Fuzzy Logic System for Coordinated Traffic Signal Control with Dynamic Phase Selection

Sistem Logika Fuzzy untuk Pengendali Sinyal Lalu Lintas Terkoordinasi dengan Seleksi Fase Dinamis

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Abstract – In this paper we will discuss a traffic light controller based on a Fuzzy Inference System (FIS) that can control multiple traffic intersections. The controller can adjust adaptively the phase lengths and phase sequences to optimize the movement of vehicles that will move straight or that will turn right. The Fuzzy System consists of three main modules namely the Green Phase Module, the Red Phase Module and the Decision Module. This system will determine which path will get the green phase and how long the green phase is given. A simulator for the intersection group has been developed to test the performance of the controller. The proposed controller is compared with two other traffic light controllers namely preset-cycle times (PCT) and vehicle-actuated (VA) controllers. The average delay time is used as the performance index. The results of simulation show good performances of proposed contoller over the PCT and AV controller. But in heavy traffic conditions, only a small improvement can be made.

Keyword : coordinated traffic systems, distributed controler, fuzzy controler, simulation

Abstrak – Pada paper ini kami akan membahas pengendali lampu lalu lintas bebasis Sistem Inferensi Fuzzy (FIS) yang dapat mengendalikan beberapa persimpangan lalu lintas yang berdekatan. Pengendali dapat menyesuaikan waktu dan urutan fase sinyal lampu lalu lintas secara adaptif untuk mengoptimalkan pergerakan kendaraan yang akan bergerak lurus maupun yang akan berbelok ke kanan. Sistem Fuzzy terdiri dari tiga modul utama yaitu Modul Fase Sinyal Merah, Modul Fase Sinyal Hijau dan Modul Keputusan Perubahan Sinyal. Sistem ini akan menentukan jalur mana yang akan mendapatkan fase hijau dan berapa lama waktu fase hijau akan diberikan. Simulator untuk kelompok persimpangan telah dikembangkan untuk menguji kinerja pengontrol. Kontroler yang diusulkan dibandingkan dengan dua pengendali lampu lalu lintas lainnya yaitu *Preset-Cycle Times* (PCT) dan *Vehicle-Actuated* (VA). Waktu tunda rata-rata digunakan sebagai indeks kinerja. Hasil simulasi menunjukkan kinerja yang baik dari pengendali yang diusulkan dibandingkan pengendali PCT dan AV. Tapi dalam kondisi lalu lintas yang padat, hanya sedikit perbaikan yang bisa dilakukan.

Kata Kunci – sistem lalu lintas terkoordinasi, pengendali terdistribusi, pengendali fuzzy, simulasi

I. INTRODUCTION

A. Motivation

Traffic congestion is one of the problems in big cities. Travel time, environmental quality, quality of life and road safety are severely affected due to this traffic congestion. One way to reduce traffic congestion at intersections is to use an effective intersection controller. Usually a conventional traffic signal controller uses the Preset Cycle Time (PCT) system or Vehicle-Actuated (VA) system. In the PCT system, the signal phase and length have been made constant. Although simple, but its performance is bad for heavy traffic conditions. In the VA system, the duration of green phase will be determined by checking wheter there still a vehicle on a track or whether the maximum time has been reached. But the large number of traffic cops at the intersections during the heavy traffic hours proves that the system is inadequate.

Because the traffic flow usually contains uncertainty and randomness, so intelligent controllers can be alternative to handle it. Fuzzy logic control has advantages to compensate nonlinearity and uncertainties. This article focuses on improving the performance of fuzzy logic systems to control a set of intersections with dynamic phase selection to optimize the movement of vehicles that will move straight or that will turn right (the vehicle can turn left directly because we use Indonesian case)

B. State of Art Overview

In recent years, the number of research based on traffic control using fuzzy theory has grown rapidly and continuously. Niittymaki and Pursula [1] report that using fuzzy logic controllers can be obtained shorter vehicle delays and lower stopping percentages based on result of isolated intersection simulation.

Zaied and Al Othman [2] developed a fuzzy logic traffic system applied to two two-way intersections and were able to adjust the time interval of traffic signal based on the level of density of traffic road. They test the proposed systems using real data collected from real intersection. They observed that the proposed system implementation proved useful to reduce vehicle delay time compared to existing systems.

Trabia et al. [3] design and evaluate fuzzy logic traffic signal controllers for isolated intersections. Controllers are built to be responsive to real-time traffic requests. Then they compare the performance of the proposed controllers with traffic-actuated controllers for various traffic conditions using traffic simulator of four intersection. They observed that the proposed controller is is capable of providing a lower vehicle delay than a traffic-actuated controller.

Jian et al. [4] proposed a two-stage fuzzy logic control model for isolated intersections, in which the traffic efficiency and fairness are considered simultaneously. Kosonen [5] presents a traffic signal control system based on a fuzzy inference system, multi-agent control scheme and real-time simulation. In control techniques, each signal operates individually as an agent and can negotiates with other signals about control strategies. The decisions are based on a fuzzy system thereby incorporating several aspects such as environment, economy, fluency, and safety.

Zarandi and Rezapour [6] proposed a fuzzy control system for incomplete intersections with two-way streets and left-turn lanes. The system will make decisions based on real time traffic information. Lee and Lee-Kwang [7] proposed a fuzzy controller for a set of intersections. Every controller can interract with its controller neighbors.

In general, the above researchers concluded that the performance of fuzzy logic controllers is better than that of pretimed and actuated controllers. However, most research only implements on a one-way street or one intersections. Whereas in the real world, especially in big city, many intersections are located close to each other, therefore, to effectively solve traffic problems, the traffic controller should be able to interract with neighbor's controllers. Indeed there are other studies that have considered a two-way street or intersection without changing the motion. But according to the best knowledge of the author, there is no previous research that discusses in detail about the traffic light with dynamic phase setting to optimize the vehicles to move either straight or turn right.

C. Content of the Paper

The paper is organized into five sections. In the second section, will be exlained summary of the basic theory of traffic signal control. In the third section, will be described the propose traffic controllers. In the fourth section, the performance of the propose traffic controller is evaluated by simulation. In the fifth section, we make a conclusion.

II. OVERVIEW OF TRAFFIC SIGNALS CONTROLLERS

A. Basic Terminologies

We will first explain some basic terms. The path connecting the two intersections is called a link. The complete sequence of all signal indications is called a cycle. The time duration of the signal generates is called a phase. **Fig. 1** shows a link between two junctions. And **Fig. 2** shows the cycle of four phases graphically. A phase is displayed through the image of the traffic flow that has a green signal. In **Fig. 2** Phase 1 shows the traffic phases from south to north and from south to east. The link capacity is the maximum number of vehicles that can exist in a link.

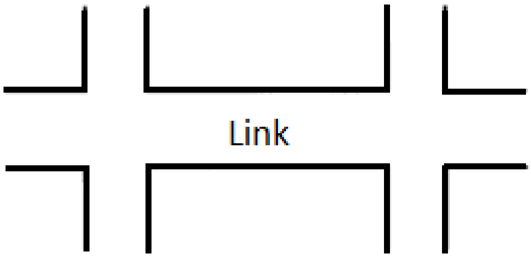


Fig. 1 Link

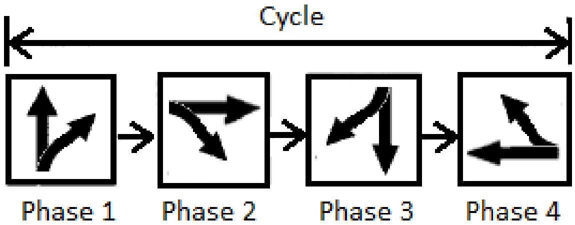


Fig. 2 Phase and Cycle

B. Preset Cycle Time (PCT) Controller

This controller has a pre-setting time (normally constans) for green, yellow and red light for each phase. The preset time cannot change adaptively according to the traffic density conditions. One of the disadvantage of this controller is if there a traffic jam on one of roads at the intersection, then the green light time can not change to prevent more vehicles from entering the roads. The next phase will continues without considering the traffic density at any intersection.

C. Vehicle Actuated (VA) Controller

The VA Controller uses a vehicle detector that will change the length of a green phase. In this controller, each lane at the intersection has a detector to detects whether there are car in the lane. This controller uses three parameters namely Initial Interval, Extension Unit and Extension Limit. When green phase started, the green light will light up during the Initial Interval time. When the Initial Interval has passed, the green signal will remain on during the Extension Unit time. If detected there are still vehicles within the Extension Unit range, then the green signal will remain on for one Extension Unit again. However, when the Extension Limit hase been reached, the green signal will not extended again. The example of phase time allocation in a VA controller is illustrated in [7, **Fig.3**]

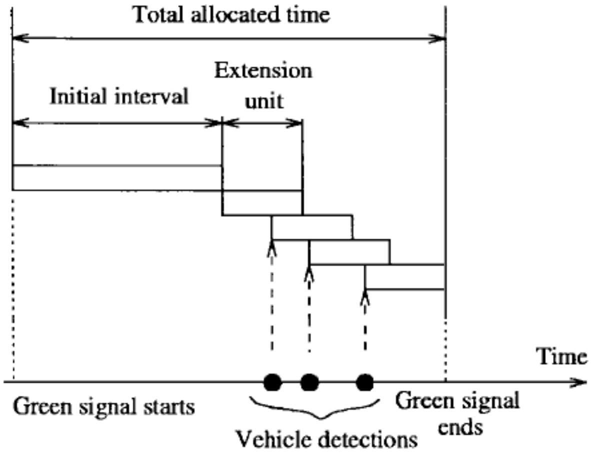


Fig. 3 Time allocation schematic diagram of the VA Controller

III. PROPOSED FUZZY CONTROLLER

A. Overview

In the design of the fuzzy controller, we consider three main features: to reduce the average waiting time of the waiting vehicle, to avoid heavy traffic jams in the intersections, and to synchronize the local traffic controller with its neighbors. So if a large numbers of vehicles are jammed at a neighboring intersection, the controller will set the traffic in such a way so the number of vehicles entering the intersection will decrease. The controller not only change the phase lengths, but also the phase sequences adaptively based onthe traffic condition.

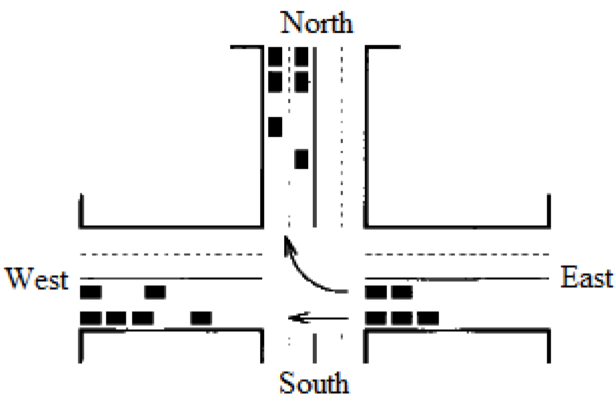
The controller uses three fuzzy inference system modules namely a Green Phase module, a Red Phase module and a Decision module.

The Red Phase module has a role to calculate the urgency to get green signal of all phases (except the green phase) and select the most urgent phase. The Green Phase Module is responsible to calculate the urgency of green phase traffic conditions to stay green, and the Decision Module decides whether to change the green phase according to the output of the Red Phase Module and The Green Phase Module. If the traffic conditions of the phase selected by the Red Phase Module are more urgent than the urgency of green phase then the Decision Module will redirect the green phase to the selected stage. Otherwise the green phase will continues.

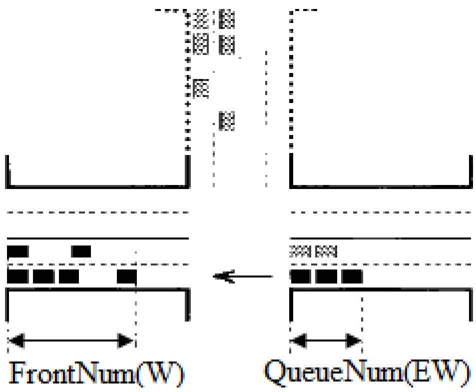
B. **Green Phase Module**

The Green Phase Module observes the green phase urgency to extend the green phase. The input of this module is *QueueNum* and *FrontNum*. The outpus is the *Extend Degree of Phase* (EDP). *QueueNum* is the number of vehicles left between Front and Rear Detector. *FrontNum* is the number of vehicles in the link where the vehicle will go. *EDP* is the level of urgency to extend the green phase.

When the green phase involves more than one traffic flow, this module evaluates the *Extend Degree* of all traffic flow associated with the phase. The *Extend Degree of a Traffic Flow (EDT*) represents the traffic condition of the trafic flow. From all EDT will be selected the minimum value becomes EDP of a phase. For example, if the current green phase is Phase 4 of **Fig. 2**. **Fig. 4** shows the variable we use in this condition. It is assumed that the outside lane is for the straight-moving vehicle and the inside is for the right-turning vehicle. Let us evaluate the EDT for each traffic flow. For the traffic from east to west, we get the number of vehicles waiting in the straight-going lanes of the east link : *QueueNum(EW)* and the number of waiting vehicles in the link between the intersection and its west intersection : *FrontNum(W)*. Then, we apply those values to the fuzzy rules of the GreenPhase Module and get the EDT of the straight-going traffic flow. The same process is also applied to the traffic from east to south. But, in this case, *QueueNum(EN)* is the number of vehicles waiting in the right-turn lanes and *FrontNum(N)* is the number of vehicles in the link between the intersection and its north intersection.



(a)



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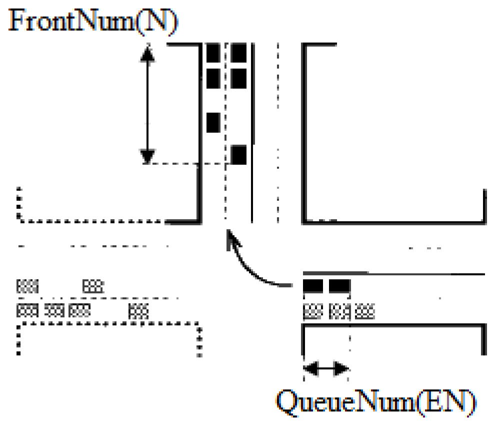

(c)

Fig. 4 *FrontNum* and *QueueNum* for evaluation the traffic from east
(a) Traffic conditions
(b) *FrontNum* and *QueueNum* of the traffic from east to west
(c) *FrontNum* and *QueueNum* of the traffic from east to north

Tabel I. The Rules of the Green Phase Module

		QueueNum				
		Z	**S**	**M**	**L**	**VL**
FrontNum	**Z**	Z	S	M	L	VL
	S	Z	S	M	L	L
	M	Z	S	S	M	M
	L	Z	S	S	S	S
	VL	Z	Z	Z	Z	Z

This module has 25 rules. **Tabel I** shows the rules of the GreenPhase Module. If the green signal has remained long enough, it will makethe number of remaining vehicles *(QueueNum)* become small. If *QueueNum* is small, the urgency of this phase to stay green will decrease. If there are many vehicles at the next intersection, we make the urgency of this phase to stay green will decrease to. So the number of vehicles that will enter the already crowded link will be reduced. **Fig. 5** shows the fuzzy membership function of *QueueNum*, *FrontNum*, and *Urgency*

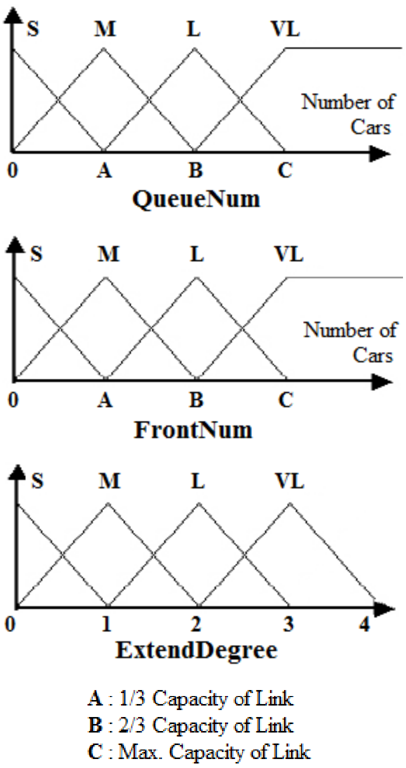

Fig. 5. The Membership Fuzzy of *FrontNum*, *QueueNum* and *ExtendDegree*

C. Red Phase Selector Module

This module calculate the urgency off all phases (except the green phase) to get green signal and select the most urgent phase as candidate for next green phase. . The inputs of this module are all phases except the current green phase and the outputs are the selected phase and its *urgency degree*. The *urgency degree of a phase* (UDP) means how bad the traffic condition of it phase. Then the UDP of all phase will compares to known which phase must be selected in the next green phase.

In order to get the UDP of a phase, this module evaluates the urgency degrees of all the traffic flows related with the phase. The *urgency degree of a traffic flow* (UDT) represents the traffic condition of the traffic flow. From all UDT will be selected the minimum value to be a UDP of a phase.

The fuzzy rules for evaluating the UDT of a traffic flow have three inputs *(QueueNum, RedTime,* and *FrontNum)* and one output *(Urgency)*. *QueueCar* is the number of vehicles waiting between the two detectors in a link, *RedTime* stands for the time duration that a traffic flow stays on red signal since the end of the last green signal for the traffic flow and *FrontNum* is the number of vehicles in the link between the intersection and the downstream intersection. The output, *Urgency*, is the UDT corresponding to the given traffic flow. The process to get UDP value from UDT is similar with process to get EDP from EDT value.

The fuzzy rules of the Red Phase Module are generated so that UDT increases proportionally to *QueueNum* and *Red-Time.* As the number of waiting vehicles increases and/or the red signal lasts longer, the traffic condition is considered to become more urgent. However, if *FrontNum* becomes large, UDT should decrease because a large value of *FrontNum* means that there are too many vehicles in the next intersection. Thus the number of vehicles entering the next intersection should be reduced.

Tabel II. The Rules of the Red Phase Module when *RedTime* is **Z**(Zero)

		QueueNum				
		Z	**S**	**M**	**L**	**VL**
FrontNum	**Z**	Z	S	S	S	M
	S	Z	S	S	S	S
	M	Z	S	S	S	S
	L	Z	S	S	S	S
	VL	Z	Z	Z	Z	Z

Tabel III. The Rules of the Red Phase Module when *RedTime* is **S**(Small)

		QueueNum				
		Z	**S**	**M**	**L**	**VL**
FrontNum	**Z**	Z	S	S	M	L
	S	Z	S	S	S	M
	M	Z	S	S	S	S
	L	Z	S	S	S	S
	VL	Z	Z	Z	Z	Z

Tabel IV. The Rules of the Red Phase Module when *RedTime* is **M**(Medium)

		QueueNum				
		Z	**S**	**M**	**L**	**VL**
FrontNum	**Z**	S	S	M	L	VL
	S	S	S	M	M	L
	M	S	S	S	M	M
	L	S	S	S	S	S
	VL	S	S	S	S	S

Tabel V. The Rules of the Red Phase Module when *RedTime* is **L**(Large)

		QueueNum				
		Z	**S**	**M**	**L**	**VL**
FrontNum	**Z**	Z	M	L	VL	VL
	S	Z	M	L	L	VL
	M	Z	M	M	L	L
	L	Z	S	M	M	M
	VL	Z	Z	Z	Z	Z

Tabel VI. The Rules of the Red Phase Module when *RedTime* is **VL**(Very Large)

		QueueNum				
		Z	**S**	**M**	**L**	**VL**
FrontNum	**Z**	Z	L	VL	VL	VL
	S	Z	L	VL	VL	VL
	M	Z	L	L	VL	VL
	L	Z	M	L	L	L
	VL	Z	Z	Z	Z	Z

In this Module, 125 rules have been developed as shown in **Tabel II – Tabel VI**. Membership Fuzzy of input and output variables are shown in **Fig. 6.**

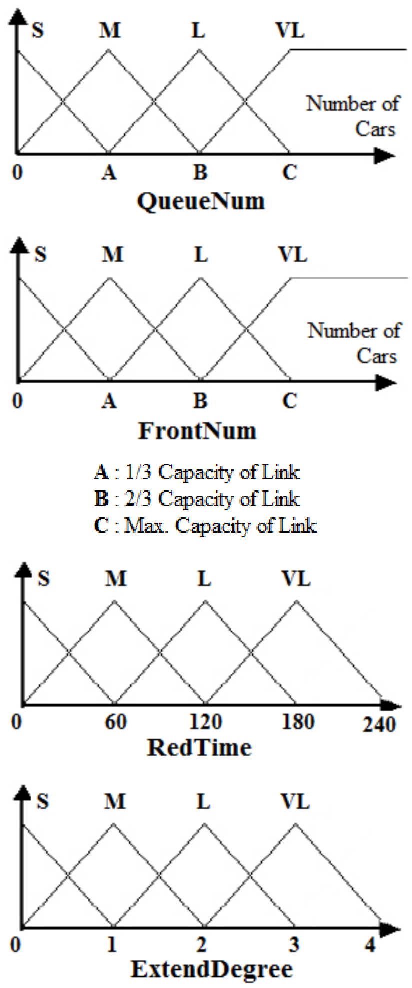

Fig. 6 The Membership Fuzzy of *FrontNum, QueueNum, RedTime* and *ExtendDegree*

D. Decision Module

The Decision Module makes decision whether to switch the green phase. Its inputs are the outputs from the Red Phase Modules and GreenPhase Module which are *Urgecy* and *ExtendDegree*. The outputs determines whether to change the phase or extend the green signal. If *Urgency* is higher then *ExtendDegree*, it means that the traffic condition for the next phase has heavier traffic than the current green phase, and thus the output will change the phase and give a green signal to the phase who has the highest value of *urgency*. The rules of this module are given in **Tabel VII**.

Tabel VII. The Rules of the Decision Module

		ExtendDegree				
		Z	**S**	**M**	**L**	**VL**
Urgency	**Z**	N	N	N	N	N
	S	Y	N	N	N	N
	M	Y	Y	N	N	N
	L	Y	Y	Y	N	N
	VL	Y	Y	Y	Y	N

This module will stop the green phase and give a green signal to *Candidate* if the urgency degree of the candidate or the stop degree of the current green phase is high. Table III contains some rules selected from the 15 rules of this module. says that although the candidate phase is congested *(Urgency* is **H**), if the stop degree is low *(Stop* is **N**) then keep the green phase *(Decision* is **N**, i.e., No changes). is the statement that `if` *Stop* `is` **M**(Maybe) `and` *Urgency* `is` **H**(High) `then` *Decision* `is` **Y**(Yes). The Membership Fuzzy of *Urgency* and *Stop* are the same as *Urgency* of the Red Phase Module and *Stop* of the Observation Module respectively. **Fig. 7** shows the Membership Fuzzy of *Decision*.

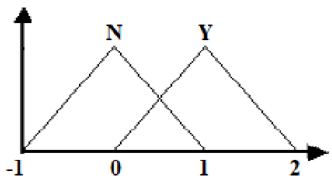

Fig. 7 The Membership Fuzzy of *Decision*

E. Vehicle Detectors

Vehicle detectors are important in the real-time control. It is assumed that there are two detectors to get local traffic information in a lane: the *Front Detector* and the *Rear Detector*. The Front Detector is located at the intersection and the Rear Detector is at a certain distance from the intersection. **Fig. 8.** shows the example location of the detectors. We assume that a detector can count the number of vehicles passing through it. Basically the detectors are located according to the link length.

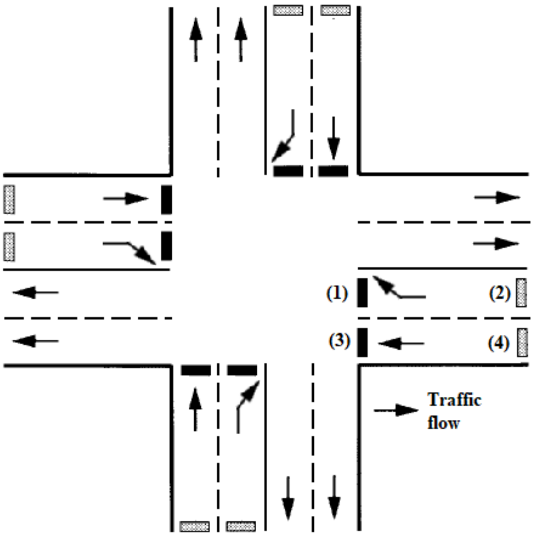

Fig. 8. Example location of the detector
(1) Front detector to detect a turning vehilce
(2) Rear detector to detect a turning vehicle
(3) Front detector to detect a straight vehicle
(4) Rear detector to detect a straight vehicle

A controller gets two kinds of information: traffic information from its local detectors and from its neighbors' through communication lines. Based on those information, the controller changes phase lengths and phase sequences dynamically. Every 5 s, the controllers gather the two types of information and decide whether to switch the green phase or not.

F. Signal Phases Proposal and Schematic Diagram of the Controller

Basically, controlling traffic signals is determining which phases are to be involved in a cycle and how long they should be. In the case of an ordinary four-way intersection, 12 phases are possible as shown in **Fig. 9.**. To create a traffic signal cycle, only a few phases are selected from the 12 phases so that all traffic flow has the opportunity to move forward. The fuzzy system will select which phases will be used in one cycle adaptively, adjusting to existing road density conditions. **Fig. 10** shows the example of schematic diagram of the controller if phase 1 of **Fig. 10** is a green phase now.

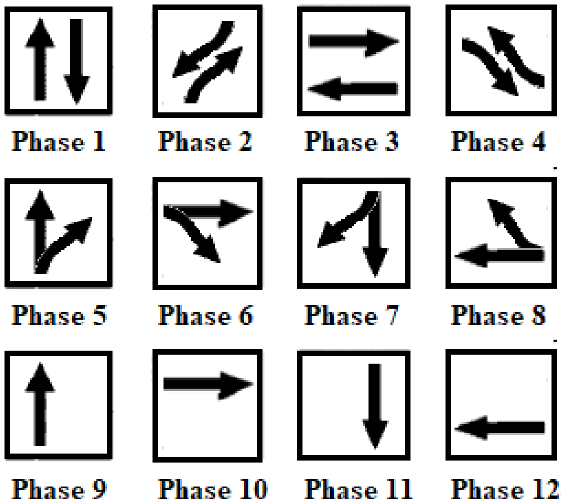

Fig. 9. Possible phase in an four-way intersection

IV. SIMULATION RESULT

The performance of the developed controller is evaluated by simulation. We will describe the developed simulator and present te simulation results.

A. Simulator

A simulator for intersection group has been developed to test the developed traffic controller. The simulated intersection model consists of nine intersections. Each intersection is connected with its neighborhoods in the four directions. Each link is two way and have capacity 250 cars. **Fig. 11.**. shows the simulated intersection group.

The intersection group are divided into four groups input-links according to the location of them: the north input-links, the west input links, the east input links and the south input links. We give the traffic generation plan to each input-link group, so all input-links in a group have the same plan. Cars are generated according to the given plan of a input link and inserted into the link. In the development of the traffic simulator, the following assumptions are made :

i) the intersection is four way junction with traffic coming from the north, west, east and south directions
ii) only passenger cars exist and there is no crosswalks.
iii) left turning traffic and right turning traffic are 30% of the traffic of a link respectively

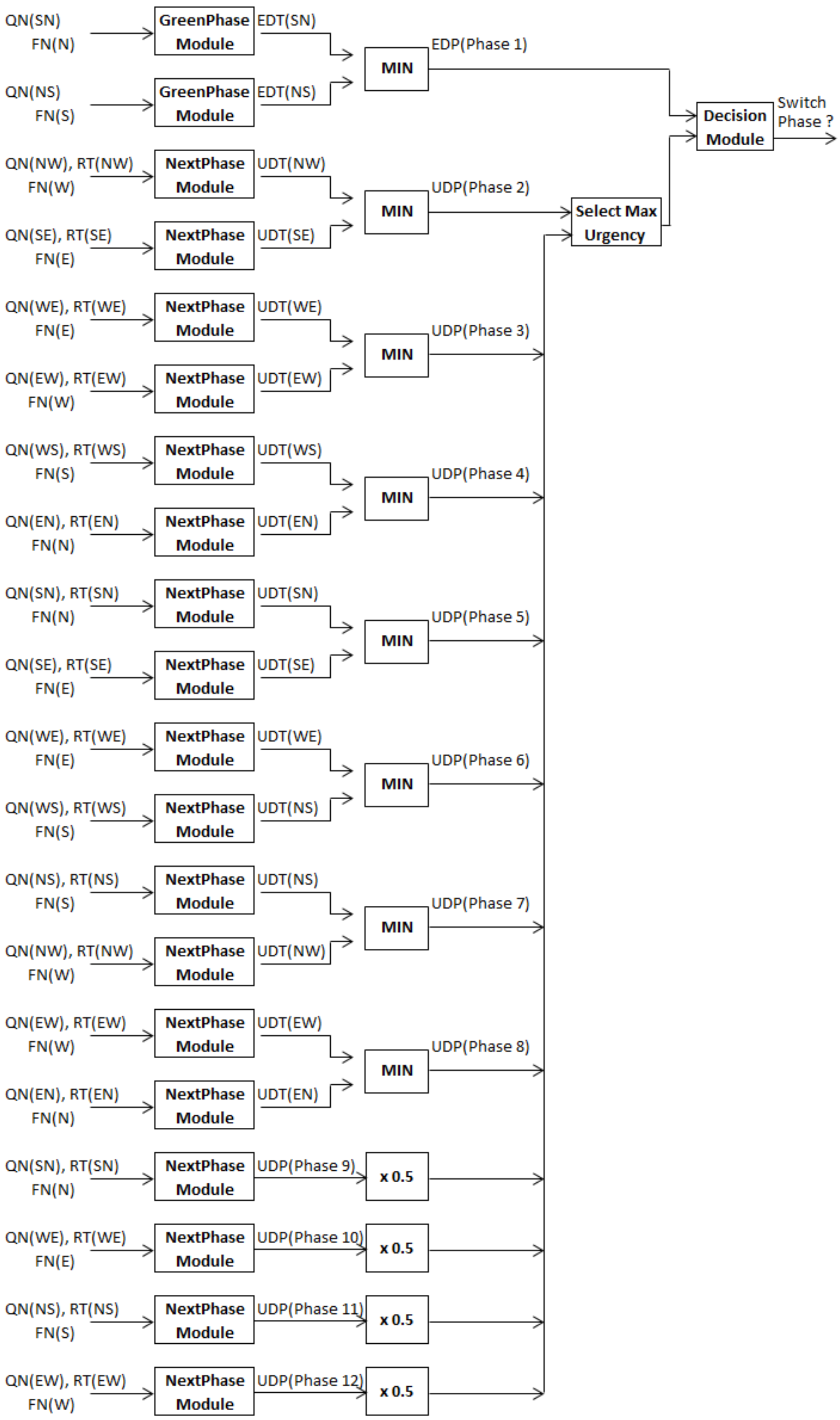

Fig. 10. Example schematic diagram of the controller if the green phase if phase 1 of **Fig. 9.**

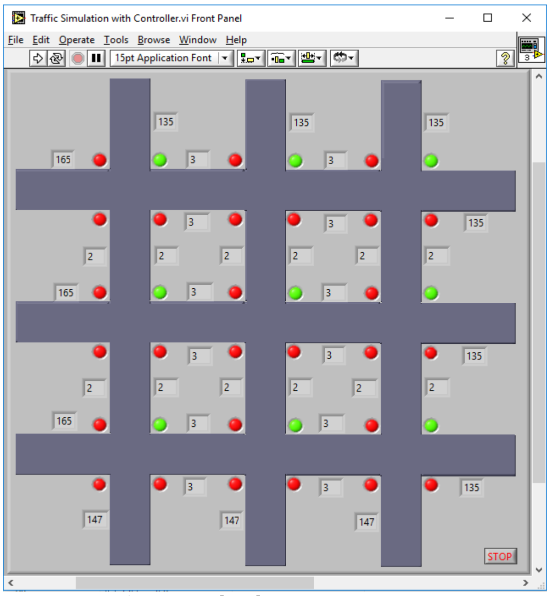

Fig. 8. Simulated Intersection Group.

In order to generate traffic flow, we use the car following model proposed by General motors. In the implementation of the model, some of the following conditioning are also applied.

1. A Driver will react to the change in speed of the front vehicle after a time gap called the reaction time.
2. The vehicle position, speed and acceleration will be updated at certain time interval
3. Vehicle position and speed is governed by Newton's laws of motion

The governing equations of a traffic flow is as follows :

$$v_n^t = v_n^{t-\Delta t} + a_n^{t-\Delta t} \times \Delta t \qquad (1)$$

$$x_n^t = x_n^{t-\Delta t} + v_n^{t-\Delta t} \times \Delta t + \frac{1}{2} a_n^{t-\Delta t} \Delta t^2 \qquad (2)$$

$$a_{n+1}^t = \left[\frac{\alpha_{l,m} (v_{n+1}^t)^m}{\left(x_n^{t-\Delta T} - x_{n+1}^{t-\Delta T}\right)^l} \right] \times \left(v_n^{t-\Delta T} - v_{n+1}^{t-\Delta T}\right) \qquad (3)$$

Where ΔT is the reaction time, Δt is the time interval, l is a distance headway exponent and can take values from -1 to +4, m is a speed exponent and can take values from -2 to +2, α is a sensitivity coefficient. The parameters can be calibrated using field data.

B. Simulation Results and Discussions

The developed controller was compared with PCT Controller and VA Controller. Simulation was performed under 18 situations. Six traffic plan

1) Case that the traffics of all input links are same :
   (a) 1600 cars/h
   (b) 1700 cars/h
   (c) 1800 cars/h
   (d) 1900 cars/h
   (e) 2000 cars/h
   (f) 2100 cars/h

2) Case that the traffic changes every 20 minutes
   (a) case of light traffic (cars/h)

Time	**0 – 20**	**20 – 40**	**40 – 60**	**60 – 80**
North	1500	1700	1900	2100
West	1400	1600	1800	2000
East	1300	1500	1700	1900
South	1500	1700	1900	2100

   (b) case of normal traffic (cars/h)

Time	**0 – 20**	**20 – 40**	**40 – 60**	**60 – 80**
North	1700	1850	2000	2100
West	1600	1750	1900	2000
East	1500	1650	1800	1900
South	1700	1850	2000	2100

   (c) case of heavy traffic (cars/h)

Time	**0 – 20**	**20 – 40**	**40 – 60**	**60 – 80**
North	1900	2000	2100	2200
West	1800	1900	2000	2100
East	1700	1800	1900	2100
South	1900	2000	2100	2200

The average delay time of a car per intersection was collected as an index of performance. The simulation results are summarized in and **Table. VIII** and **Table IX.** Each table shows the delay time measured in second and the improvement of the proposed method over the PCT Controller and VA Controller.

Table VIII. Average delay time for Case 1

Case	**Fuzzy Controller**	**VA Controller**	**PCT Controller**	**Improvement than VA Controller**	**Improvement than PCT Controller**
1.a	52.2	55.6	57.6	6.2%	9.4%
1.b	60.7	68.5	69.8	11.4%	13.0%
1.c	63.7	68.3	70.3	6.8%	9.4%
1.d	65.4	69.2	70.8	5.5%	7.6%
1.e	71.6	77.6	79.2	7.8%	9.6%
1.f	99.7	102.5	104.2	2.8%	4.3%

Table IX. Average delay time for Case 2

Case	Fuzzy Controller	VA Controller	PCT Controller	Improvement than VA Controller	Improvement than PCT Controller
2.a	59.2	65.0	65.6	8.9%	9.8%
2.b	64.6	71.9	72.9	10.2%	11.4%
2.c	72.4	75.1	75.4	3.6%	4.0%

The proposed method shows good performance in all cases. In steady traffic conditions, it shows improvements from 2.8% to 11.4 over the VA controller and from 4.3% to 13.0 % over the PCT controller. In time-varying conditions, improvement from 3.6 % to 10.2 % were obtained over VA controller and from 4.0% to 11.4% over PCT controller. Only in heavy traffic conditions, the proposed method only shows small improvement (.8% - 4.3%).

V. CONCLUSIONS AND FUTURE WORKS

In this paper, we have proposed a traffic contoller base fuzzy logic system for controlling a set of intersections with respect to the presence of vehicles which will move straight or that will turn right. To control a set of intersection, we distribute controls to each controller. The controller not only manages its local traffic but also cooperates with its neighbors. The controller gets information from its detectors and its neighbors. According to the simulation results, the proposed controller show the better performancein terms of average delay time over the AV Controller and PCT controller. But in heavy traffic conditions, the proposed controller only show a small improvement.

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