Application of fuzzy logic to traffic signal control under mixed traffic conditions

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Fuzzy logic has been widely used to develop an adaptive traffic signal controller because it allows qualitative modelling of complex systems. However, existing research has developed fuzzy logic signal controller (FLSC) based on non-mixed traffic conditions. These FLSC are not appropriate to the mixed traffic conditions of developing countries where the traffic streams consist of different types of vehicles with a wide variation in their static, dynamic and operating characteristics. This paper describes an adaptive fuzzy logic signal controller for an isolated four-way intersection suitable for mixed traffic, including a high proportion of motorcycles. Simulations are used to analyse the effectiveness of the proposed FLSC which is contrasted with an optimised fixed time controller.

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Traffic signal control is one measure that is commonly used at road intersections to minimise vehicular and/or pedestrian travel times and delays. Traffic signal control at road intersections allows vehicle movements to be controlled by allocating time intervals, during which separate traffic demands for each approach of the intersection can make use of the available road space. Traffic signal control in most signalised intersections in Indonesia is done with fixed time signal control. Under fixed time control, all signal timing parameters are pre-computed and kept constant. These parameters are calculated based on historical traffic data. This method usually shows good results in normal traffic conditions, but sometimes they fail to cope with complex, time varying traffic conditions (Lee et al, 1995; Trabia and Kaseko, 1996; Kim, 1997). Vehicle actuated (VA) control presents an improvement over fixed time control. The VA control principle aims to adjust the length of green time in response to the real traffic flow variations. VA control requires vehicle detectors to provide accurate information of traffic in real-time. This method has limited ability to respond to real-time traffic demand, where its performance generally deteriorates with heavy traffic conditions (Trabia et al, 1999). To overcome such problems adaptive traffic signal controllers are designed to address those deficiencies.

Figure 1: The layout of an intersection

Fuzzy logic has been used widely to develop an adaptive traffic signal controller, because it allows qualitative modelling of complex systems, where it is not easy to solve using mathematical models (Lee et al, 1995; Kou, 1995; Niittymaki and Pursula, 2000) and is good for systems that have inherent uncertainties (Trabia et al, 1999). Many researchers have proposed the prototype traffic signal control systems using fuzzy logic. Pappis and Mamdani (1977), Chakraborty and Sarkar (1997), and Niittymaki and Pursula (1996, 2000) developed a fuzzy logic signal controller (FLSC) for an isolated intersection of simple one-way east-west/north-south without turning movement. Kelsey and Bisset (1993), Kim (1994), Khiang et al. (1995), and Trabia and Kaseko (1996) proposed a FLSC for an isolated intersection of four-way east-west/north-south without turning movement.

All of the above research has reported generally a better performance of the FLSC when compared to fixed time and actuated controllers. However, all existing research has developed FLSC based on non-mixed traffic conditions (developed countries), where they considered the passenger car only and neglect motorcycles in their traffic. It is quite different to that in mixed traffic conditions (developing countries), where the traffic streams are heterogeneous, consisting of different types of vehicle with wide variation in their static, dynamic and operating characteristics, and with a particularly high proportion (30% - 70%) of motorcycles. Due to lack of lane discipline, queues at intersections are built up based on the optimum road space utilisation which means vehicles can occupy any position across the road based on the available space. It is obvious that traffic behaviour in mixed traffic conditions is different to that in non-mixed traffic conditions. Therefore, the main objective of this research is to design an adaptive fuzzy logic signal controller for an isolated four-way intersection with reference to mixed traffic (including high proportion of motorcycles). Simulations are used to examine and analyse the effectiveness of the proposed FLSC. Then, the performance of the proposed controller is contrasted with an optimised fixed time controller.

DESIGN CRITERIA AND CONSTRAINTS

In designing the FLSC system the following assumptions are made:

1. The intersection is an isolated four-way intersection with traffic coming from west, east, north and south, without turning movements (Figure 1).
2. The signal is a two-stage signal, east-west and north-south.

OVERVIEW OF CONTROL STRATEGIES

The performance of an isolated intersection under the control of the proposed FLSC is contrasted to that under the optimised fixed time controller. The performance criteria used for comparison are the average travel time and average delay of vehicles. Thus, the objective of the traffic controller is to minimise the average travel time and average delay of vehicles.

Fixed time control

Fixed time control uses a preset cycle time and green time to change the signals. The design of a signal-timing plan in Indonesian traffic is carried out using the techniques delineated in the Indonesian Highway Capacity Manual (1997). The optimum cycle length (seconds), according to the Indonesian Highway Capacity Manual, is calculated by the equation below:

$$C = \frac{1.5LTI + 5}{1 - \sum FR_{CRIT}} \qquad [1]$$

where, LTI is the lost time per cycle (seconds) and FR_{CRIT} is the summation of maximum ratios of flow to saturation flow for all N stages. for all N stages.

$$\sum FR_{CRIT} = \sum_{n=1}^{N} FR_{CRIT\,n} \qquad [2]$$

The green time of the n^{th} stage which gives the least overall delay to all traffic using the intersection is calculated by:

$$g_n = (C - LTI)\frac{FR_{CRIT\,n}}{\sum FR_{CRIT}} \qquad [3]$$

where, FR_{CRITn} is the maximum ratios of flow to saturation flow among the signal group for the same stage.

Proposed fuzzy logic signal controller

The structure of the proposed FLSC system is illustrated in Figure 2. As an adaptive traffic signal controller, the FLSC needs vehicular detectors to provide accurate information of the prevailing traffic conditions in real-time. This information is used as an input data for the controller. In this research, an advanced video image processing (VIP) is used to detect traffic parameters, instead of inductive loops. The reasons are: the wide area of coverage by VIP results in improved detection in multi-lane or non-lane based conditions (as found in mixed traffic conditions) and with inter-vehicle space (where motorcycles are likely to be found) being treated with the same importance as the centre of a lane (Powell, 1997). Also, VIP can measure directly queue length (in metres) every second, where inductive loops cannot (Higashikubo et al, 1996).

In the proposed FLSC two fuzzy input variables are chosen, namely:

1. Maximum Queue Length (in metres). Queue length is defined as the distance in metres from the stop-line over which vehicles have queued. During the red period VIP records the longest tail of queue (i.e. maximum queue length) irrespective of the lane in which it occurred. Then the maximum queue length at the onset of green periods is used as an input.
2. Average Occupancy Rate (in %). Occupancy Rate is the percentage of time that the detection area was occupied by one or more vehicles. The detection area is placed on 1 metre downstream of the stop-line. During the green period VIP records occupancy rate and the average occupancy rate on that period is used as an input.

The output fuzzy variable of the proposed FLSC is Weight. Weight (a value between 0 and 100) is an indicator of the degree of need signal group (SG) requires green. For example, if Weight SG1 is 75 and SG2 is 25, it means that, SG1 needs green longer than SG2.

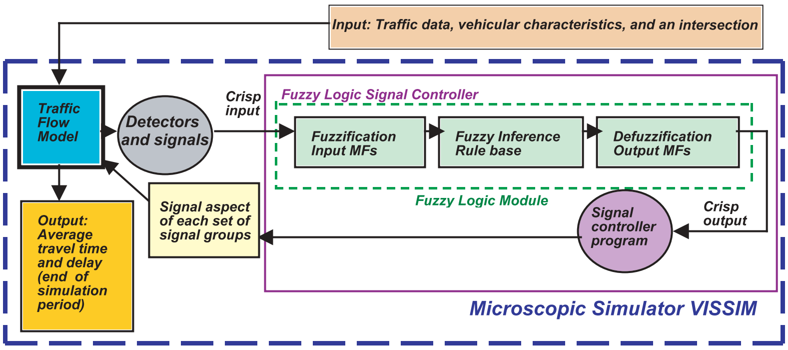


Figure 2: Structure of the fuzzy logic signal controller system

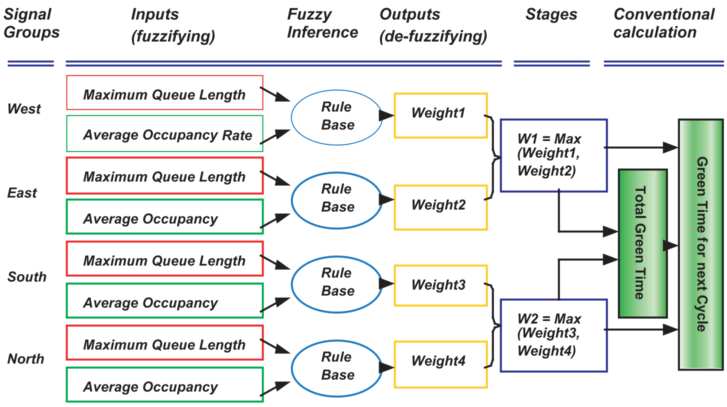


Figure 3. Calculation of new green time value for the next cycle using traffic data from previous cycle

Fuzzy control strategies

Figure 3 shows the process of calculation of new green time required by each set of signal groups (stage) during the next cycle using traffic data from previous cycle.

The Fuzzy Logic Module uses the fuzzy input variables maximum queue lengths and average occupancy rates collected during the previous cycle to derive weight values of each SG using the fuzzy rule base. The maximum weight value between SG west and east is chosen as the weight value for stage 1 (W1). This method is applied for stage 2 (W2) as well. Then weight values of stage 1 and stage 2 are used to calculate the total green time in a cycle. The weight values of stages and the total green time in a cycle are then used to estimate the duration of green time that stages require in the next cycle. Both total green time and green time of each stage are calculated using conventional calculation. The calculation of total green time is according to equation 4.

$$Total\_GT = (\Sigma W_n - Min1)*\left[\frac{(Max2 - Min2}{Max1 - Min1}\right] + Min2 \qquad [4]$$

The green time of each stage is calculated by equation 5.

$$GT\_Stage_n = \frac{W_n * Total\_GT}{\Sigma W_n} \qquad [5]$$

where:

ΣW_n = total weight of stages

Min1 and Max1 = minimum and maximum value of total weight, namely 0 and 200 respectively

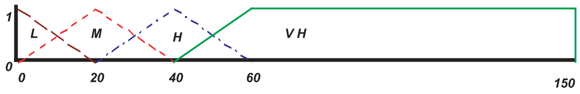
Min2 and Max2 = minimum and maximum value of total green time in a cycle

n = stage index

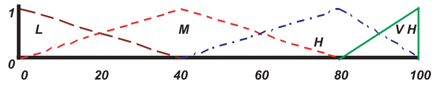
Input and Output Membership Functions

The types of membership function used in this study are triangular and trapezoidal due to computational efficiency (Zimmermann, 1996). Membership functions (MFs) of each input and output fuzzy variable of the proposed FLSC are as follows: Maximum Queue Length and Average Occupancy Rate have {Low, Medium, High and Very High} and Weight has {Very Very Low, Very Low, Low, Medium, High, Very High and Very Very High} linguistic labels respectively. The graphical representation of the MFs of these linguistic variables is presented in Figure 4. The configuration of these MFs is done according to expert observation of the system; the MFs are tuned by studying the performance of the controller under various conditions to improve the performance of the controller (Trabia et al, 1999; Sayers et al, 1996).

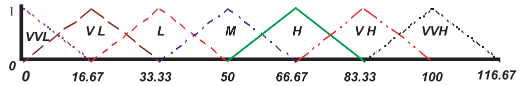
Figure 4: Graphical representation of input and output membership functions of the proposed FLSC



(a) Input Fuzzy Variable 1: Maximum Queue Length (metres)



(b) Input Fuzzy Variable 2: Average Occupancy Rate (%)



(c) Output Fuzzy Variable: Weight

Fuzzy rule base

The basic function of the fuzzy rule base is to represent the expert knowledge in a form of If-Then rule structure. The fuzzy rule base is a set of fuzzy rules. It maps the combination of the fuzzy inputs to the fuzzy output. The number of rules is equal to the number of input combinations derived from the number of MFs per input. The proposed FLSC has two inputs each having four MFs, so the number of fuzzy rules would equal sixteen. The configuration of fuzzy rules in matrix structure of the proposed FLSC is shown in Figure 5. An example of fuzzy rule 9 is:

IF Max. Queue length is High AND Avg. Occupancy rate is Low THEN Weight is Medium

Figure 5: Fuzzy rule base in matrix structure to derive weight value for each signal group

Maximum Queue Length

Average Occupancy Rate

	L	**M**	**H**	**VH**
L	VVL	L	**M**	H
M	VL	L	H	VH
H	L	M	H	VVH
VH	M	H	VH	VVH

Inference engine and defuzzification

The fuzzy inference evaluates the control rules stored in the fuzzy rule base. The fuzzy inference system used is Mamdani (1975) method (max-min composition). Defuzzification is a process to convert the fuzzy output values of a fuzzy inference to real crisp values. In this research, the Centre-of-Sum is used to process defuzzification of the output variable Weight. This method gives better performance in term of continuity, disambiguity, plausibility, computer complexity and weight counting (Driankov et al, 1996).

SIMULATION TOOL

The simulation package VISSIM has been interfaced with the proposed FLSC to examine and analyse the effectiveness of the controller (Figure 2). VISSIM consists internally of two primary components. The first is the traffic flow model, where the user graphically builds the network and generates traffic. Built-in fixed time control can be implemented in the traffic flow model. Secondly is the signal control model (external signal state generator), where the user has the ability to define actuated signal control logic. The actuated control logic is developed using VAP (Vehicle Actuated Programming).

VISSIM is a lane-based model. It means that all vehicles move in clearly defined lanes, each lane being occupied by one vehicle transversely. This is not the norm in mixed traffic, where one lane can be occupied by more than one vehicle, especially motorcycles. In this research, therefore, a packet approach was applied for simulating mixed traffic conditions. The principle of the packet approach is not new. It has been used in CONTRAM (Taylor, 1990) quite successfully. However, in the current study, the packet approach is applied exclusively for motorcycles. A packet (called motorcycle packet/MCP) in this case consists of two or more motorcycles. Based on the results of the performance analysis, the model containing 50% 2MCP (2 motorcycles in a packet) and 50% 4MCP (4 motorcycles in a packet) produced outputs that consistently matched the observed data, in terms of queue length, throughput, travel time and delay (Yulianto, 2002).

A new approach has been proposed in this research in that both the fuzzy logic module and signal controller program were developed using VAP. By this approach, the signal controller program can interact directly with VISSIM via external signal state generator. This approach is of less computational complexity than if we develop fuzzy logic module using commercial fuzzy logic toolbox (eg SIEFUZZY) or using C programming language. This is because by this approach we need several interfaces, such as firstly we need to interface between the fuzzy logic module and the signal controller program, and then between signal controller program and VISSIM via Dynamic Data Exchange to transfer data from signal controller program to VISSIM and vice versa.

CASE STUDY AND RESULTS

In order to evaluate the effectiveness of the controllers, we carried out four different types of case, namely:

- Case that the traffic flow is constant during one-hour period.
- Case that the traffic flow varies, every 15 minutes the traffic changes .
- Similar to case 2, but the traffic composition is different
- Case that the traffic flow used is based on real data from Sutomo-Diponegoro signalised intersection in the city of Surabaya-Indonesia .

For the optimised fixed time controller, the cycle length and green time was calculated using equations 1 and 3, respectively. Table 1 shows the cycle time and green time used for the fixed time controller. In the proposed FLSC, minimum and maximum total green time is 10 and 52 seconds, respectively. Amber and all red period are 3 and 1 seconds, respectively for both controllers. A simulation run is made for approximately one-hour periods to produce the output average travel time and average delay of vehicles.

Table 2 gives the simulation results of the optimised fixed time controller and the proposed FLSC in terms of the average travel time and average delay of vehicles for cases 1, 2, 3 and 4. The results for case 1 show that generally the proposed FLSC and the optimised fixed time controller produce little difference in results. The results for case 2 indicate that the proposed FLSC performs much better than the optimised fixed time controller for all different set traffic volumes (2a–2k). The results for case 3 show that the proposed FLSC outperforms the optimised fixed time controller for all different set traffic volumes, except on case 3e. In saturated conditions (3e), the proposed FLSC and the optimised fixed time controller produce similar results. The results for case 4 indicate that the proposed FLSC has lesser average travel time and average delay than the optimised fixed time controller. It reveals that the proposed FLSC can adjust the duration of green time in response to changing traffic conditions on a real-time basis.

Case	Green Time		Cycle Time	Case	Green Time		Cycle Time	Case	Green Time		Cycle Time
	N-W	N-S			N-W	N-S			N-W	N-S	
1a ; 2a	10	11	29	1g ; 2g	16	20	44	3a	12	12	32
1b ; 2b	11	14	33	1h ; 2h	18	27	53	3b	13	17	38
1c ; 2c	11	18	37	1i ; 2i	21	37	66	3c	14	24	46
1d ; 2d	12	24	44	1j ; 2j	22	22	52	3d	19	19	46
1e ; 2e	14	31	53	1k ; 2k	26	32	66	3e	22	28	58
1f ; 2f	15	15	38					4	24	24	56

Table 1:
Cycle time and green time (in seconds) used for the optimised fixed time controller

CONCLUSIONS

In this paper, a new FLSC for an isolated four-way intersection with specific reference to mixed traffic including high proportion of motorcycles has been proposed. An advanced VIP was used to capture maximum queue length (in metres)

Table 2: The average travel time and average delay of vehicles of the optimised fixed time controller and the proposed FLSC for cases 1, 2, 3 and 4.

Case	Average Travel Time (sec)			Average Delay (sec)		
	Fixed Time	FLSC	Improvement (%)	Fixed Time	FLSC	Improvement (%)
1a	29.0	28.8	0.5	10.1	10.0	1.5
1b	29.9	30.4	-1.5	11.0	11.5	-4.1
1c	31.3	31.2	0.2	12.4	12.4	0.4
1d	33.8	33.1	2.1	14.9	14.3	4.6
1e	36.1	36.6	-1.4	17.2	17.7	-2.8
1f	31.6	31.9	-0.8	12.7	13.0	-2.0
1g	33.3	33.6	-1.2	14.4	14.8	-2.7
1h	35.8	35.5	0.9	17.0	16.6	1.8
1i	40.5	39.3	3.0	21.6	20.4	5.5
1j	35.7	35.5	0.7	16.9	16.6	1.5
1k	39.4	39.1	0.9	20.6	20.2	1.6
2a	33.1	29.6	10.4	14.2	10.8	24.1
2b	35.4	31.8	10.4	16.5	12.8	22.3
2c	41.7	33.0	20.9	22.8	14.0	38.3
2d	48.7	36.4	25.2	29.8	17.5	41.3
2e	52.9	42.9	18.9	33.9	23.9	29.4
2f	37.1	32.6	12.0	18.2	13.7	24.5
2g	40.7	35.8	12.0	21.7	16.8	22.6
2h	49.5	40.5	18.1	30.6	21.6	29.4
2i	58.3	48.9	16.2	39.4	30.0	23.8
2j	38.2	36.8	3.7	19.3	18.2	5.8
2k	44.6	43.2	3.2	25.8	24.3	5.6
3a	41.8	33.8	19.2	22.4	14.3	36.0
3b	48.1	39.6	17.6	28.7	20.2	29.7
3c	51.4	40.7	20.7	31.9	21.2	33.4
3d	51.8	48.3	6.7	32.4	28.9	10.7
3e	52.2	52.3	-0.2	32.7	32.9	-0.4
4	35.8	34.7	3.0	17.3	16.3	6.1

Figure 1A: Set of traffic volumes (vehicles/hour) used in th simulation for Cases 1,2,3,4.

Case	Traffic Volumes		Case	Traffic Volumes		Case	Traffic Volumes	
	E-W	N-S		E-W	N-S		E-W	N-S
1a ; 2a	1080	1080	1g ; 2g	1440	1800	3b	1080	1440
1b ; 2b	1080	1440	1h ; 2h	1440	2160	3c	1080	1800
1c ; 2c	1080	1800	1i ; 2i	1440	2520	3d	1440	1440
1d ; 2d	1080	2160	1j ; 2j	1800	1800	3e	1440	1800
1e ; 2e	1080	2520	1k ; 2k	1800	2160	4	1935 (E)	2071 (N)
1f ; 2f	1440	1440	3a	1080	1080		2031 (W)	1848 (S)

and average occupancy rate (in %) from each approach of the intersection as an input data for the proposed FLSC. The proposed FLSC uses maximum queue length and average occupancy rate collected during the previous cycle in order to estimate the length of green time required by each stage during the next cycle. This enabled the framework signal plan to be adapted on a cycle-by-cycle basis.

The proposed FLSC and optimised fixed time controller produce little difference in results in terms of average travel time and average delay when used in cases with constant traffic flow. Whereas, in cases of time-varying traffics, the proposed FLSC is superior to the optimised fixed time controller. But when the traffic becomes saturated, the proposed FLSC produces similar results to the optimised fixed time controller.

The performance of FLSC is affected by the configuration of the MFs of input/output variables and the rule base. In order to optimise the performance of the proposed controller it can be done by optimising the MFs and the rule base using genetic algorithms. This case is beyond the scope of this research. The proposed FLSC is currently being extended to include right turning movements for an isolated intersection.

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