Abstract - This paper presents two optimal approaches of two-stage fuzzy controller for traffic signals at isolated intersections. Firstly, in the light that traffic status variables in two-stage controller leads to the inefficiency of traffic status weakening under low traffic flow, a two-stage combination fuzzy controller is designed from the perspective of structural optimization; this controller introduces 0-1 combination and determines the variables of fuzzy controller’s inputs according to real-time traffic status identification. Secondly, aiming at the problems of fuzzy controller parameter empirical settings and functional disability of learning, a two-stage fuzzy logic traffic signal controller with online optimization is proposed; this controller introduces the rolling horizon framework and optimizes parameters of membership functions and controller rules by an improved hybrid genetic algorithm. The performance of the two proposed models is validated via online Paramics-based simulation platform, and extensive relative simulation tests have demonstrated the potential of the proposed controllers for adaptive traffic signal control.

Keywords: Traffic signal; fuzzy logic; combination fuzzy; hybrid genetic algorithm; isolated intersection

1 Introduction

Single fuzzy controller considers all of status variables which lead to the increasing number of control rules and interference among status variables, or the only selection of queue length as status variable could not respond to traffic status[1,2]. Multi-stage fuzzy controller takes traffic status variables such as queue length, phase time, and saturation etc., into account, and processes these status variables disperedly, optimizes phase sequences, and improves the performance of fuzzy controllers[3,4]. However, the adoption of standard four phase structures ignores the noncritical traffic flow and right turn flow, leading to insufficient response to fluctuation of complex traffic flow and weekending of traffic status under the low or medium saturation at intersections, and due to empirical parameters assured by experts, multi-stage fuzzy controller is still without learning ability[5]. From previous optimization work on the selection of traffic status variables and structure of fuzzy controller to current optimization of controller parameters with intelligent algorithms. Optimization of fuzzy logic-based control for traffic signals at isolated intersection have attracted the attention of scholars at home and aboard.

Ballester[6], Henry[7], and Bingham[8] etc., introduces artificial intelligent algorithms, such as genetic algorithm, neural networks, reinforcement learning, to learn fuzzy controller’s parameters in the course of traffic signal control’s interaction with traffic environment, and the simulation results indicate effectiveness of multi-stage fuzzy optimizing control, but many of which are off-line optimizing methods, and performance of these controllers mainly depend on the efficiency of optimizing algorithm, the valid sample sets, and the design of the feedback function. Genetic algorithm(GA) has the ability of global search and does not depend on gradient information and experiential knowledge[9]. In the light of this, Lekova[10], Kim[11] and Yang[12] etc., widely employs GA in researches of parameter optimization of fuzzy controllers, which could be divided into three categories: optimizing fuzzy membership parameter under experimental fuzzy rules, optimizing of fuzzy rules under experimental membership parameters, and optimizing membership parameters and fuzzy rules at the same time. Moreover, the majority of existing methods applies Matlab and computer program to simulate operation of traffic flow at intersections which does not represent the actual traffic flow in the road network, and thus lacks simulation evaluation method to evaluate implementation of fuzzy optimal controller[13].

Along the line of previous studies and in response to the above critical issues of traffic intensity-based two stage fuzzy controller, this paper presents adaptive two-stage fuzzy controllers for traffic signals at isolated intersections: architecture, algorithms, and online Paramics simulation. The remainder of this paper is organized as follows. Section II will detail the research scope and illustrate traffic intensity-based two-stage fuzzy control model for traffic signals. Section III illustrates two-stage combination fuzzy control model for traffic signals, including modeling theory analysis and conceptual models. Section IV details HGA-based two-stage fuzzy controller, which includes rolling horizon framework, online optimization design of two-stage fuzzy controller, objective function based on traffic status identification, and solution algorithm. Section V evaluates the proposed fuzzy controller with extensive experimental tests via Paramics-based simulation platform of online two-stage fuzzy optimal
control, which still includes development of Paramics-based simulation platform via Matlab and VC++ hybrid programming, and Paramics simulation experiment design. Section VI analyzes simulation results in detail. Section VII concludes the work.

2 Research scope and two-stage fuzzy model for traffic signals

2.1 Experimental test intersection

A typical cross intersection is shown in the left of Fig.1. The intersection has four approaches, and each approach has three types of traffic flow named straight flow, left flow and right flow. When right traffic volume is heavy, to avoid that vehicles interweave with each other and affect the passing efficiency by disrupting the straight flow in the opposite direction and the left flow in the same direction, the right-turn vehicles are under the signal control to simulate a real-world control environment, and the revised standard four-phase is shown in the right of Fig.1.

![Traffic Signal Diagram](image)

Figure 1. Experimental test intersection

To detect real-time traffic flow arrival and departure of each lane at intersection, the strategic and tactical loops are respectively deployed in each lane of each approach. As shown in left part of Fig.1, the tactical loops are deployed before the stop line to detect the throughput of each lane, including the number of leaving vehicles and their departure time, while the strategic loops are deployed at a distance of 150m away from tactical loops upstream of each approach to detect the arrival traffic demand of each lane, including the number of arrival vehicles and their arrival time.

2.2 Two-stage fuzzy control algorithm

Following basic principles of traffic signal control such as the maximum and minimum cycle and the maximum and minimum green time, the two-stage fuzzy control algorithm is as follows: (1) give minimum green time to the current green phase until the remainder of green time is 2s; (2) traffic intensity module determine red-urgency or green-urgency of each phase according to real-time detected traffic flow data, and select the red phase with maximum red-urgency as the next target green phase; (3) decision module determines extension time of current green phase \( g_e \) based on green-urgency and maximum red-urgency; (4) whether to switch current phase is determined by control logic that phase switch to next target green phase if \( g_e \) is less than 6s.

2.3 Structure of two-stage fuzzy controller

The Control rules of traffic signal fuzzy controller increase by exponent with the increase of the number of status variables, and each status variable interferes with each other. In order to make traffic signal fuzzy controller to respond to traffic flow change swiftly, this paper introduces traffic intensity to apply the two-stage fuzzy control model for isolated traffic signals, and denominates traffic intensity of red light phase and traffic intensity of green light phase as red urgency and green urgency respectively depending on their control features. Following this, the number of control rules decreases through multi stage and the interference between status variables of green light phase and those of red light phases is avoided. The structure of traffic signal two-stage fuzzy controller is shown in Fig.2.

![Fuzzy Controller Diagram](image)

Figure 2. The structure of traffic signal two-stage fuzzy controller

The first stage is to determine the level of the traffic statuses, which includes determining the urgent degree of red phase, the urgent degree of green phase and the optimal choice of next target phase. Among the three items, analyzing the traffic flow data collected at intersections, the urgent degree of red phase and the urgent degree of green phase are determined by green urgency module and red urgency module to evaluate the traffic intensity of signal phases. As to adapt to the dynamic features of traffic flow at intersections and the non-uniformity of traffic flow distribution, the function of the optimal choice of next target phase is aimed at selecting the highest phase among the urgent degree of red phases as the next target phase of green light, so as to achieve the optimization of phase sequence.

The second stage is to determine the extension time of the phase of green light. Based on the urgent degree of the current green phase and the urgent degree of the current red phase, the values of the current extension time of current green phase is determined by decision module.

The details on the above three fuzzy modules that determine red urgency, green urgency and decision time
respectively could see Yang’s models[12]. Because of the uncertainty of traffic flow arrival for different phases, to consider non-critical flows, the average value of traffic flow parameters is selected as the input of controllers. And to formulate the reasonable control scheme representing traffic reality, vehicle flows of right turn are taken into account.

3 Two-stage combination fuzzy model

3.1 Theory analysis of modeling

The urban traffic signal two-stage fuzzy controller is influenced by the choice of traffic status variables and the reasonable setting of control parameters. When saturation of traffic flow is high, a certain number of queuing vehicles appears in each red light phase, thus it is hard to accurately represent the traffic status at intersections only considering the number of queuing vehicles, and two-stage fuzzy control based on traffic intensity, considering the phase time traffic status variables, meets control demands. However, the traffic flow is free under the condition of low vehicle flow and the number of queuing vehicles is less[3-5]. Under this situation, traffic status at intersections is weakened due to consideration of phase time and two-stage fuzzy control under low traffic flow approximately equals to the minimum-cycle based control. The reasons of the worse performance in low traffic flow condition is illustrated as follows: (1) Because of the short extension time of green phase, the phases switches frequently, and most of new coming vehicles have to queue before going through intersections; (2) Because of the consideration of time of red light phase, the waste of green time under no queuing vehicles is severe as the queuing vehicle of the new green light phase is less.

Thus, the status variables’ choice of two-stage fuzzy controller’s inputs should be directly relevant to traffic status at intersections. The choice of status variables is determined by features of traffic status. Based on respective traffic status variables of different traffic status at intersections, the structure of fuzzy controller under different traffic status should be adaptive.

3.2 Conceptual model of comination fuzzy

In the light that the standard fuzzy controller has achieved better control performance under low traffic flow and two-stage fuzzy control based on traffic intensity has achieved effective performance under high or middle traffic flow, the two-stage combination fuzzy control for urban traffic signals introduces “0-1” combination[14], in which choose the number of queuing vehicles as the traffic status variable under the condition of low traffic flow and thus apply the standard traffic signal single-stage fuzzy control (SFTSC)[2], while choose the phase traffic intensity as the traffic status variable under the condition of high traffic flow, and thus apply the traffic signal two-stage fuzzy control (TFTSC)[12]. The conceptual model of traffic signal two-stage combination fuzzy control is shown in (1).

\[
\begin{align*}
SFTSC & \quad \text{if } Y \leq Y_0 \\
TFTSC & \quad \text{if } Y > Y_0
\end{align*}
\]

In (1), \(Y_0\) denotes total flow rate of intersections. And the identification of high or low traffic flow at intersections applies the method of two-dimension traffic status identification in reference [15]. According to the features of high or low traffic flow, the standards of identification of high and low traffic flow uses the threshold of free status that is \(Y_0\) is 0.42 while occupancy of intersections is lower than 0.33.

Based the real-time ability of traffic signal control schemes and demand of the balanced transition of control schemes, \(T_c\) is selected as roll optimization cycle of two-stage combination fuzzy controller, that is at every \(T_c\), by judging the traffic status of the intersection, the model of fuzzy controller for the following control interval is selected based the traffic status at isolated intersections.

4 Online optimization design for two stage fuzzy control

4.1 The rolling horizon framework

This paper optimizes parameters of membership functions and parameters of fuzzy rules at the same time[9]. To set the parameters of two-stage fuzzy controller response to real-time traffic conditions at intersections, this study introduces the rolling horizon[16]. With detecting traffic data, at each control interval, the controller parameters can be updated to adapt to real-time traffic flow characteristics accordingly. The framework of rolling horizon is shown in Fig.3. And the illustration of rolling horizon are as follows.

1. Detect real-time traffic data during entire control time horizon \(H\), such as arrival and leaving vehicles, etc.; (2) Setting length of projection stage \(T\), decide each roll period length or each control interval (the accumulated time under latest controller with optimal parameters is just over \(T_k\)), and optimize parameters of fuzzy controller by hybrid genetic algorithm (HGA) according to quasi real-time historical traffic data; (3) Update parameters of fuzzy controller in time after optimization; (4) Repeat the above optimization process when it comes to the next control interval.

![Illustration of the rolling horizon](image-url)
And the structure of two-stage fuzzy controller based hybrid genetic algorithm for traffic signals is shown in Fig.4.

![Figure 4. Structure of optimal two-stage fuzzy control system](image)

In Fig.4, the designed HGA-based optimal fuzzy control system includes four following sub-modules: the two-stage fuzzy control in implementation, the reappearance of quasi real-time historical traffic flow, HGA-based optimization of parameters of fuzzy controllers and history database for managing traffic data.

4.2 Objective function based on traffic status identification

This study adopts average delay at an intersection as evaluation index of each controller with specific controller parameters. There are two methods to calculate delay: Mesoscopic numerical simulation[17] and Microsimulation [18]. Limited to the support of secondary development kits of most simulation software, this study employs mesoscopic numerical simulation to model the average delay.

To model the discrete process of vehicle arrival at intersections, the assumption that one vehicle is queuing when it just arrives strategic loops is mostly used. Though delay models based this assumption fit better relatively under high saturation that traffic volume at intersection is heavy and there are certain queuing vehicles at most approaches, the delay error is larger under low saturation due to vehicle’s discrete process between strategic and tactics loops. Therefore, this study models average delay at intersections based traffic status identification[15]. Under low saturation, the newly arrived vehicles enter the queuing with the possibility of 50%[12], while the newly arrived vehicles enter the queuing with the possibility of 100% under high saturation[17].

4.3 Solution algorithm

(1) Decoding for controller parameters

The traffic intensity-based two-stage fuzzy controller employed in this study has two input variables and one output variable, and all of which are divided into five fuzzy sets. Decoding for this controller includes parameters of membership function and fuzzy rules. To improve control algorithm’s accuracy and solution algorithm’s convergence speed, real number encoding is designed to decrease the length of the chromosome. As shown in the left part of Fig.5, this study adopts triangle membership function to reduce the number of controller parameters, and let the base vertices of each membership function separately superpose centers of two adjacent membership function, consequently, with the center of membership functions, its position and shape could be effectively given.

For the chromosome of control rules, to decrease the complexity and enhance the real-time ability of controller, utmosly 25 controller rules could be selected. considering following integer matrix $R: R = [r_{ij}]_{6 \times 5}, i \in [1,5], j \in [1,5]$, while $r_{ij}$ is an integer within $[1,5]$, denoting the index value of output of fuzzy sets. Then $R$ can be converted into a row vector $R^*$ that can denote the chromosome of fuzzy rule, i.e. replacing the first element of the next row just behind the last element of the former row. Individual coded schema of two-stage fuzzy controller is shown in the right part of Fig.5.

![Figure 5. Decoding for parameters of fuzzy controller](image)

(2) Hybrid genetic algorithm

A GA-based heuristic(HGA) extended form the method by Yang has been developed to yield approximate solutions for each control interval during the entire optimization period[15]. The proposed heuristic features its capability to identify the solution closest to the best solution by introducing simulated annealing algorithm to enhance the local optimal capability of genetic algorithm. The process of improved hybrid genetic algorithm is as follows:

i) Initialization: generate initial population, and initialize GA and SA parameters. According to generation and fitness value, crossrate and mutationrate is adaptive.

ii) Fitness evaluation: Evaluating performance of each controller with specific controller parameters is to calculate average delay at intersection ($d$) based traffic status identification, then the fitness value is computed in (2).

$$f(d) = \frac{1}{1 + d}$$  \hspace{1cm} (2)

iii) Selection: roulette wheel selection.

iv) Crossing: non-uniform arithmetic crossover operator.

v) Mutation: non-uniform mutation operator, by which the degree of mutation is adaptively adjusted with generation and fitness value.
vi) Elitist strategy: replace the worst individual by the best.

vii) Local optimization by Simulated Annealing: introduced the best individual of cur-generation as initial vector, enhancing the local optimization via SA.

a) Generate new individuals by status function of SA;
b) Select the individual by metropolis principle in SA;
c) Judge the stability of SA, if non-steady, go to a); Otherwise, execute annealing operation and go to step viii);
viii) Judgment of termination principle: if n<Gen, go to Step2. Otherwise, output the best solution.

5 Case study

5.1 Quasi-online Paramics-based simulation platform

Traffic simulation, which could simulates the operation of traffic flow under different control strategies, is an effective evaluation approach for urban traffic signal controls. The microscopic simulator Paramics was employed as an unbiased evaluator for model performance, and a Paramics-based simulation platform of quasi-online two-stage fuzzy optimization control is developed. The Paramics-based simulation platform of two-stage fuzzy optimization control consists of implementation module for actual control and optimizing module for learning parameters. Taking the efficiency of optimizing module into account, in the process of optimizing, the implement module is still operating. The novel optimizing codes come into operation just at the end of previous optimizing request. The following are the features of the developed simulation platform:

(1) To shorten the development cycle and improve the accuracy of fuzzy decision, three types of fuzzy controller are developed via Matlab;

(2) To make Paramics simulation platform of fuzzy control interact with above three fuzzy controller, the hybrid programming of Matlab and VC++ is introduced by which interface between VC++ and Matlab is defined and control strategies such as actuated control, two-stage fuzzy control, and HGA-based two-stage fuzzy control are secondarily developed into Paramics via Paramics API[18], and to establish the communication between implementation module and optimal module, database-based command queuing technology is used;

(3) Physical simulation network for a typical urban isolated intersection is developed via Paramics’s Modeler module, and by loading control strategies’ Plug-in into Paramics, the performance of those traffic signal controllers could be validated under different traffic scenarios designed in Paramics.

5.2 Paramics simulation

(1) Simulation algorithm

Following the basic algorithm of two-stage fuzzy control, in the two-stage combination fuzzy controller, $T_i$ is 5min, that is when the accumulated time is just over 5min, two-stage combination fuzzy optimization module selects the most appropriate fuzzy controller based real-time traffic status at intersections; For HGA-based fuzzy controller, $T$ is 10min and $T_i$ is 8min, that is when the accumulated time under latest controller with optimal parameters is just over 8min, HGA-based two-stage fuzzy optimization module learns parameters of three fuzzy controllers, and updates the parameters of fuzzy controllers of implementation module at the end of parameter optimization.

(2) Simulation scenarios

In order to examine the proposed control method under different traffic flow conditions and different traffic flow fluctuation, this paper designs a variety of simulation scenarios, including uniform arrival for each approach, a sudden change in one of direction flows, and unbalanced arrival for each approach. The specification of simulation scenario is as follows:

i) Simulation length is 13h, approach arrival flow ranges from 400 to 1600 per hour. And every per hour is a simulation time period, and the turning ratio of left-straight-right 0.25-0.60-0.15;

ii) To simulate traffic fluctuation in short-term, vehicle's departure rate in 10min intervals per hour, set in the Profiles of Paramics, is as follows: 15-11-17-22-16-19;

iii) According to the design standard of urban roads in china that the capacity of straight, left and right are 1650pcu/h, 1550pcu/h and 1550pcu/h, the key simulation parameters of mean driver reaction time(MDT) and mean headway time (MHT) are respectively calibrated to1.8s and 1.5s;

iv) To overcome the stochastic nature of simulation results, an average of 20 simulation runs has been used.

(3) Simulation experiments

Experiment I is designed to verify two-stage combination fuzzy control (CTFIFuzzy), compared to fixed-timing, actuated, and traffic intensity-based two-stage fuzzy control. Here, fixed-timing scheme (Fixed) is Webster signal timing under average traffic flow at intersections (05:00-06:00)[19], while in actuated control (Actuated), detector loop is 30m away from the stop line, and the extension unit time is 3s[15]; and traffic intensity-based two-stage fuzzy control (TFIFuzzy) adopt Yang’s method[12]. And compared to fixed-timing, actuated and two-stage fuzzy control based...
traffic intensity, experiments II are designed to validate two-stage fuzzy control based HGA (GAFuzzy).

Considering traffic flow characteristics and safety demands at signalized intersections, simulation parameter settings are as follows: maximum green time for phase 1 and phase 3 is 80s, while 50s for phase 2 and phase 4, and minimum green time for four phases is 12s.

6 Results

Performance indices in this study are average delay (Delay), average queuing number (Queue) and average speed (Speed), and approach throughput (Count). Among them, speed and throughput are benefit indicators, while delay and queue are efficiency indicators.

(1) Two-stage combination fuzzy controller

Simulation results of the two-stage combination fuzzy control’s performance are shown in Fig. 6. The performance of two-stage fuzzy controller is poor in the low traffic flow due to the weakening of traffic status, which result in the frequent shifts of phases and the waste of phase green time when less vehicles passing. Throughout the whole simulation process, combination fuzzy control is stable, and compared to the fixed, actuated or two-stage fuzzy control, the performance of combination fuzzy controller are improved greatly. For example, the delay decreases by 30% to 10%. And simulation results indicate that this controller improves the performance of two-stage fuzzy control in low traffic flow conditions.

(2) HGA-based two-stage fuzzy controller

Simulation results of HGA-based two-stage fuzzy controller’s performance indices are shown in Fig. 7. Throughout the simulation process, HGA-based two-stage fuzzy control is stable. Performance of delay, queue length etc., are better than those of fixed-timing, actuated control and two-stage fuzzy control. Furthermore, performance of this controller is still getting better as traffic arrival volume of each approach is increasing. Taking delay as an example, compared to the actuated control, fixed control, and two-stage fuzzy control, GA-based fuzzy control decreases delay by 27%, 30% and by 13% respectively.

At a certain control interval, taking the red urgency module as an example, the differences between membership functions with empirical parameters and membership functions with optimized parameters are shown in Fig. 8.

7 Conclusions

This paper presents two adaptive two-stage fuzzy controllers for urban traffic signals at isolated intersections. From the perspective of structural optimization, the two-stage combination fuzzy controller introduces 0-1 combination, in which the single-stage controller will be applied under low traffic flow, while the traffic intensity-based two-stage fuzzy controller will be used under medium or high traffic flow. This combination controller determines traffic status variables of fuzzy controller’s inputs depending on the traffic status at intersections, and adapts to the influence of traffic flow change on the performance of different fuzzy controllers. Then, aiming at the problems of fuzzy controller parameter empirical settings and functional disability of learning, the HGA-based two-stage fuzzy control introducing rolling horizon framework develops an adaptive optimization framework of fuzzy controller to adjust fuzzy membership functions and controller rules with on-line learning. At regular time intervals, HGA-based controller employs a hybrid genetic algorithm to efficiently yield the reliable solution through reapparance of statistical traffic flow. Experiments are carried on typical urban isolated intersection and the performance of proposed model and algorithm is validated via Paramics-based simulation platform of on-line two-stage fuzzy optimization control.
Extensive Paramics simulation results indicate that different traffic signal controller has its application boundaries. It is reasonable that combination fuzzy control selects traffic state variables of fuzzy controller according to traffic status at intersection, which improves the performance of two-stage fuzzy control in low flow conditions; and HGA-based fuzzy controller learns parameters with quasi-online optimization, which is stable and get better performance. Compare to fixed-time, actuated, and two-stage fuzzy controller for different traffic conditions, the two proposed controller offer a better performance as the traffic flow increases, and control effects are consistent with traffic manager’s control object.

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9 References


