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A Fuzzy Traffic Controller Considering the spillback on the Multiple Crossroads

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Abstract

In this paper, we propose a fuzzy traffic controller of Sugeno's fuzzy model so as to model the nonlinear characteristics of controlling the traffic light. It use a degree of the traffic congestion of the preceding roads as an input so that it can cope with traffic congestion appropriately, which causes the loss of fuel and our discomfort. First, in order to construct fuzzy traffic controller of Sugeno's fuzzy model, we model the control process of the traffic light by using Mamdani's fuzzy model, which has the uniform membership functions of the same size and shape. Second, we make Mamdani's fuzzy model with the non-uniform membership functions so that it can exactly reflect the knowledge of experts and operators. Last, we construct the fuzzy traffic controller of Sugeno's fuzzy model by learning from the input/output data, which is retrieved from Mamdani's fuzzy model with the non-uniform membership functions. We compared and analyzed the fixed traffic light controller, the fuzzy traffic controller of Mamdani's fuzzy model and the fuzzy traffic controller of Sugeno's fuzzy model by using the delay time and the proportion of the entered vehicles to the occurred vehicles. As a result of comparison, the fuzzy traffic controller of Sugeno's fuzzy model showed the best performance.

Key words : Fuzzy traffic controller, Membership function modification algorithm, Traffic congestion, Crossroad

Ⅰ. Introduction

FLC(Fuzzy Logical Controller) is able to use knowledge of experts and operators as the control rules and to process the ambiguous information. For that reason, it has been applied to control complex nonlinear systems that have no mathematical model[1].

There have been many researches[2, 6, 7, 8, 9] on FTC(Fuzzy Traffic Controller), which is FLC for controlling a traffic light, that used such advantages as the linguistic description and the qualitative modeling of FLC. They used the number of entering vehicles at the green light, the number of waiting vehicles during the red light, the mean density of vehicles, the duration time of the red light and etc. as input variables, and they used the duration time of the green light as output variable[2].

Though the existing researches were simulated and evaluated in various situations, they have several problems. First, they could not be applied to crossroads with the congestive traffic flow because they have been developed and applied for a non-congestive traffic flow. Under the congestive traffic flow, spillback on crossroads unavoidably happens. Spillback on crossroads leads to over-saturation of roads. If spillback on upper crossroad happens, the loss of green light on lower crossroad is unavoidable[3]. Second, an object of simulating the traffic flow and analyzing their performance is mostly a single crossroad. In a single crossroad, the number of passed vehicles is able to become a meaningful measure. However, it can't be used as a meaningful measure under such multiple crossroads that spillback on crossroads happens. Third, it is an issue that the inference of FTC can generate the exact result that experts and operators expect. The most of the inference models used in FTC represent approximately the control knowledge of experts and operators.

In the consequences of the above issues, FTC must consider the traffic congestion of the preceding road, which vehicles on a crossroad are to proceed to, in order to cope successfully with the traffic congestion and the change of traffic situation. The inference model of FTC is modified and tuned up in order to make it generate the exacting result that experts and operators expect.

Therefore, in this paper, we propose a FTC that can cope with the traffic congestion appropriately by using a degree of traffic congestion of the preceding roads as an input variable, which vehicles on a crossroad are to proceed to.

The proposed FTC employs the first-order Sugeno's fuzzy model, which is constructed on the basis of Mamdani's fuzzy model with the uniform membership functions of the same size and shape. The membership functions of Mamdani's fuzzy model are tuned up and modified by the membership function modification algorithm[4] so that the inference of FTC can generate the exact result that experts and operators expect. From Mamdani's fuzzy model tuned up by the membership

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function modification algorithm, we construct FTC of the first order Sugeno fuzzy model of 3 inputs and 1 output.

We compared and analyzed the fixed traffic light controller, FTC of Mamdani's fuzzy model and the proposed FTC of Sugeno's fuzzy model by using the delay time, the proportion of entered vehicles to occurred vehicles. As a result of comparison, the proposed FTC shows the best performance level of them .

Chapter 2 describes the membership function modification algorithm and ANFS briefly. Chapter 3 proposes FTC of Sugeno's fuzzy model with 3 inputs and 1 output. Chapter 4 compares and analyzes performance of the traffic light controllers. Chapter 5 is a summary of the research work.

II. Membership function modification algorithm and ANFIS

In Mamdani's fuzzy model that is well suited to human intuitive input, the triangular membership is well suited to simple computation, and its position and width can be used easily as parameters. But it cannot exceed the definite performance if it employs the uniform membership functions of the same size and shape for all linguistic variables. In this case, we can design more accurate controller, which can generate the exact result that experts and operators expect, by clustering an input/output data set from controlling process[1, 10].

The membership modification function algorithm, which is referred to *MFM algorithm*, modifies the size and shape of the membership functions of FLC with the uniform membership functions by clustering the input/output data from it, and makes it generate more exact result that experts and operators expect, and can enhance the performance of FLC with uniform membership functions.

Figure 1 shows MFM algorithm. And the fitness measure is defined as Eq.1.

$$fitness = |X_{incons}| \ / \ |X_{all}| \qquad \text{(Eq.1)}$$

where, $|X_{incons}|$ is the number of input/output data which does not satisfy the control knowledge, and $|X_{all}|$ is the cardinality of input/output data set.

If an input/output data set, which represents exactly the knowledge of experts and operators, is given, we can construct a more compact and computationally efficient FLC by using the adaptive techniques that learn from the given data. ANFIS(Adaptive Network based Fuzzy Inference System) is the learning algorithm suitable to this purpose.

ANFIS allows fuzzy systems to learn from the data that they are modeling, by using the adaptive techniques[11, 12]. Using a given input/output data set, ANFIS constructs a fuzzy inference system whose membership function parameters are tuned and adjusted using either a backpropagation algorithm alone, or in combination with a least squares type of method.

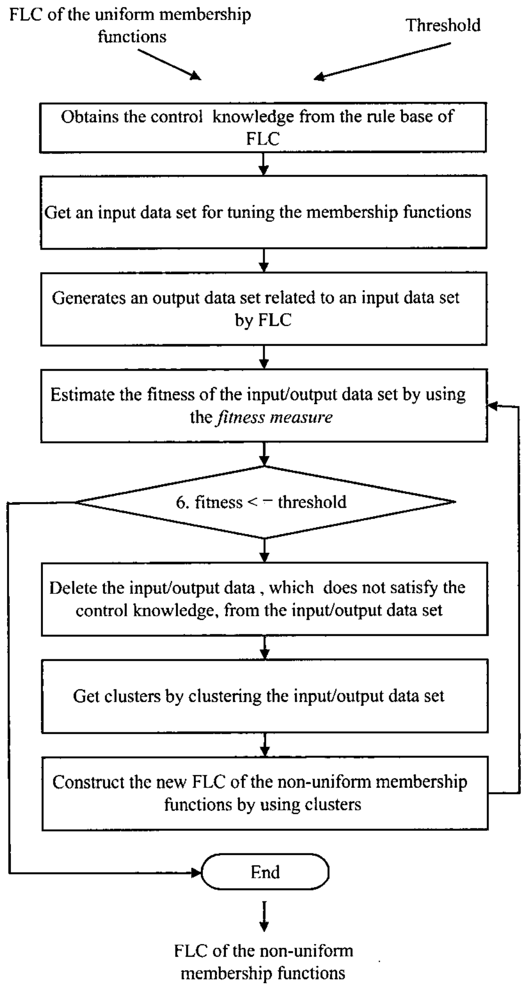


Fig. 1. Membership function modification algorithm

Mamdani's fuzzy model is the most commonly seen fuzzy methodology. It is intuitive, and has widespread acceptance and is well suited to human input.

Compared with Mamdani's fuzzy model, Sugeno's fuzzy model is computationally efficient, and works well with linear techniques and with optimization and adaptive techniques, and has guaranteed continuity of the output surface, and is well suited to mathematical analysis. It is suited for modeling nonlinear systems by interpolating multiple linear models[11].

Sugeno's fuzzy inference method lends itself to the use of adaptive techniques for constructing fuzzy models, because it is a more compact and computationally efficient representation than Mamdani's fuzzy inference method. Therefore, if an input/output data set is given, we can employ ANFIS in order to compute the membership function parameters that best allow Sugeno's fuzzy model to track the given input/output data.

In general, ANFIS works well if the training data presented to it for training membership function parameters is fully representative of the features of the data that the trained FLC is intended to model. We collect the training data from FLC with the non-uniform membership functions tuned up by MFM algorithm, which generates the numerical data that experts and operators expect.

In this paper, we use Sugeno's fuzzy model trained by ANFIS in order to model the nonlinear characteristics of controlling the traffic light.

III. Fuzzy traffic controller of Sugeno fuzzy model

The purpose of controlling the traffic flow by FLC is to lighten the traffic congestion and to decrease the delay time on crossroads by finding out the traffic flow of the current crossroads and changing the traffic light appropriately.

In order to achieve this purpose, we design FTC based on the following assumptions: First, sensors can detect the congestion of corresponding roads. Second, the width of crossroad and the length of vehicles decide the duration time of yellow light.

In order to identify FTC of Sugeno's fuzzy model that models the nonlinear characteristics of controlling the traffic light, we use the similar modeling approach to many system identification techniques. First, we hypothesize a parameterized model structure, which is modeled by FTC of Mamdani's fuzzy model with the uniform triangular membership functions, which is called to the *uniform FTC*. Second, we tune up and adjust the uniform FTC by the MFM algorithm so as to generate FTC of Mamdani's fuzzy model with the non-uniform membership functions, which is the *non-uniform FTC*. Last, in order to identify FTC of Sugeno's fuzzy model, we collect input/output data from the non-uniform FTC, and train data presented to it and modify the membership function parameters by ANFIS.

Figure 2 shows the model structure of FTC with Sugeno's fuzzy model with 3-inputs and 1-output that is proposed in this paper. The rule base of the proposed FTC is consisted of 8 rules for the purpose of simplifying inference and design.

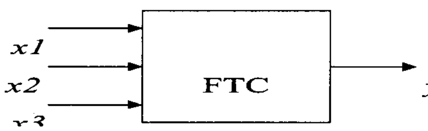


Fig. 2. The model structure of the proposed FTC

Input variables of the proposed FTC for controlling the traffic light are $x1$, $x2$, $x3$. $x1$ is a degree of the duration time of the red light, which indicates the proportion of the duration time of the red light to the predefined cycle time of traffic lights.

$$DDRL = \frac{DRL}{PCT} \quad \text{(Eq.2)}$$

In eq.2, DDRL is a degree of the duration time of the red light, and DRL is the duration time of the red light, PCT is the predefined cycle time of traffic lights.

$x2$ is a degree of the traffic congestion of the current road.

$$DTC_c = \frac{\sum_{i=1}^{m}\sum_{j=1}^{n} LV_{ij}}{\sum_{i=1}^{m} LL_i} \quad \text{(Eq.3)}$$

In eq.3, DTC_c is a degree of the traffic congestion of the current road, LV_{ij} is the length of j-th vehicle on i-th lane of a road and LL_i is the length of i-th lane of a road.

$x3$ is the mean degree of the traffic congestion of the preceding roads, which vehicles on a crossroad are to proceed to.

$$MDTC_p = \frac{\sum_{i=1}^{n} DTC_i}{n} \quad \text{(Eq.4)}$$

In eq.4, $MDTC_p$ is the mean degree of the traffic congestion of the preceding roads, DTC_i is a degree of the traffic congestion of i-th proceed road.

Figure 3 shows the membership function of input variables $x1$, $x2$, $x3$ for the proposed FTC of Sugeno's fuzzy model. They all is consisted of 2 membership functions. Figure 4 shows the rule base for conditionals of it.

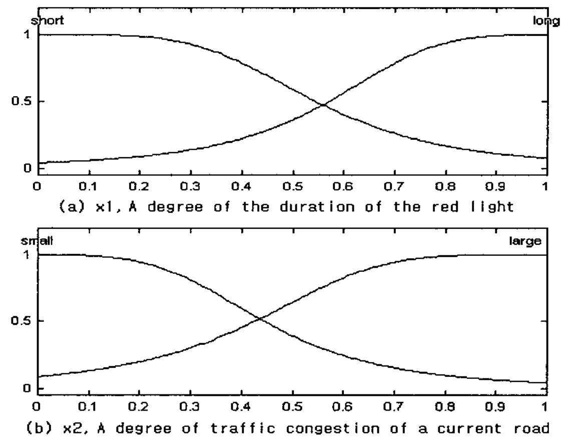
Output variable is y, which is a degree of increase and decrease of the duration time of the green light on a crossroad. The first-order linear equation for deciding y for the proposed FTC is as follows.

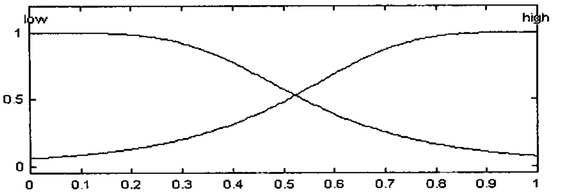
$$y = p_0 + p_1x_1 + p_2x_2 + p_3x_3 \quad \text{(Eq.5)}$$

The duration time of the green light is obtained by the follows.

$$DGR = PDGR + (PDRG * y) \quad \text{(Eq.6)}$$

In eq.6, DGR is the duration time of the green light, PRGR is the predefined duration time of the green light.





(c) x3, The Mean degree of traffic congestion of a proceed roads

Fig. 3. The membership functions for the input variables of the proposed FTC

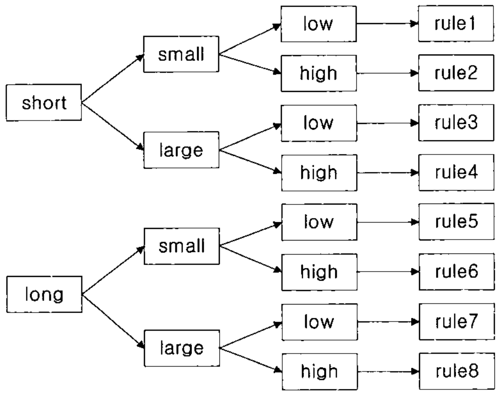
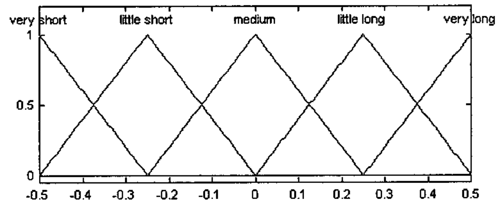


Fig. 4. Rule base for conditionals of the proposed FTC

In order to identify coefficients of eq.5, we first model the traffic light control by the uniform FTC. Figure 5 shows the membership functions of the input and output variables of the uniform FTC. Figure 6 is the rule base of it, which is consisted of 125 rules.

Figure 7 shows the membership functions of the input and output variables of the non-uniform FTC, which is generated by tuning up and adjusting the uniform FTC by MFM algorithm.



(d) y, A degree of increase and decrease of the duration of the green light.

Fig. 5. The membership functions for input/output variables of the uniform-FTC.

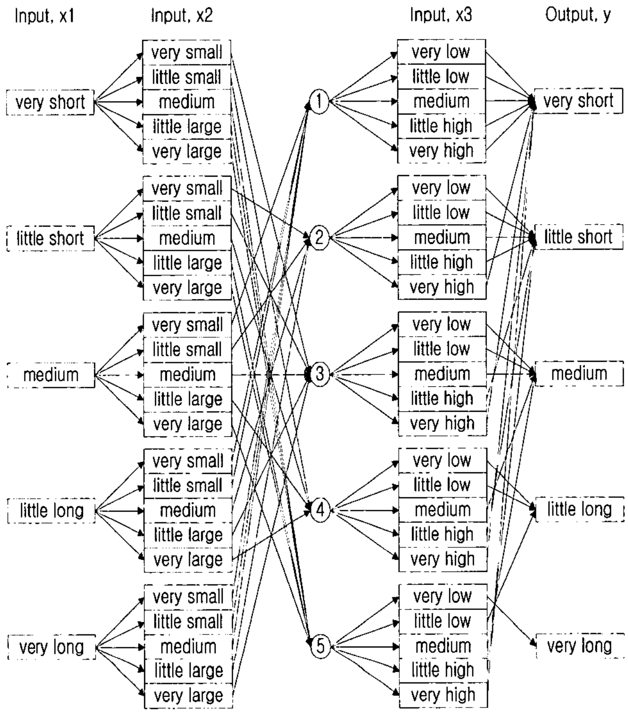
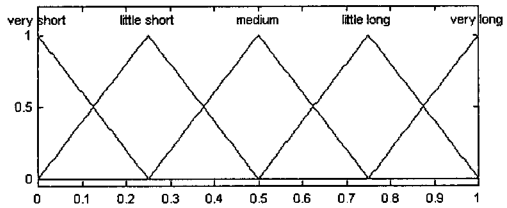
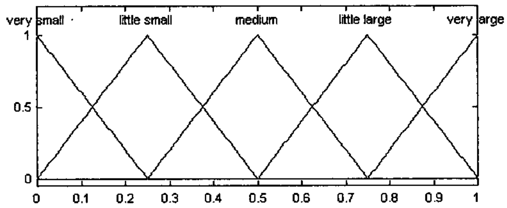


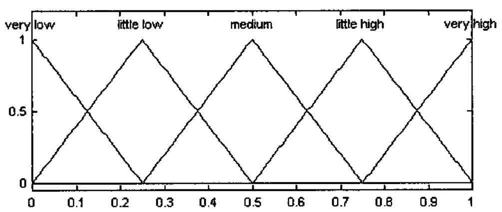
Fig. 6. The rule base of the uniform FTC



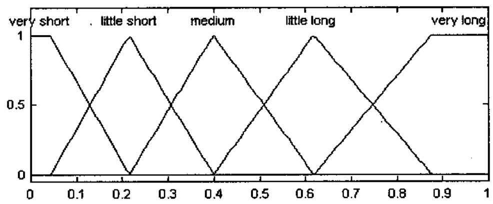
(a) x1, A degree of the duration of the red light



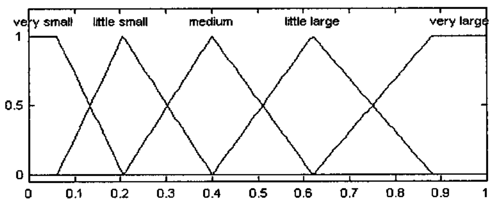
(b) x2, A degree of traffic congestion of a current road



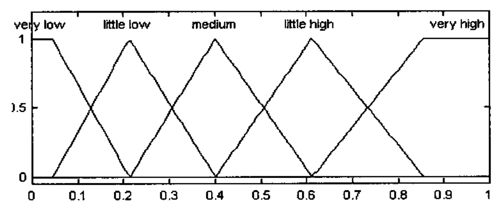
(c) x3, The Mean degree of traffic congestion of a proceed roads



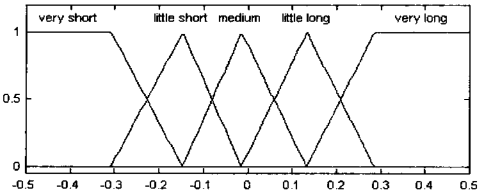
(a) x1, A degree of the duration of the red light



(b) x2, A degree of traffic congestion of a current road



(c) x3, The Mean degree of traffic congestion of a proceed roads



(d) y, A degree of increase and decrease of the duration of the green light

Fig. 7. The membership functions for input/output variables of the non-uniform FTC.

Table 1. Coefficients of deciding y

Rules	p_0	p_1	p_2	p_3
1	-1.0746	1.0342	0.2479	-0.04
2	0.19508	-0.089	-0.278	-0.163
3	0.19616	0.0824	-0.981	0.2649
4	-0.0177	0.004	-0.429	0.0618
5	-0.1386	-0.423	-0.104	-0.145
6	0.00108	0.0803	0.008	-0.396
7	-0.2498	0.3629	0.4118	-0.152
8	0.00794	-0.151	-0.295	-0.033

Table 1 shows the coefficients for deciding y of the proposed FTC, which are retrieved by training a data set from the non-uniform FTC by ANFIS.

Ⅳ. Experiment and Results

We developed the traffic-flow simulator and estimated the performance of the proposed FTC. The number of the used crossroads is 16. The configuration for simulating the traffic flow was assumed as show in figure 8.

In figure 8, the length of vehicles was assumed to be $4m$ and the length of all roads was $50m$. We did not consider crosswalk and vehicles of right-turn. The green light was circulated based on the straight and left-turn (that is, A->B->C->D...). We assigned 18 seconds for the straight and left-turn and 2 seconds for yellow light. We used 4■(18+2)=80 seconds as the basic signal-cycle.

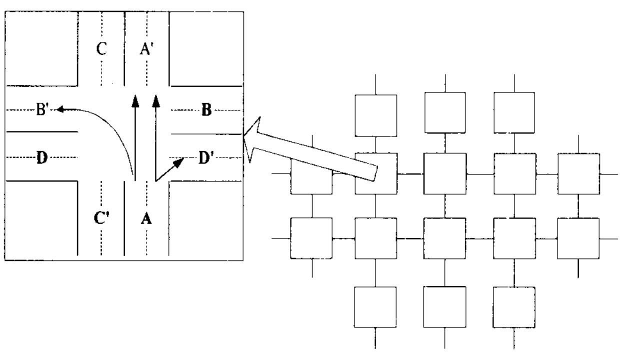


Fig. 8. Configuration for simulating the traffic flow

For simulation, occurrence of vehicles was assumed as six levels. The number of the occurred vehicles were 1710, 3156, 4076, 5427, 8052 and 10860 respectively. Velocities of vehicles were 10km/h, 20km/h, 30km/h, 40km/h, 50km/h and 60km/h respectively.

During the green light, only if the preceding roads(that is, A′, B′, C′ and D′ in figure 8) have enough space to accommodate a vehicle, vehicles on the current roads(that is, A, B, C and D in figure 8) could enter the preceding roads.

Service level of a crossroad with the traffic lights is decided by the delay time. Delay time indicates the loss of fuel and time, and is the measure of discomfort. It generally happens on the red time. A degree of saturation, which is called DOS, indicates whether assignment of signal-cycle is pertinent or not. However it is difficult to decide service level based on DOS because delay time is not always decided according to DOS [5]. Therefore, we estimated performance of controllers by using not a degree of saturation but the delay time.

The number of the passed vehicles, which is commonly used for estimating performance of FTC, is able to become a meaningful measure for a single crossroad. On a single crossroad, the traffic congestion never happens. It, however, can't be used as a meaningful measure under such multiple crossroads that spillback on crossroads happens.

Therefore, it was not used for comparing and estimating performance of the traffic light controllers. Instead of it, we use a degree of entrance and a degree of passage. A degree of entrance indicates the proportion of the entered vehicles to the occurred vehicles, and a degree of passage indicates the proportion of the passed vehicles to the traffic volume.

$$DOE = \frac{NEV}{NOV} \qquad \text{(Eq.7)}$$

$$DOP = \frac{NTV}{NPV} \qquad \text{(Eq.8)}$$

In eq.7, DOE is a degree of entrance, NEV is the umber of the entered vehicles and NOV is the number of the occurred vehicles. In eq.8, DOP is a degree of passage, NTV is the number of the passed vehicles and NTV is the number of the traffic volume.

DOE and DOP are measures considering the traffic congestion. The traffic congestion of a crossroad results to loss of green signal, and decreases the number of passed vehicles on a crossroad, and increases a degree of traffic complexity on roads, and obstructs vehicles from entering roads.

First, we compared and analyzed the fixed traffic light controller that is called to the *fixed TLC*, the uniform FTC and the proposed FTC on a single crossroad by using the delay time, DOP and DOS. Figure 9, 10, 11 show the delay time, DOP and DOS according to the number of the occurred vehicles on a single crossroad, which has the most traffic volume, respectively. Table 3 shows the means of the delay time, DOS and DOP.

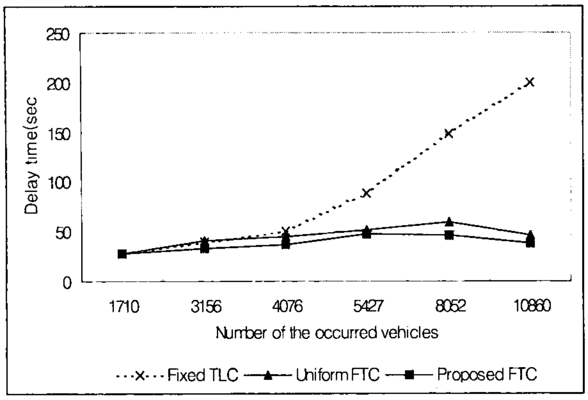


Fig. 9. Delay time on a single crossroad

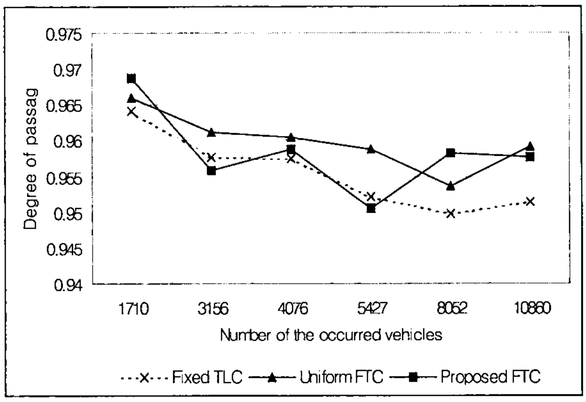


Fig. 10. A degree of passage on a single crossroad

In tables 3, the proposed FLC decrease the delay time about 58% in comparison with the fixed TLC and 15% in comparison with the uniform FTC. DOS of the proposed FTC is lower than the fixed traffic light controller and the uniform FTC. DOP of the proposed FTC is higher than the fixed TLC but lower than the uniform FTC.

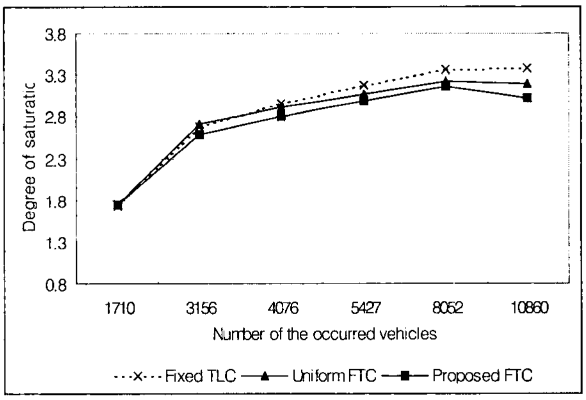


Fig. 11. A degree of saturation on a single crossroad

Table 2. The means of the delay time, DOS and DOP on a single crossroad.

	Delay time	DOP	DOS
Fixed TLC	92.23055	0.955412	2.880277
Uniform FTC	45.05833	0.959862	2.806945
Proposed FTC	38.14417	0.958272	2.720278

Next, we compared and analyzed the fixed TLC, the uniform FTC and the proposed FTC on all crossroads by using the delay time, DOP and DOE. Figure 12, 13, 14 show the delay time, DOP and DOE on all crossroads, respectively. Table 4 shows the means of the delay time, DOP and DOE.

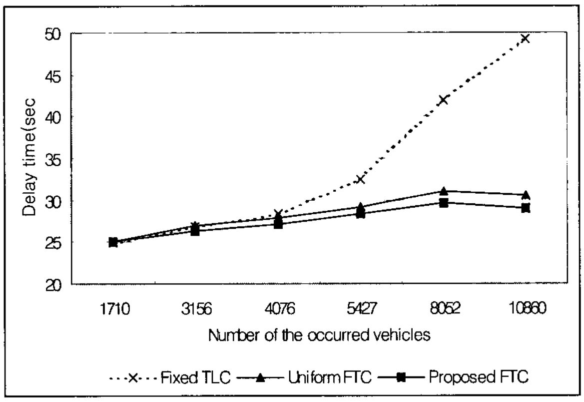


Fig. 12. A delay time on all crossroads

In tables 4, DOE and DOP of the proposed FLC are higher than the fixed TLC, but lower than the uniform FTC. The delay time of the proposed FTC is smaller than the fixed traffic light controller and the uniform FTC.

In the result, the proposed FTC of them shows the best service level. In particular, the more traffic volume is, the better it's performance is.

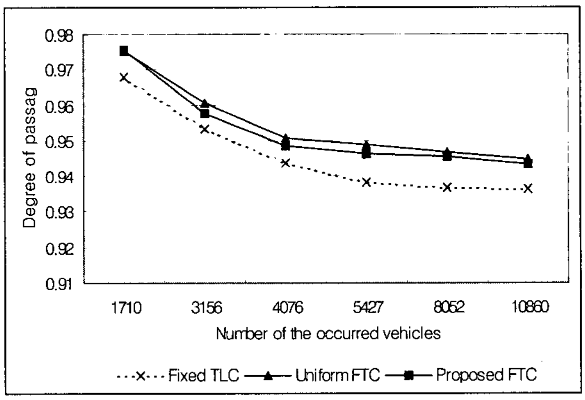


Fig. 13. A degree of passage on all crossroads

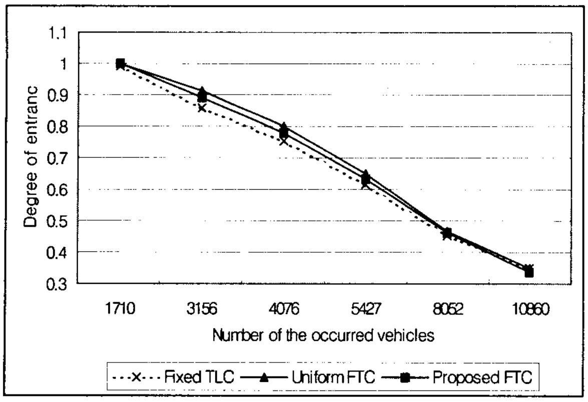


Fig. 14. A degree of entrance on all crossroads

Table 3. The means of the delay time, DOP and DOE on all crossroads

	Delay time	DOP	DOE
Fixed TLC	33.94387	0.946063	0.670737
Uniform FTC	28.42262	0.954488	0.697428
Supposed FTC	27.57601	0.952833	0.684250

V. Conclusion

In this paper, we proposed a FLC of Sugeno's fuzzy model for controlling a traffic light that can cope with the traffic congestion well. In order to consider such situation as loss of the green light caused by the traffic congestion of the preceding roads, we used as an input variable a degree of the traffic congestion of the preceding roads, which vehicles on a crossroad are to proceed to.

In situation of the same velocity, the same controller and the same number of the occurred vehicles, we simulated the traffic flow. We evaluated performance of the proposed FTC, the uniform FTC and the fixed traffic light controller, by using the delay time, a degree of passage and a degree of entrance.

As a result of experiment, the proposed FTC showed more enhanced performance than the fixed traffic light controller and the uniform FTC on situation of the most traffic volume. The delay time of the proposed FTC is smaller than the others.

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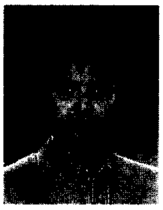

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