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OPTIMIZATION OF TRAFFIC SIGNAL TIMING ON ROAD NETWORK USING CELLULAR AUTOMATA AND FUZZY INFERENCE SYSTEM

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ABSTRACT

The large number of vehicles in big cities has become a serious problem in adjusting the timing of traffic signal at intersections of road networks. Traffic light control is an important factor in road traffic system. In this paper, optimization of traffic signal timing at signalized intersections on road network is presented. The movement of vehicles on road network is modeled by cellular automata while the fuzzy inference system is used to obtain optimal traffic signal timing. The performance of fuzzy inference system is determined by the delay time average at signalized intersections. Delay time is addition time required by a vehicle to pass through signalized intersection compared to road without intersection. Cellular automata and fuzzy inference system are running together through computer simulation program. The optimal signal timing from the simulation is compared to fixed time or static scheme which is obtained from historical data of six signalized intersections in Bandung City, Indonesia. The numerical results show that traffic signal duration obtained from fuzzy inference system is more efficient than the existing historical data of observation and it can reduce the level of congestion. The simulation results also show that the traffic signal timing can adjust with the number of incoming and outgoing of vehicles at the intersections on road network. The results can be suggested to the local government to improve the traffic signal system.

Keywords: *Optimization, Traffic Signal Timing, Road Network, Fuzzy Inference System, Cellular Automata*

1. INTRODUCTION

In big cities with large population, the number of vehicles increases every day. In contrast, there is no improvement of traffic infrastructures such as traffic light at an intersection. It has made traffic congestion is getting worse mainly at intersections. One of the solution to reduce heavy traffic congestion is by readjusting traffic signal with the number of incoming and outgoing vehicles in order to remain proportionate. The solution refers to adaptive setting of traffic light control system.

Fuzzy inference system is a method that can be used to assign an adaptive setting of traffic light control system. Through the adaptive control scheme, timing of the traffic light can be more appropriate with the number of vehicles on each road. There are several methods in traffic light control, such as genetic algorithm [1-3], fuzzy inference system [4-5], queue theory [6], and PSO algorithm [7]. However, fuzzy inference system has not been able yet to give the performance of traffic light control system. Fuzzy inference system only shows the green light timing without measuring its performance. Therefore, besides fuzzy inference system, it requires another method to measure the performance.

Cellular automata can be used to estimate fuzzy inference system performance. Cellular automata method can model the movement of vehicles [8-9]. By using cellular automata, all vehicle delays at a signalized intersection are stored as information. Then, the information is analyzed so that the performance of any given traffic light duration can be calculated. By combining cellular automata and fuzzy inference system into simulation program, the optimal traffic light timing can be obtained. Fixed time or static traffic light timing which is obtained from historical data of observation can be used as a comparison for fuzzy inference system performance.

This study focuses on optimization of traffic signal timing on road networks using cellular automata and fuzzy inference system. The optimal

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results are then compared to fixed time scheme which is obtained from historical data of six signalized intersections in Bandung City, Indonesia. The results of this study are delay time average and optimal green light timing for each signalized intersection. This paper is organized as follows. In Section 2, vehicles movement model on road network using cellular automata is briefly presented. Fuzzy inference system which is used to obtained optimal traffic sginal timing is discussed in Section 3. Simulation setup and discussion of simulation results are presented in Section 4 and Section 5, respectively.

2. VEHICLES MOVEMENT MODEL

Vehicles movement on road networks can be modeled by using cellular automata. Cellular automata can be described as collection of cells or arrays which can change the state in each time step according to certain rules. Here, the rules operate based on the principles of neighborhood system [10]. In cellular automata, the rules are aimed to change the state cells from one time step to the next time step until all iterations are completed. Cellular automata are also used as model to various kinds of physical case studies and some cases that can be transformed into a discrete form [10]. Moreover, in cellular automata, every road characteristic is approached by the actual situation.

The procedure of vehicles movement using cellular automata consists of change lane rules and movement rules. Change lane rules are operated in order to a vehicle which is represented by a single cell can move to the cell located on the left or right [8]. The change lane rules refer to Von Neumann neighborhood [10]. Illustration of how the vehicles can change the lanes is described in Fig. 1. The change lane of vehicles is addressed only on lanes which certain conditions such as the blocked lanes and or on the lanes with no vehicles. Furthermore, the change lane rules will be assigned if the following conditions are fulfilled [11]:

a. the next vehicle is too near (velocity > gap),
b. line next to vehicle is empty,
c. *f_gap* ≥ velocity,
d. *b_gap* ≥ maximum velocity,
e. probability to change lane is fulfilled.

The next procedure of vehicles movement is movement rules. The rules are assigned to vehicles so that it can change lane position based on its velocity. According to Nagel-Schreckenberg rules, the position of each vehicle is updated based on its velocity by using four-step rules, i.e. acceleration, distance adjustment, randomization, and vehicles movement [9].

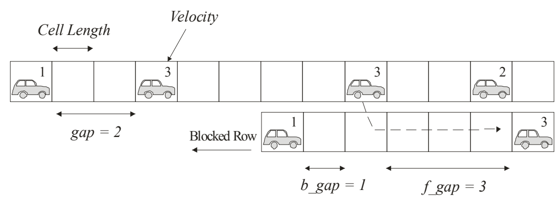

Figure 1: Illustration of change lane rules of vehicles.

The increasing of acceleration and the decreasing of velocity of four-step rules is still static. Acceleration and speed reduction are still in the form of a constant that is one. Therefore, some modifications are applied into the basic rule [11] in order to make the model more dynamics. Here, the variation of acceleration is not only as constant one, but also the value is one until the maximum acceleration value. By this technique, the rate of change of acceleration becomes varies. In addition, the reduction scale of the velocity value for the randomization process is varied between one and the decreasing limit of velocity.

3. FUZZY INFERENCE SYSTEM

Fuzzy inference system is used to determine optimal timing of the traffic light on signalized intersections. Through fuzzy set, it can be represented and addressed various uncertainty parameter. In this case, it can be doubt, inaccuracy, uncomplete information, and partly truth. Fuzzy inference system consists of fuzzyfication, inference, and defuzzyfication [4]. In this study, the process of fuzzyfication, inference, and defuzzyfication use a combined of fuzzyfication trapezoidal-triangular function, Sugeno inference, and weight average defuzzyfication method [11]. Further, Sugeno inference method is used since it has fast computational process. Thus, it appropriates to apply in control system [4]. The combined functions of trapezoid-triangles are used, since based on observations, and also consideration of the utilization of these functions in [12-13], it appears that these two functions have more variation output value so that making it possible to minimize the delay time of vehicles at intersections.

Before fuzzy inference system is executed, fuzzy C-means (FCM) algorithm is applied.

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Membership function boundaries should be known to use this algorithm. The mechanism of FCM algorithm is by varying the center of the cluster on each iteration until cluster of data being studied was reached [11]. FCM algorithms can be seen in [14]. FCM input consists of variation of the green light duration and the number of vehicles. Grouping parameter in the FCM is the number of linguistic variables that will be used. It is the value of interval grouping to the number of vehicles.

The computation results of FCM are cluster center matrix which can be represented as follows:

$$V_1 = \begin{bmatrix} 32.3351 & 111.5242 & 188.5360 & 254.6073 \end{bmatrix}$$

$$V_2 = \begin{bmatrix} 47.0468 & 78.8886 & 91.3305 & 159.9431 \end{bmatrix}.$$

V_1 is used as number of vehicle membership function boundaries and V_2 is used as green light duration membership function boundaries. Because the number of vehicle value must be discrete, then V_1 matrix become discrete values:

$$V_1 = \begin{bmatrix} 32 & 112 & 189 & 255 \end{bmatrix}$$

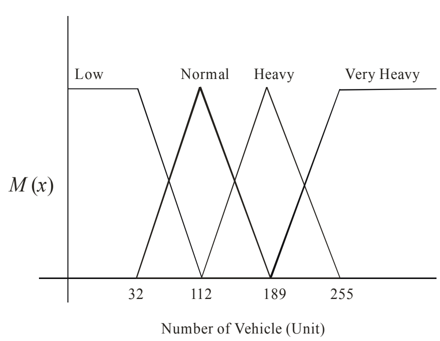

Figure 2: Membership function of the number of vehicles.

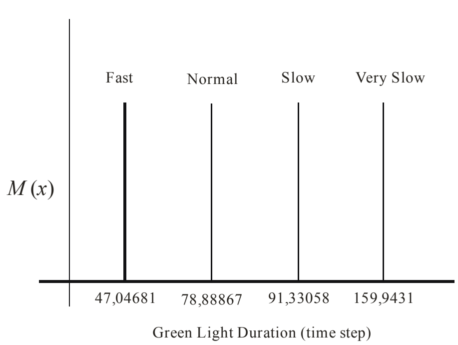

Figure 3: Membership function of green light duration.

After the membership function boundaries have been obtained then membership function for the first and second antecedent are assigned. These antecedent are shown by Fig. 2 and Fig. 3, respectively.

The output of fuzzy inference system is delay time average and green signal timing of each signalized intersection. The green signal duration is given to address a road arm. Each road arm is handled by green light duration one by one (based on its turn). If output of fuzzy inference system produces green light timing in the real number, then the result is rounded using round function because cellular automata model only works on discrete domain.

Table 1 shows fuzzy rules that used in fuzzy inference system. This fuzzy rules are accordance with a design derived from [12].

Table 1: Fuzzy rules.

	Low	Normal	Heavy	Very Heavy
Low	Fast	Normal	Slow	Very Slow
Normal	Fast	Normal	Slow	Slow
Heavy	Fast	Normal	Normal	Slow
Very Heavy	Fast	Fast	Normal	Normal

In this study, there are two fuzzy inference system input variables. The first is the number of vehicles on the road arm being addressed to be given the green signal. The second is the total number of vehicles on three other road arms which lined up to be given the green signal. The next process of fuzzy inference system method is fuzzyfication, inference, and defuzzyfication until crisp value of green light duration is produced in each signalized intersection. See [4] for more comprehensive review.

4. SIMULATION SETUP

Fig. 4 shows simulation scenario of this study while Fig. 5 illustrates the simulation process and describes combination works between cellular automata (CA) and fuzzy inference system (FIS). Here, the simulation results using combined fuzzy inference system and cellular automata will be compared to fixed time results which are obtained from historical data for six intersections. The

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historical data of observation are taken from drones which are placed on six signalized intersections. Moreover, Fig. 6 shows video screen shot which is taken from drone at a signalized intersection. Each intersection is connected to each other. The task of each intersection is addressed sequentially, but the task still works in the one time step period so that it can be said that it is running simultaneously.

The simulation is conducted for road network with six signalized intersections as shown by Fig. 7. The six intersections are located on Bandung City, Indonesia. The six intersections are:

- Soekarno Hatta Street – Ibrahim Adjie Street (Intersection 1)
- Soekarno Hatta Street – Buah Batu Street (Intersection 2)
- Buah Batu Street – Pelajar Pejuang Street (Intersection 3)
- Pelajar Pejuang Street – Gatot Subroto Street (Intersection 4)
- Gatot Subroto Street – Ibrahim Adjie Street (Intersection 5)
- Buah Batu Street – Tol Buah Batu Street (Intersection 6)

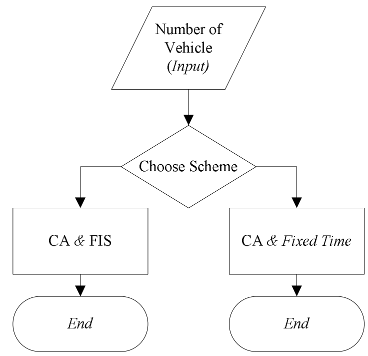

Figure 4: Simulation scenario of cellular automata and fuzzy inference system.

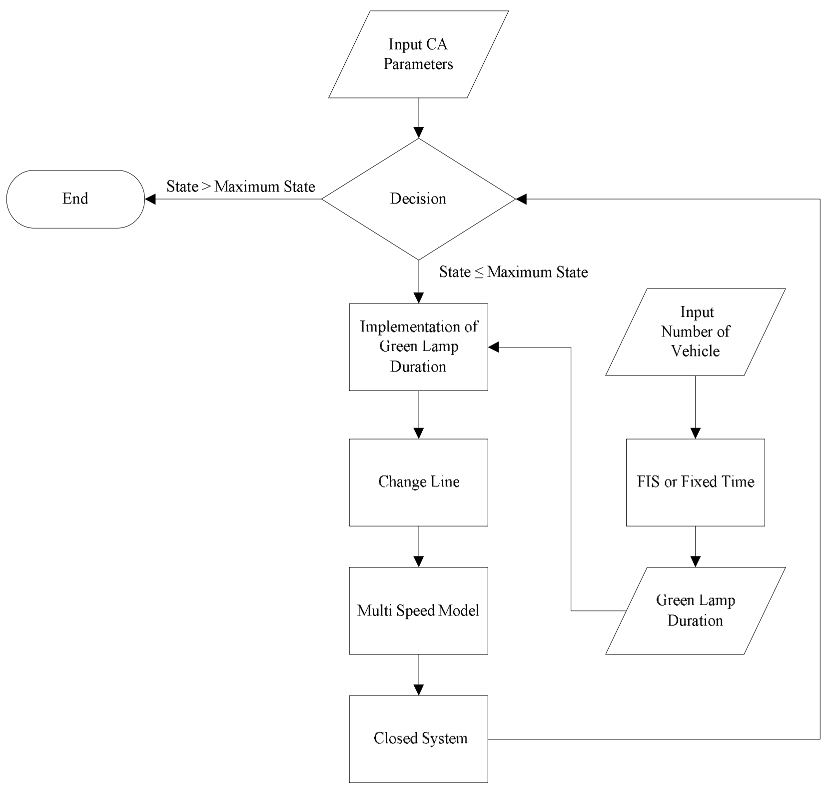

Figure 5: Simulation process using cellular automata and fuzzy inference system.

Figure 6: Video screen shot of traffic flow at a signalized intersection in Bandung City, Indonesia.

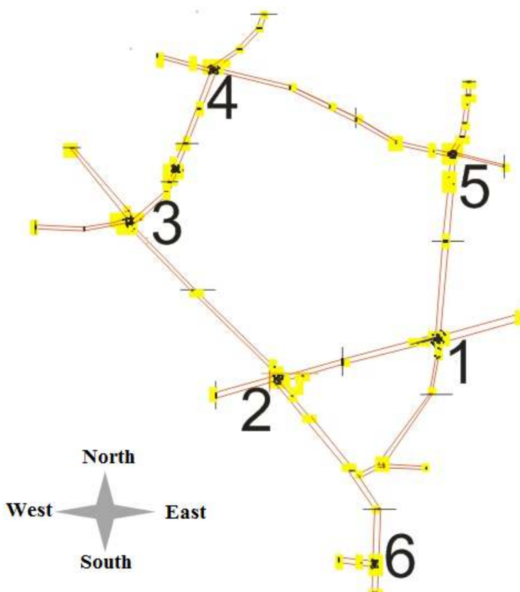

Figure 7: Road network with six intersections.

Table 2: Fixed time of green signal based on historical data of observation for six signalized intersection in Bandung City, Indonesia.

Inter-section	Fixed time (in seconds)			
	West	South	North	East
1	90	60	90	195
2	65	80	110	130
3	50	85	0	50
4	50	105	110	135
5	65	45	45	65
6	25	30	30	0

Fixed time green signal from historical data at six signalized intersections are summarized in Table 2. Data from this table are then used as initial condition for fuzzy inference system. The historical data of observation and simulation results only show green light duration. However, it is easy to compute red light duration if green light duration of each road arm is known.

5. RESULTS AND DISCUSSION

Output of fuzzy inference system and fixed time scheme is then analyzed to measure the performance. The output of simulation is delay time average and traffic light timing on road network with six signalized intersections. Delay time is addition time required by a vehicle to pass through signalized intersection compared to road without intersection.

Delay time average obtained from simulation for six intersections is summarized in Table 3. It can be observed from the table that the delay time average resulted by the fuzzy inference system is faster than the fixed time scheme except for Terusan Buah Batu Street – Buah Batu Exit Toll Gate intersection. It can be revealed that fixed time (historical data) has inappropriate green light duration which yields longer delay time average. However, in fact, the FIS has a mechanism that can produce more appropriate green light duration than fixed time scheme.

Table 3: Delay time average obtained from simulation.

No	Intersection	Delay time average (time step)	
		FIS	Fixed Time
1	Soekarno Hatta Street – Ibrahim Adjie Street	126.850	331.089
2	Soekarno Hatta Street – Buah Batu Street	108.291	478.465
3	Buah Batu Street – Pelajar Pejuang Street	128.627	168.268
4	Pelajar Pejuang Street – Gatot Subroto Street	99.462	144.684
5	Gatot Subroto Street – Ibrahim Adjie Street	128.500	323.926
6	Terusan Buah Batu Street – Buah Batu Exit Toll Gate	133.900	103.703

The performance of delay time average from FIS and fixed time scheme can be measured by level of service (LoS) criteria [15]. LoS is used to give a category for delay time. The LoS consists of six level from A to F. On heavy traffic, the delay time may approach to level F. On low traffic, the delay time may approach to level A. Table 4 displays LoS criteria based on delay time average value. The smallest delay time resulted the best level of service obtained. Moreover, the smaller delay time average, the more efficient system performance. It can also be seen from Table 3 and Table 4 that both FIS and fixed time include in level F. The results depict that all signalized intersections are in heavy traffic congestion. However, in this case, delay time average of FIS is smaller than fixed time scheme. Therefore, the FIS scheme yields more efficient green signal timing than fixed time scheme.

From the simulation results, for most of signalized intersections, one cycle duration of FIS is achieved faster than fixed time scheme. One cycle duration is total time of green and yellow light in one lap. The red light duration is only as a result from the implementation of the yellow and green light. The delay time can be reduced when the traffic light setting is appropriate. If the timing of the green light is appropriate with the traffic condition, then the red light timing is more optimal and timing of one cycle is more efficient.

Table 4: Level of Service Criteria

LoS	*Delay time (second)*
A	$t \leq 10$
B	$10 < t \leq 20$
C	$20 < t \leq 35$
D	$35 < t \leq 55$
E	$55 < t \leq 80$
F	$t > 80$

Table 5 until Table 10 reveals optimal timing of green signal using FIS scheme for six signalized intersections in Bandung city. The simulation is running for 10 cycles. From these tables, it can be seen that all signalized intersections have faster green duration compared to fixed time listed in Table 2. It is also can be observed that in each cycle, the green light duration is changed adjusting with number of vehicles. From these results, it can be said that by adjusting the green light duration with the number of incoming and outgoing vehicles, the delay time is faster than without optimization so that traffic congestion at signalized intersection can be reduced.

Table 5: Optimal timing of green signal using fuzzy inference system (FIS) at Soekarno Hatta Street – Ibrahim Adjie Street.

Cycle	Green signal (in seconds)			
	West	South	North	East
1	79	47	63	78
2	76	47	62	66
3	69	47	55	61
4	61	47	57	60
5	59	47	53	60
6	56	47	54	57
7	56	47	57	58
8	65	47	51	60
9	55	47	49	60
10	67	47	50	61

Table 6: Optimal timing of green signal using fuzzy inference system (FIS) at Soekarno Hatta Street – Buah Batu Street.

Cycle	Green signal (in seconds)			
	West	South	North	East
1	50	62	71	82
2	47	59	52	71
3	51	47	76	68
4	58	47	47	63
5	61	47	66	60
6	63	47	82	65
7	61	47	47	61
8	62	47	69	65
9	65	47	47	62
10	63	47	67	61

Table 7: Optimal timing of green signal using fuzzy inference system (FIS) at Buah Batu Street – Pelajar Pejuang Street.

Cycle	Green signal (in seconds)			
	West	South	North	East
1	47	47	0	47
2	47	72	0	47
3	47	55	0	47
4	47	61	0	47
5	47	61	0	47
6	47	47	0	47
7	47	59	0	47
8	47	51	0	47
9	47	49	0	48
10	47	60	0	47

Table 8: Optimal timing of green signal using fuzzy inference system (FIS) at Pelajar Pejuang Street – Gatot Subroto Street.

Cycle	Green signal (in seconds)			
	West	South	North	East
1	49	57	54	84
2	47	58	47	69
3	47	53	47	54
4	47	55	47	47
5	47	47	47	47
6	47	49	57	47
7	49	56	47	47
8	47	53	47	47
9	47	49	47	47
10	47	56	52	47

Table 9: Optimal timing of green signal using fuzzy inference system (FIS) at Gatot Subroto Street – Ibrahim Adjie Street.

Cycle	Green signal (in seconds)			
	West	South	North	East
1	47	47	47	47
2	47	57	47	47
3	47	55	47	47
4	47	49	47	47
5	47	51	47	47
6	47	57	47	47
7	47	64	47	47
8	47	64	47	47
9	47	65	47	47
10	47	66	47	47

Table 10: Optimal timing of green signal using fuzzy inference system (FIS) at Terusan Buah Batu Street – Buah Batu Exit Toll Gate.

Cycle	Green signal (in seconds)			
	West	South	North	East
1	47	47	53	0
2	47	47	57	0
3	47	47	47	0
4	47	47	47	0
5	47	47	53	0
6	47	47	47	0
7	47	47	49	0
8	47	47	49	0
9	47	47	47	0
10	47	47	50	0

Traffic signal timing using FIS scheme has made an adaptive regulatory system. In this study, an adaptive traffic system is defined as the decision of traffic signal timing depends on the number of vehicles that was predicted from the simulation not from real traffic situation. In general, the duration of the green light resulted from FIS scheme is lower than the duration of the green light resulted from fixed time scheme. If the duration of green light is lower, then the duration of the red light becomes faster. If the adjustment of green light duration is appropriate with the state of the queue of vehicles, then the delay time can be reduced so that the level of traffic congestion can be reduced. The results can be suggested to the local government to improve the traffic signal system.

5. CONCLUSION

Optimization of traffic signal timing has been successfully conducted via numerical simulation. Cellular automata were used to model vehicles movement on the signalized intersections and fuzzy inference system was used to optimize the duration of traffic light for each signalized intersection. The numerical results show that fuzzy inference system method is more efficient than the existing historical data of observation and it can reduce the level of congestion. Further, it has been shown that fuzzy inference system can generate delay time average faster than the fixed time scheme and the traffic signal timing can adjust with the number of incoming and outgoing of vehicles at the intersections on road network in Bandung city, Indonesia. The future works of this research are implementation to the real time, parallelization of the algorithm, and vehicles movement can be adjusted based to the driver behavior.

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