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RESEARCH ARTICLE

DESIGN OF TRAFFIC SIGNAL CONTROL SYSTEMS BASED ON FUZZY CONTROL

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ABSTRACT

With a gradual increase in urban road traffic volume and traffic congestion degree, how to improve and solve the current traffic pressures has been a problem requiring urgent solution. To improve the traffic congestion status in urban road intersections and heighten the road traffic efficiency, the principle of fuzzy control is employed in this paper. Moreover, the multi-phase signal traffic control of intersections is performed together with vehicle queue lengths in lanes corresponding to the key traffic flow, and a traffic signal fuzzy control system is designed. Finally, this paper compares the simulation results between the fuzzy control system designed herein and the existing fixed traffic signal control methods. The comparative test results have shown that the fuzzy control method can well better actual congestion and traffic efficiency at intersections to a greater degree than the fixed timing method does.

KEYWORDS

fuzzy control, traffic signals, intersections, multi-phase.

1. INTRODUCTION

Now as people's living standards and economic conditions continue to improve, more and more families have one or more motor vehicles, which have brought tremendous pressure to urban road traffic and led to increasing traffic congestion on a yearly basis. In this regard, it is particularly necessary to develop and apply a set of intelligent transportation systems that can help to improve current traffic congestion. In the intelligent transportation systems, the traffic signal control system is its core content, and thus enabling intelligent control of traffic signals at intersections can reduce the waiting time, thus greatly improve traffic efficiency.

In 1977 Pappis, C. P. from Greece and Mamdani, E. H from Britain carried out a fuzzy control experiment at intersections of one-way streets and proposed the Pappis control algorithm. However, this algorithm is way too idealistic and the model they used is applicable to theoretical research but not the actual traffic conditions (Asmita et al., 2005). In 1992, a traffic signal analog control scheme was developed by Chinese scholars based on neural networks at intersections of one-way streets by using theinductive road vehicle flow, as to which the experiment yielded good results.

Although the above two examples regarding traffic signal fuzzy control yielded significant effects at that time, the traditional method targeting only at one-way traffic control at intersections cannot be used to solve problems on the road provoked by uncertainty in time, ambiguous driving directions, number of lanes at intersections and traffic control complexity. Therefore, a new direction of research will be using the latest technology for multi-phase traffic control at intersections combined with the presently complex traffic situations.

Given the current two-way traffic at multilane intersections, aiming at four go-through modes (the east-west straight lane, the east-west left-turning lane, the north-south straight lane, and the north-south left-turning lane), in accordance with the queue length of vehicles waiting for the traffic light to change under each go-through mode, general distance between cars and other parameters, combined with fuzzy control, this paper executes different configuration schemes for traffic signal cycle lengths for different go-through modes to help mitigate the current pressure on the road (Xing, 2003).

2. THE DEFINITION OF 4-PHASE INTERSECTIONS

In this paper, the traffic signal control model for four go-through modes at intersections is designed based upon the actual situation. In order to more intuitively show the go-through control scheme hypothesized herein, a model is constructed which can reflect go-through at intersections, as shown in Figure 1. According to the daily traffic diversion specifications, regardless of all driving directions, it will either be turning left, turning right or going straight. The figure intuitively represents the coils installed in each one-way lane (Ostrowska, 2003).

The coils installed in each lane are divided into two parts: front or back, with a distance of about 80-300 meters in between. The back coils can collect the number of cars driving into the current lane inside the region within the time $(t-\Delta t\,,\,t)$, while the front coils (near the stop line) can count the number of cars driving away from the region. Using coils to collect traffic data can grasp the current traffic flow in real time.

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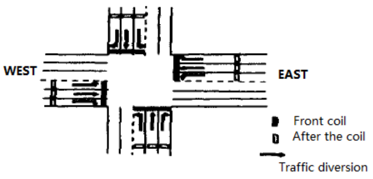

Figure 1: Cross intersection traffic situation model

Figure 2 clearly and intuitively describes combinations of four go-through modes (the east-west straight lane, the east-west left-turning lane, the north-south straight lane, and the north-south left-turning lane). According to the daily driving experience, time for each go-through mode should be neither too long nor too short, and there should be sufficient time for a considerable part of vehicles to drive through the current intersection. In terms of timing and cycles of traffic signals, we must take into account the traffic volume on the current road and waiting time that drivers can accept psychologically.

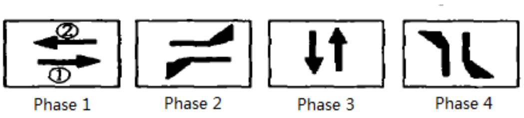

Figure 2: Cross the intersection to traffic four ways

3. Principle of Fuzzy Control

3.1 Structure of signal control system

Fuzzy control, as the name suggests, is a control method that models the behavior with no rule to follow or that cannot use normal motion patterns. This control method is based on a complete set of fuzzy control theories and technologies, combined with new, practical method for engineering system control generated by automation and control technologies. Fuzzy control can convert humans' thinking logic and theoretical control strategies into program languages that computers can recognize and run in accordance with the set switching theory. In other words, we can take advantage of people's thinking to achieve fuzzy control of the target object without relying on the operating model.

3.2 Fuzzification of controlled quantity

For example, there are many left-turn cases at intersections and we consider all of the mas a unified phase. In this case, prompted by every left-turn traffic signal phasing, coils at many traffic roads can collect traffic flow data in left-turn lanes, and we define one of the left-turn lanes, which has the largest traffic flow, as the intersection inlet with the key traffic flow.

All control systems involve determining the input and output objects and their values. In this paper, the queue length of vehicles waiting for the traffic light to change in lanes corresponding to the key traffic flow as aforementioned and the queue length of vehicles after the next traffic signal changes in lanes corresponding to the key traffic flow are input as the control system. In this paper, the thres hold can be set to range from $[0, Q_{\max}]$ and the quantization factor is set as k_1; the duration for vehicles waiting ata red light (Sundermann et al., 1998). under the current go-through mode is output. However, depending on different go-through modes, there should be different durations for vehicles waiting at a red light. Under normal circumstances, the duration for straight-going vehicles waiting at a red light should be greater than that for left-turning vehicles waiting at a red light. Herein, the duration for straight-going vehicles waiting at a red light is set for the range $[0, g_{\max}]$, and the scaling factor is k_2, and the duration for left-turn vehicles waiting at a red light is set for the range $[0, g'_{\max}]$, and the scaling factor is k_3 (Willis and Kobrinsky, 2005).

(1)

(2)

(3)

From real-life experience, generally $g_{\max}$ can be set for the range 35 to 75 seconds, while $g'_{\max}$ for the range 15 to 45 seconds. Fuzzifying control objects and their parameters plays a role of transforming the actually collected correct values into fuzzy input values through some logical relation. Focusing on the current road conditions, a fuzzy control set based on a triangular correction curve may be employed (Litescu et al., 2004). In order to achieve better fuzzy control operations of the traffic signal control system, here seven kinds of fuzzy switching modes are introduced, which are ES, VS, S, M, L, VL, EL.

3.3 Fuzzy rule bases

The switching set of fuzzy control is theoretically supported by the integrated accumulation of conclusions derived from experiments in this field and the practical experience of experts. The control status achieved by each system varies wildly, which requires collecting and testing fuzzy rules on the premise of ensuring the running performance of the current control system. Only in this way can we obtain a table for standardly converting fuzzy rules tailoring to the current system (Leidner and Norfazlina, 2004). The switching rules shown in Table 1 are standardized and developed based upon the work experience of traffic police.

Table 1: Rules for conversion of fuzzy control

l_{i+1}	l_i						
	ES	VS	S	M	L	VL	EL
EL	ES	ES	ES	VS	M	L	VL
VL	ES	ES	VS	S	M	L	VL
L	ES	VS	S	S	L	VL	VL
M	ES	VS	S	M	L	VL	VL
S	ES	VS	S	M	L	VL	EL
VS	ES	S	M	M	VL	VL	EL
ES	VS	S	M	L	VL	VL	EL

From the table, after allocating and dividing fuzzy control of inputs and outputs, the current two-dimensional table lists $7 \times 7 = 49$ system control rules, indicating that the current system controller supports the switching of 49 kinds of rules.

In this paper, "If A or B, then C" is used for the next operation of switching rules (Bojanc and Litescu, 2006). For example, the i -th rule is:

$IF\ l_i\ is\ L\ and\ l_{i+1}\ is\ L'\ THEN\ e\ is\ ei$

The Cartesian product of the rule is (Effenberger and Popescu, 2007):

$$R_i = l_i \times l_{i+1} \times ei \quad (4)$$

After gaining the Cartesian product under the corresponding rule, we can further get an overall fuzzy relational matrix; $i = 49$ represents the current controller supports up to 49 switching rules.

$$R = \bigvee_{i=1}^{49} R_i \quad (5)$$

Furthermore, according to the non-linearity and experience reference of fuzzy rules, different phase-change strategies are inevitably required for different data acquired.

$R1: If(q = VS)and(qs = VL)and(qt = M)Then\ g = ES$

$R2: If(q = VS)and(qs = L)and(qt = l)Then\ g = ES$

...

$Ri: If(q = Ai)and(qs = Bi)and(qt = Ci)Then\ g = Gi$

It should be supplemented that the fuzzy inference method used in this paper is max-min synthesis of the Mamdani fuzzy inference system, and the membership function of Ri is as follows (Makarov, 2003):

$$\mu_{R_i}(q,qs,qt,g)=\mu_{A_i}(q_i)\wedge\mu_{B_i}(qs_i)\wedge\mu_{C_i}(qt_i) \qquad (6)$$
$$\forall_{q_i}\in q, qs_i\in qs, qt_i\in qt$$

In this paper, gathering and union is adopted to get all control rules involved in the rule conversion table above, and the specific expression is as follows:

$$R=\bigcup_{i=t}^{n}R_i \qquad (7)$$

The membership function for R is:

$$\mu_R(q,qs,qt,g)=\bigvee_{i=1}^{n}\left[\mu_{R_i}(q,qs,qt,g)\right] \qquad (8)$$

According to the membership function, we may further derive the delay output time that represents phase switching in the controller:

$$G=(A\times B\times C)\circ R \qquad (9)$$

The membership function for G is:

$$\mu_G(g)=\vee\mu_R(q,qs,qt,g)\wedge\left[\mu_A(q)\wedge\mu_B(qs)\wedge\mu_C(qt)\right] \qquad (10)$$

3.4 Control system output

Assuming that at an interaction at time t, in the current traffic light switching phase, set $l_1(t)$ as vehicle queue lengths in lanes with the key traffic flow corresponding to the current phase, and set $l_2(t)$ as the queue length of vehicles in lanes with the key traffic flow for the next traffic signal switching phase. Quantitative simulation and logic fuzzification are performed of the two accurate values acquired, and we can get corresponding linguistic variables $L_1(t)$ and $L_2(t)$, thus facilitating computer recognition. At this time, $L_1(t)$ and $L_2(t)$ can be input into the fuzzy controller and an output from the fuzzy controller is acquired by using the rules stated in the fuzzy switching table (Chuprina, 2006):

$$E(t)=(L_1(t)\times L_2(t))\circ R \qquad (11)$$

When actually carrying out switching control, not every phase switching requires this fuzzy calculation. We can get a standard value just by weighting one fuzzy output under one go-through mode and call the data value stored previously whenever handling this step, which can greatly improve the switching rate.

3.5 Defuzzification to obtain the exact value

As inferred from the previous chapter, fuzzy sets corresponding to switching time-delay at a phase should be really applied in actual traffic signal control, but actual traffic signal control cannot directly apply data from the fuzzy sets, so the exact value for the signal switching time g can be weighted by the fuzzy subset G (Lang and Unsalan, 2006):

$$g=\frac{\sum_{i=1}^{n}\mu(G_i)\cdot G_i}{\sum_{i=1}^{n}\mu(G_i)} \qquad (12)$$

4. Fuzzy Controller Design

In order to fit the needs of the actual road traffic congestion, it is necessary to optimize phase-switching time of the traffic signal control system. Also time-delay priority in traffic signals for each phase should be optimized based upon the actual traffic conditions. To achieve this function, the fuzzy controller should contain three functional modules, which are the phase priority determination module, the traffic light switching determination module and the phase-switching control module, as show in Figure 2 (Dorogovs and Kouziokas, 2007). All of these three modules have their own fuzzy control mechanisms. Therein, the phase priority determination module can prejudge an urgent phase depending on the current traffic light phase, in combination with the queue length and car-body spacing in traffic lanes.

This module allows for rational allocation of time and mitigates the most urgent traffic congestion. The traffic light switching determination module is used to determine the traffic signal in the current phase and judge whether it should switch to the next phase pursuant to the actual traffic flow. The phase-switching control module is the operating result undertaking the former two modules. It performs functional operations at a certain time interval to determine whether it should switch the current phase. The three modules have reflected the phase switching sequence and changes in actual traffic conditions at intersections over time, so traffic flow data collected by coils installed in traffic lanes plays a decisive role in whether the controller can obtain accurate prediction results.

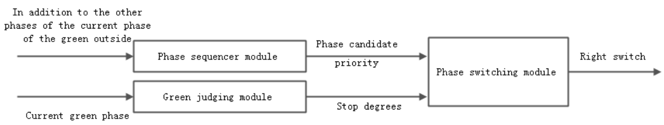

Figure 3: Structure of controller

Currently, fixed timing is the most commonly used mechanism for traffic lights, which is to preset fixed time lengths for three traffic lights (Green, Yellow and Red) and switch them in turn at fixed intervals. However, though this is easy to set and implement, it cannot distinguish between free flow and peak hours at intersections. This sweeping approach makes the traffic signal configurations very unscientific and is largely responsible for low traffic efficiency on the road. There will be very few vehicles passing through a green light and a long queue waiting at a red light.

Throughout the entire traffic signal control system, we need to focus on these main control objects: traffic signal cycle lengths at intersections, length of green light and length of vehicles waiting behind a red light in each lane (Bendaoud and Hart, 2009). These parameters are controlled in accordance with the traffic flow data collected by coils installed in traffic lanes. According to the working principle of traffic signal fuzzy control system designed herein, based on a four-phase switching mechanism, this paper inputs the traffic flow data of actually passing vehicles on the road as a control to the system, and outputs the traffic signal waiting lengths which are adjusted as per actual needs so as to achieve traffic control at intersections. Figure 3 is the control structure diagram using q, qs and qt as inputs (Delamer and Briffaut, 2010).

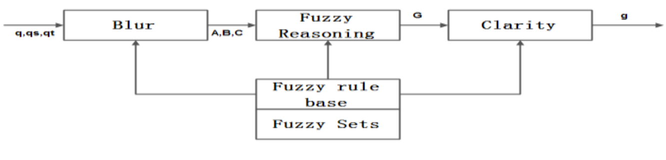

Figure 4: In (q, qs, qt) to control the amount of construction

As shown in Figure 3, the output value (g) denotes the value corresponding to the optimal signal timing scheme given by the current fuzzy controller; q, qs and qt denote the vehicle queue length in lanes with key traffic flow under the current phase and the estimated vehicle queue length before switching to the next phase. This cycle is set to reduce the number of vehicles in the queue and vehicle waiting time. In this paper, the sum of traffic signal cycle in the last phase and traffic signal length corresponding to the current phase is defined as the cycle time of the signal. Assuming there is small traffic flow in a phase through the current intersection, we can use small-cycle phase control to reduce the waste of resources; assuming there is large traffic flow in a phase through the current intersection, we can use large-cycle phase control to reduce congestion. Therefore, reasonable configurations of signal time-delay for the phase can effectively alleviate the traffic pressure and help improve traffic efficiency.

5. The Simulation Test of The Control System

By using binomial distribution of traffic flow, the simulation test of the control system randomly selects values to simulate traffic conditions at intersections in reality. Assuming that when passing through an intersection, 25% of vehicles will turn left, and that when vehicles should go through at a green light, they will travel at 0.6 per second; and when they should make a left turn at a green light, they will travel at 0.4 per second. Table 3 compares the fuzzy control method designed in this paper and the commonly seen fixed timing signal switching method. In the comparison test, fixed timing for going straight and making a left turn is set as 80 seconds and 30 seconds, respectively. The concrete test results are demonstrated in Table 2.

Table 2: Comparison of fuzzy control and simulation results of the fixed timing control

Intersection Traffic (Veh/h)	Intersections vehicle queue length (Veh/cycle)			Intersection Traffic (Veh/h)	Intersections vehicle queue length (Veh/cycle)		
	Fuzzy Control	Timing Control	cut back (%)		Fuzzy Control	Timing Control	cut back (%)
1100	11.5	22.07	46.54	2187	9.37	18.23	47.97
1360	7.4	13.85	43.56	2289	9.02	19.5	55.99
1700	6.52	15.2	50.86	2505	10.03	21.1	53.18
1590	7.54	15.4	48.67	2459	10.11	21.9	53.98
1790	7.4	16.59	52.19	2630	11.29	22.85	49.68
1880	8.75	16.38	51.02	2860	10.57	24.22	55.89
1870	7.69	17.04	53.2	2870	11.39	24.39	51.98
1980	7.45	22.23	65.5	2890	13.16	24.33	45.17

We can directly see the comparative test results in Table 2 that in terms of rationalizing time configurations, the fuzzy control system designed in this paper can well avoid problems caused by the currently used traffic signal control system, thus largely mediating queuing congestion at intersections.

6. Conclusions

There is a great demand for more intelligent urban traffic control systems in the transportation industry due to present-day modern development. As thus, how to work out an optimal traffic control scheme to alleviate traffic congestion is a hot issue in contemporary society, while this problem can be tackled from another perspective: applying fuzzy control to nonlinear, non-mathematical problems like traffic signal control. Hence, grounded upon fuzzy control technology, this paper has designed a set of traffic signal fuzzy control systems with the purpose of achieving multi-phase traffic signal control at intersections. Judging from the comparative results of the simulation test, we can find that employing the fuzzy control method is of greater help to improving vehicle capacity than the fixed-timing signal control method.

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