C = long	THEN	B
IF	QN_B = very long	AND	QN_C = medium	THEN	B
IF	QN_B = very long	AND	QN_C = short	THEN	B
IF	QN_B = long	AND	QN_C = very long	THEN	C
IF	QN_B = long	AND	QN_C = long	THEN	C
IF	QN_B = long	AND	QN_C = medium	THEN	B
IF	QN_B = long	AND	QN_C = short	THEN	B
IF	QN_B = medium	AND	QN_C = very long	THEN	C
IF	QN_B = medium	AND	QN_C = long	THEN	B
IF	QN_B = medium	AND	QN_C = medium	THEN	C
IF	QN_B = medium	AND	QN_C = short	THEN	C
IF	QN_B = short	AND	QN_C = very long	THEN	C
IF	QN_B = short	AND	QN_C = long	THEN	C
IF	QN_B = short	AND	QN_C = medium	THEN	C
IF	QN_B = short	AND	QN_C = short	THEN	C

The fuzzy inference is based on weights $W(p_i)$ of each phase p_i =*A*, *B*, *C*. The weights can be defined by the number of queuing vehicles, or by the total waiting time of the vehicles waiting for the green signal in each red phase. In this paper we use the number of queuing vehicles. The rules are formed to give priority to the phase with highest demand for green time. If the phase *A* is just terminated the phase selection rules are in Table 1, where QN_i=Average queue length on lane *i* with red which may receive green in the next phase, in veh/lane.

For example, the first line of Table 1 can be expressed as:

IF Average queue length on lane B with red is very long AND
Average queue length on lane C with red is very long
THEN lane C is chosen as next green phase

Initial version of these rules was proposed by traffic experts but then modified by the results of simulations.

If the phase *B* is just terminated, the phase selection rules are in Table 2:

Table 2: Phase selector *A* or *C*

	Length of queue		Length of queue		Chosen phase
IF	QN_A = very long	AND	QN_C = very long	THEN	A
IF	QN_A = very long	AND	QN_C = long	THEN	A
IF	QN_A = very long	AND	QN_C = medium	THEN	A
IF	QN_A = very long	AND	QN_C = short	THEN	A
IF	QN_A = long	AND	QN_C = very long	THEN	C
IF	QN_A = long	AND	QN_C = long	THEN	A
IF	QN_A = long	AND	QN_C = medium	THEN	A
IF	QN_A = long	AND	QN_C = short	THEN	A
IF	QN_A = medium	AND	QN_C = very long	THEN	C
IF	QN_A = medium	AND	QN_C = long	THEN	A
IF	QN_A = medium	AND	QN_C = medium	THEN	A
IF	QN_A = medium	AND	QN_C = short	THEN	C
IF	QN_A = short	AND	QN_C = very long	THEN	C
IF	QN_A = short	AND	QN_C = long	THEN	C
IF	QN_A = short	AND	QN_C = medium	THEN	C
IF	QN_A = short	AND	QN_C = short	THEN	A

For example, the first line of Table 2 can be expressed as:

IF Average queue length on lane A with red is very long AND
Average queue length on lane C with red is very long
THEN lane A is chosen as next green phase

Initial version of these rules was proposed by traffic experts and then modified by the results of simulations.

If the phase *C* is just terminated, the phase selection rules are in Table 3.

Table 3: Phase selector *A* or *B*

	Length of queue		Length of queue		Chosen phase
IF	QN_A = very long	AND	QN_B = very long	THEN	A
IF	QN_A = very long	AND	QN_B = long	THEN	A
IF	QN_A = very long	AND	QN_B = medium	THEN	A
IF	QN_A = very long	AND	QN_B = short	THEN	A
IF	QN_A = long	AND	QN_B = very long	THEN	A
IF	QN_A = long	AND	QN_B = long	THEN	A
IF	QN_A = long	AND	QN_B = medium	THEN	A
IF	QN_A = long	AND	QN_B = short	THEN	A
IF	QN_A = medium	AND	QN_B = very long	THEN	B
IF	QN_A = medium	AND	QN_B = long	THEN	A
IF	QN_A = medium	AND	QN_B = medium	THEN	A
IF	QN_A = medium	AND	QN_B = short	THEN	A
IF	QN_A = short	AND	QN_B = very long	THEN	B
IF	QN_A = short	AND	QN_B = long	THEN	B
IF	QN_A = short	AND	QN_B = medium	THEN	A
IF	QN_A = short	AND	QN_B = short	THEN	A

For example, the first line of Table 3 can be expressed as:

IF *Average queue length on lane A with red is very long AND*
Average queue length on lane B with red is very long
THEN *lane A is chosen as next green phase*

Again the initial version of these rules is proposed by traffic experts but then they are modified by the results of simulations.

2.2 Fuzzy Green Extender Function

Signal control is basically a process for allocating green time among conflicting movements. Alternatively, signal control is a process for determining whether to extend or terminate the current green phase based on a set of fuzzy rules. The fuzzy rules compare traffic conditions with the current green phase and traffic conditions with the next candidate green phase. The set of control parameters is:

QC = Average queue length on the lanes served by the current green, in veh/lane.
QN = Average queue length on lanes with red which may receive green in the next phase, in veh/lane.
AR = Average arrival rate on lanes with the current green, in veh/sec/lane.
T_{MIN} = minimum green time for each phase, in sec.
T_{MAX} = maximum green time for each phase, in sec.

The fuzzy logic controller determines whether to extend or terminate the current green phase after a minimum green time of T_{MIN} has been displayed. If the green time is extended, then the fuzzy logic controller will determine whether to extend the green after a time interval Δt. The interval Δt may vary from 0.1 to 10 second, depending on the controller processor's speed. In this study, we choose Δt = 5 second. If the fuzzy logic controller determines to terminate the current phase, then the signal will go to the next phase. If not, the current phase will be extended and the fuzzy logic controller will make the next decision after Δt and so forth until the maximum green time is reached. The decision making process is based on a set of fuzzy rules in Table 4 [15], where *E* is short for *Extension*, and *T* is short for *Terminate*.

For example, the first line of Table 4 can be expressed as:

IF *Average queue length on lanes with green is short AND*
Average arrival rate on lanes with green is low AND
Average queue length on lanes with red is short
THEN *Extend the current green phase*

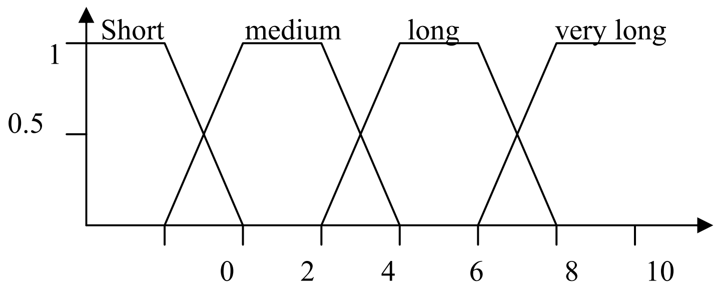

Figure 4: Fuzzy sets for QC and QN [15]

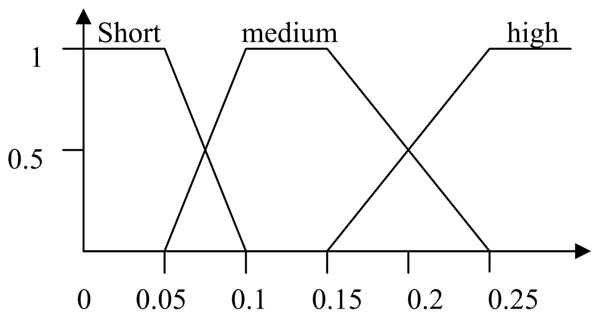

Figure 5: Fuzzy sets for AR [15]

Table 4: Fuzzy rules of green extender [15]

	Queue length		Arrival rate		Queue length		E/T
IF	QC is short	AND	AR is low	AND	QN is short	THEN	E
IF	QC is short	AND	AR is low	AND	QN is medium	THEN	T
IF	QC is short	AND	AR is low	AND	QN is long	THEN	T
IF	QC is short	AND	AR is low	AND	QN is very long	THEN	T
IF	QC is short	AND	AR is medium	AND	QN is short	THEN	E
IF	QC is short	AND	AR is medium	AND	QN is medium	THEN	T
IF	QC is short	AND	AR is medium	AND	QN is long	THEN	T
IF	QC is short	AND	AR is medium	AND	QN is very long	THEN	T
IF	QC is short	AND	AR is high	AND	QN is short	THEN	E
IF	QC is short	AND	AR is high	AND	QN is medium	THEN	E
IF	QC is short	AND	AR is high	AND	QN is long	THEN	T
IF	QC is short	AND	AR is high	AND	QN is very long	THEN	T
IF	QC is medium	AND	AR is low	AND	QN is short	THEN	E
IF	QC is medium	AND	AR is low	AND	QN is medium	THEN	E
IF	QC is medium	AND	AR is low	AND	QN is long	THEN	T
IF	QC is medium	AND	AR is low	AND	QN is very long	THEN	T
IF	QC is medium	AND	AR is medium	AND	QN is short	THEN	E
IF	QC is medium	AND	AR is medium	AND	QN is medium	THEN	E
IF	QC is medium	AND	AR is medium	AND	QN is long	THEN	T
IF	QC is medium	AND	AR is medium	AND	QN is very long	THEN	T
IF	QC is medium	AND	AR is high	AND	QN is short	THEN	E
IF	QC is medium	AND	AR is high	AND	QN is medium	THEN	E
IF	QC is medium	AND	AR is high	AND	QN is long	THEN	E
IF	QC is medium	AND	AR is high	AND	QN is very long	THEN	T
IF	QC is long	AND	AR is low	AND	QN is short	THEN	E
IF	QC is long	AND	AR is low	AND	QN is medium	THEN	E
IF	QC is long	AND	AR is low	AND	QN is long	THEN	E
IF	QC is long	AND	AR is low	AND	QN is very long	THEN	T
IF	QC is long	AND	AR is medium	AND	QN is short	THEN	E
IF	QC is long	AND	AR is medium	AND	QN is medium	THEN	E
IF	QC is long	AND	AR is medium	AND	QN is long	THEN	E
IF	QC is long	AND	AR is medium	AND	QN is very long	THEN	T
IF	QC is long	AND	AR is high	AND	QN is short	THEN	E
IF	QC is long	AND	AR is high	AND	QN is medium	THEN	E
IF	QC is long	AND	AR is high	AND	QN is long	THEN	E
IF	QC is long	AND	AR is high	AND	QN is very long	THEN	E
IF	QC is very long	AND	AR is low	AND	QN is short	THEN	E
IF	QC is very long	AND	AR is low	AND	QN is medium	THEN	E
IF	QC is very long	AND	AR is low	AND	QN is long	THEN	E
IF	QC is very long	AND	AR is low	AND	QN is very long	THEN	E
IF	QC is very long	AND	AR is medium	AND	QN is short	THEN	E
IF	QC is very long	AND	AR is medium	AND	QN is medium	THEN	E
IF	QC is very long	AND	AR is medium	AND	QN is long	THEN	E
IF	QC is very long	AND	AR is medium	AND	QN is very long	THEN	E
IF	QC is very long	AND	AR is high	AND	QN is short	THEN	E
IF	QC is very long	AND	AR is high	AND	QN is medium	THEN	E
IF	QC is very long	AND	AR is high	AND	QN is long	THEN	E
IF	QC is very long	AND	AR is high	AND	QN is very long	THEN	E

The parameters QC, QN and AR are characterized by trapezoidal fuzzy numbers depicted in Figures 4 and 5 [15].

The max-min composition method is applied for making inferences. The membership grades for E (Extend) and T (Terminate) are compared. The one with the highest membership grade is chosen as the control action.

3 Simulation Results

FSCS is evaluated against pre timed control strategies. The criteria used for the evaluation is the average length of queues in different roads of the intersection. The best control strategy is the one that provides the shortest average queue length.

The geometry of this intersection is shown in Figure 3. In addition, to present detectors at the stop line, all lanes have passage detectors upstream the stop line. Each simulation run is based on a 30-minute simulation time and the arrival rate of vehicles varying from 0.05 to 0.5. We consider the vehicle queue lengths of each lane, the vehicle numbers between the upstream detector and stop-line detector, so our method is better than the traditional control methods. The simulation results are listed in Tables 5 and 6, respectively.

Table 5: Simulation results with same arrival rate

road	T_{max} (s)	Arrival rate (veh/s)	Pretimed control	FSCS control
A	30	0.05	1.1528	1.1205
B	30	0.05		
C	30	0.05		
A	50	0.2	7.9444	6.0849
B	50	0.2		
C	50	0.2		
A	70	0.25	13.3135	9.5187
B	70	0.25		
C	70	0.25		
A	70	0.33	17.92	13.46
B	70	0.33		
C	70	0.33		
A	70	0.35	19.6071	14.1705
B	70	0.35		
C	70	0.35		
A	70	0.5	27.2937	13.6060
B	70	0.5		
C	70	0.5		

Table 6: Simulation results with different arrival rate

road	T_{max} (s)	Arrival rate (veh/s)	Pretimed control	FSCS control
A straight	70	0.25	7.6111	5.4450
A left turning	70	0.1		
B right turning	70	0.15		
B left turning	70	0.1		
C straight	70	0.15		
C turning	70	0.15		
A straight	60	0.25	6.2674	4.6775
A left turning	60	0.1		
B right turning	60	0.15		
B left turning	60	0.1		
C straight	60	0.15		
C turning	60	0.15		

The FSCS controller in all three trials for low arrival rates (0.05, 0.2, 0.25 veh/s) produces small improvements over the pre timed control strategy in term of average queues' length (Table 5), but in the other three trials for heavy arrival rates (0.33, 0.35, 0.5 veh/s), FSCS controller produces more significant improvements in the average queues' length over the pre timed control strategy (Table 5).

This simulation results indicate that FSCS controller can cause more improvement over pre timed control strategy at over-saturated intersections (Figure 6). The simulation results indicated in Table 6 imply that when arrival rates are different in roads of the intersection, FSCS controller also performs better than pre timed control strategy.

This fuzzy controller can be developed easily for every full intersection with two-way streets and left-turn lanes.

This fuzzy controller simulates the control logic of experienced humans such as police officers directing traffic who often replace signal controls when intersections experience unusual heavy traffic volumes. This fuzzy controller has the potential to improve operations at oversaturated intersections.

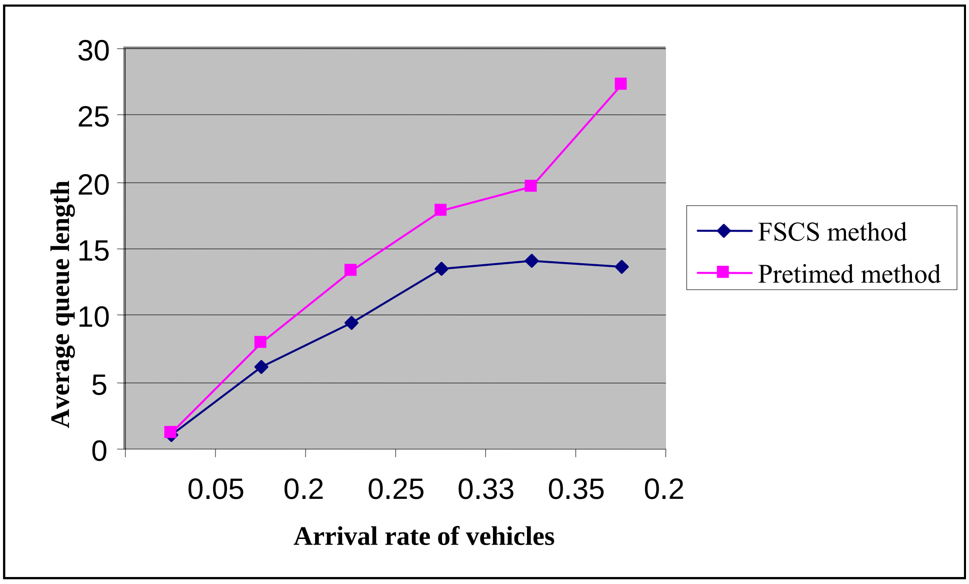

Figure 6: Simulation results with same arrival rate

4 Conclusions

The intelligent control of traffic in urban areas is the inevitable trend in future works, and FSCS is one of the most efficient methods. This paper proposed a new fuzzy control system for signal control of full intersection with two-way streets and left-turn lanes, which made decision based on the fuzzy rules and real time traffic information. Proposed fuzzy control system contained phase selector and green phase extender, which are located in different levels of the multi-level signal control strategy. The phase selector was working on the sequence level, while the green extender belonged to the green extension of the multi-level signal control system.

Some phase selecting methods will always be better than no selecting function at all. Relatively high improvement was found especially with high volumes, when the fuzzy phase selector was used. The green extender controller made the decision whether to extend or terminate the current green phase based on a set of fuzzy rules and real-time traffic information.

FSCS was compared with pre timed control strategy using a typical intersection in different traffic volume levels. FSCS showed substantial improvements over pre timed control strategy. Overall, the simulation results indicated that FSCS has the potential to improve operations at intersections.

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