

# Multimode Speed Control Based on Fuzzy Decision-Making for Automatic Train Operation

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## Abstract

Based on the analysis of train running process and train motor-driven models, an ATO compound control algorithm of multimode fuzzy decision making is proposed, which will improve the effects of dynamic and static control of ATO system. Control weighting coefficients of PID controller output and fuzzy controller output are obtained by fuzzy reasoning, fuzzy decision-making and dynamic calculations of error and error rate of train speed, and also the weighting coefficients are used for the output calculation of fuzzy decision-making controller. Simulation results show the speed and accuracy of ATO speed control are improved effectively by the compound multimode decision controller algorithm, which help to improve the comfort of trains and its stop precision.

**Keywords:** ATO, fuzzy decision-making, multimode control, speed control

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## 1. Introduction

The ultimate goal of ATO (Automatic Train Operation) system is to select reasonable operation mode and running track automatically to complete automatic driving task according to line conditions and external signal of railways in unmanned cases. The main function of ATO is to adjust the train's running speed, and only on the basis of accurate speed regulation can the ATO complete positioning and parking tasks; The speed regulation in the premise that passenger feel comfort improve the efficiency of the train operation [1]. Therefore, train speed control system's performance will directly affect the development of the rail transit system.

Researchers have applied classical control theory, intelligent control theory and methods to train ATO speed control since the early 60's. Great progress of the ATO system development has been brought by introducing of these algorithms and theory, but there is also some lack of improvement. For example, PID application was introduced to modulate train's speed accurately by using steady-state error of control system. PID control, however there are also disadvantages of slow response, acceleration not easy to control, and not meeting the requirements of comfort. Fuzzy and expert control mainly simulate experience from control experts, which meets the requirements for comfort and fast speed, but its accuracy of control cannot be essentially changed [2, 3]. Low stability and slower learning speed are problems from neural networks [4].

Single control method is applied to ATO speed control, and the overall effect is not particularly desirable. More and more researchers are trying to apply a variety of control methods in ATO, which are composite control methods. Therefore, the composite control algorithm is the focus of the ATO speed control system of the current and future research. Based on the trend, PID control and fuzzy control algorithm are integrated together to get a new composite method. The fuzzy decision-making output of different stages is achieved by introducing fuzzy decision, which improves control accuracy and robustness of the ATO system.

## 2. Train Operation Process and Dynamic Model of the Train Operation

### 2.1. ATO Speed Control Process

In the case of a fixed railway line, ATO, according to the driving command and the current state of the train, modulates train's speed in the different operating conditions, while

different speed is corresponding to different operating target of the control. All of the stages of the train traction, coasting, speed control and braking are under the complete supervision and protection of the ATP(Automatic Train Protection) which is part of ATO system. The ATO maintains the actual vehicle speed to a certain value under the limit from the ATP, and once the train speed exceeds the ATP's speed limit, emergency braking will be done. Due to the excessive grading brake (multi-stepped braking mode), the train will take up a line more longer time, affecting transport efficiency. Now one level speed adjustment has replaced multi-stepped braking mode before braking and parking in accordance with established brake curve [5]. This speed control mode does not only guarantee the train positioning parking, but also help to improve the transport efficiency of the train. The train speed control and braking mode is shown in Figure 1.

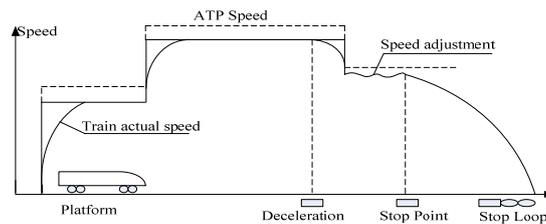


Figure 1. Train Speed Control Operating Mode

In the case of fixed section length of the train operation, railway line conditions, and the running speed of each point on the line, ATO, according to the traction / braking characteristic curve, obtains a given running speed curve by traction calculation. One of the main tasks of the ATO is to control the train to track a limited running speed curve fast and smoothly for a high-speed and stable train operation. So the design of ATO controller is absolutely the research focus.

**2.2. Dynamic Model of the Train Running**

According to the literature [6], the dynamic model of train running, such as Equation (1) is shown:

$$\begin{cases} \frac{ds}{dt} = v \\ \frac{dv}{dt} = \frac{C - W}{M} \end{cases} \tag{1}$$

Wherein, s is traveling distance of the train; v is train's speed; t is operation time of the train; C is traction/braking force, and C = F is the traction state, C = -B is the braking state; W is the drag force; M is total mass the train.

As the plant, the electric locomotives not only include the traction motor controlled directly, but also the train altogether. If take the rectified voltage as the input applied to the traction motor, the speed of the train is the output. Take a separately excited motor to analysis of the speed modulation of the train [7, 8] as a example, the armature circuit of traction motor is shown in Figure 2.

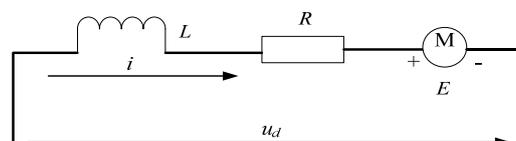


Figure 2. Armature Circuit of Traction Motor

Armature circuit voltage balance equation of the traction motor is below:

$$L \frac{di}{dt} + Ri = u_d - E = u_d + C_v \phi_v \quad (2)$$

Wherein, L and R, are respectively the total inductance and total resistance of the armature circuit, and  $i$  is the armature circuit current,  $u_d$  is the total voltage applied to the motor, E is the counter electromotive force of the motor.

Based on the relationship between the train acceleration and traction of the electric locomotive traction as well as the relationship between each traction motor on the train and its current, if acceleration resistance of train is ignored, can the total mass of the train be converted to each traction motor. Derivate Equation (2) and Equation (3) can be got [8].

$$\frac{v}{u_d} = \frac{1/C'_v}{T_M T s^2 + T_M s + 1} \quad (3)$$

Wherein,  $C'_v = C_v \phi$ ,  $T_M = \frac{RM}{C'_F C'_v}$ ,  $T_i = \frac{L}{R}$ ,  $C'_v$  coefficient of induced electromotive force,  $C'_F$  is constant coefficient of traction motor.

Visibly, a second-order transfer function can be used to describe the train drag system, and the selection of the parameters can be combined with the experimental data.

### 3. The Multi-modal Control and Fuzzy Decision-making Structure of ATO System

Three parts are included in the ATO controller of multi-modal system: the fuzzy controller, PID controller and fuzzy decision controller. In Figure 3 is target speed, and is the actual train speed.

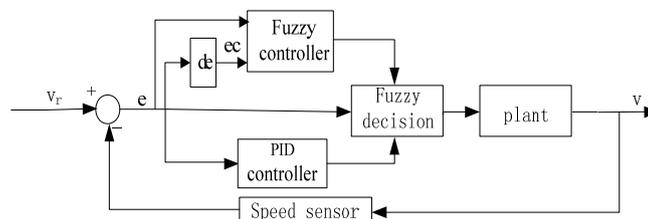


Figure 3. ATO System Multi-modal Control Block Diagram

#### 3.1. Multimode Control

The nature of multimode control is to mimic strategies of control experts on the transition process of the controlled system, namely segment control. In the process of control, the amount changes of the object controlled determine the state of the current object, and then appropriate control strategies are taken. The design task of multi-mode controller is to use structure as simple as possible and control mode and parameters as few as possible to achieve the control requirements.

PID regulating rule for linear time-invariant systems control is very effective, and the quality depends on the parameters of the PID controller. However conventional PID controller cannot tuning parameters online, and for nonlinear time-variant systems of the train ATO operating system, it can not control the system well. Simple fuzzy controller does not have the integral unit and it is difficult for it to completely eliminate the steady state error; there are often small oscillations near the equilibrium point in the case of not enough variable grading. For the above reasons, if the two control modes are combined, can the multi-modal controller be got, which have both the advantage of the two methods mentioned above.

A critical problem need to be solved for a multi-modal controller of train: identify the controlled system state information to achieve better control of the system, and these characteristics reflect the characteristics of the input and output response. Speed deviation  $e$  and error change rate  $ec$  are used for judgment of dynamic characteristics, and thus achieve effective control.

### 3.2. Fuzzy Controller Design of ATO System

There are variety of ways to design a fuzzy controller, and the wider use one is look-up table fuzzy controller design method:

Step 1: Determine the number of language variables of input and the output of fuzzy controller, which is the dimension of fuzzy controller. Select  $e$  and  $ec$  as the input linguistic variables, and  $u$  as the output of fuzzy controller.

Step 2: According to the actual circumstances of application, determine the range of variation of input and output variables, the quantization level, factors of quantization and decision; the range of  $e$ ,  $ec$  and  $u$  are all 7.

Step 3: Definition fuzzy subset of each variable (the variable range) within their quantified domain. Firstly, determine the number of fuzzy subset of its linguistic variables; secondly take appropriate membership function for linguistic variables. The  $e$  and  $ec$  have the range of  $[-3\ 3]$ , and the range of the output  $u$  is  $[-4.5\ 4.5]$ ; Triangle membership function is selected, the variable classification using  $\{NB\ NM\ NS\ ZO\ PS\ PM\ PB\}$ .

Step 4: Determine the fuzzy control and fuzzy inference rules. Summarize the control experience of the experienced operator and derive the set of fuzzy rules, and the corresponding output control of each input can be got. The method to design fuzzy rule of the controller of the ATO system is common, no longer given.

Step 5: To strike fuzzy control table, that is the process of precisizing. In this study, the wider used method of center of gravity is applied.

Though the above five steps, fuzzy controller of the ATO has been designed.

### 3.3. Fuzzy Decision Controller Design of ATO

In order to improve the response speed and accuracy of the ATO system, a fuzzy decision-making controller is built to integrate both advantages of the PID controller and fuzzy controller. PID control usually has good control accuracy, but it can not simultaneously take the rapid system response and stability into account. Fuzzy control has good robustness and fastness, while it can not identify small error and its control accuracy is not enough. The role of fuzzy decision-making controller is to enhance the smoothness of the ATO's velocity modulation, by fuzzy reasoning and judgment, and to achieve the control of the two control methods intensity switch.

Decision-making unit itself is also a fuzzy controller, whose inputs are absolute value of deviation  $e$  and deviation change rate  $ec$  between the speed feedback and a reference one, namely  $|e|$  and  $|ec|$ . Weight coefficient  $w_{pid}$  and  $w_{fuzzy}$  are outputs for the PID controller and fuzzy controller, which means that the fuzzy decision is a dual-entry and dual-output controller. The design steps of decision-making unit are similar to the fuzzy controller's, and the following only give the different parts between them.

The fuzzy domains for both  $|e|$  and  $|ec|$  of the decision-making unit are  $[0\ +3]$ , and the output  $w_{pid}$  and  $w_{fuzzy}$  of decision-making unit is  $[0\ +4.5]$ . Fuzzy sets  $\{S\ M\ B\}$  are used to describe input and output, and the membership functions of the input and output of the decision-making unit are shown in Figure 4. Table 1 shows the fuzzy decision rules. Control weight coefficients of decision-making unit and PID controller can be output by decision rules in Table 1.

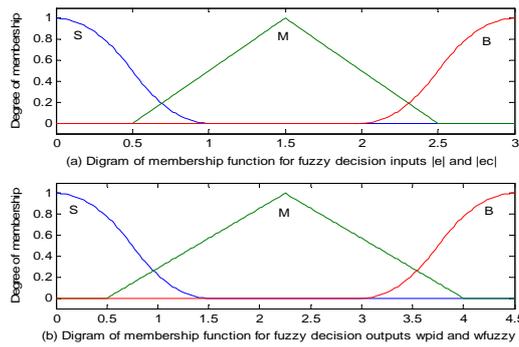


Figure 4. Diagrams of Membership Functions. (a) is the diagram of membership function for inputs  $|e|$  and  $|ec|$  while (b) is the one for outputs  $wpid$  and  $wfuzzy$ . S, M and B respectively means small, medium and big.

Table 1. Rule Table of Fuzzy Decision-making Controller. S, M and B respectively means small, medium and big.

$ e $	S	M	B
$ ec $	$wpid / wfuzzy$		
S	B/S	M/S	S/B
M	S/M	M/M	M/S
B	S/B	M/B	B/B

Order and denote the output of the PID controller and a fuzzy controller respectively, then the output of decision-making unit can be represented by the weighted average algorithm of formula Equation (4).

$$U = \frac{wpid * Upid + wfuzzy * Ufuzzy}{wpid + wfuzzy} \tag{4}$$

**4. Simulation and Analysis**

According to the literature [9], select appropriate parameters for the kinetic model of the train and the object model which is converted to a single traction motor system. The simulation objects presented as formula Equation (5) below.

$$G(s) = \frac{0.07128}{s^2 + 0.4356s + 0.0324} \tag{5}$$

Figure 5 shows the simulation results of a running train at a certain train section. Subgraph (a) to Subgraph (d), is respectively corresponding to the ATO fuzzy control, ATO threshold decision-making control, the ATO PID control and ATO multimode fuzzy decision-making control [10]. From start-up, the train experiences accelerated traction, smooth traction, coasting and braking and parking sessions [11, 12]. The whole running process is completed under the supervision of ATP system. Subgraph (e) to Subgraph (h) show the partial magnified areas (corresponding to area (A) to area (D)) of the acceleration traction and smooth traction control effect of the conversion. From (e) and (f) it can be seen that there are always slight oscillation of the fuzzy control and the threshold control under the train traction braking curve; (g) presents the control effect of PID control, and there is static error, too. (h) presents the effect of a multi-modal fuzzy control of decision-making control. It can be seen that fuzzy decision-making control can maximally track the target speed curve produced by ATP. As a

result, the control accuracy of the train is improved, maintaining the train's comfort and improving the accuracy of the train's positioning and parking.

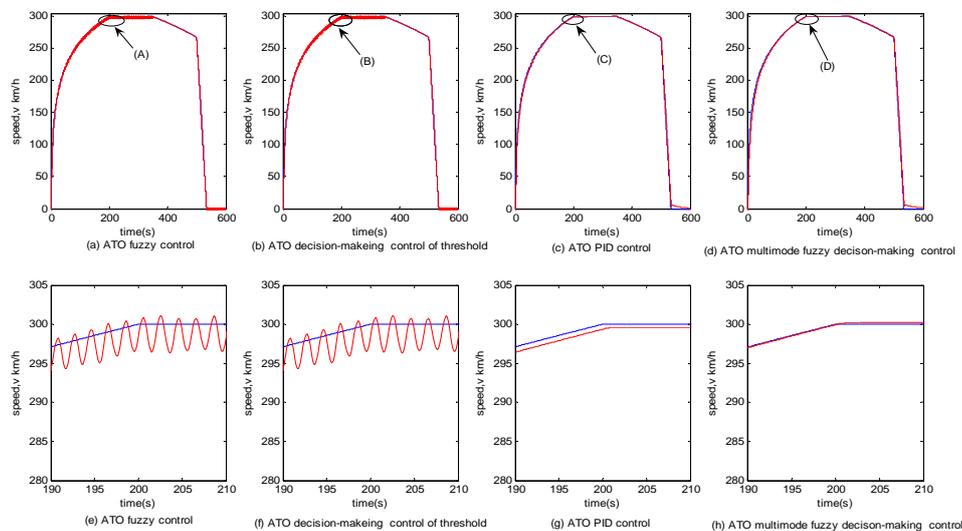


Figure 5. Traction and Braking Simulation Curves of a Train's Running Process  
Partial Magnified Traction and Braking Curves

## 5. Conclusion

ATO system under the monitoring of ATP is a typical non-linear, multi-variable, and complex system. Single control strategy can hardly reach good control effect. The multi-mode controller of ATO traction and speed modulation is designed based on basic fuzzy controller, PID controller and fuzzy decision controller, and simulation is done as well. Control requirements in different operating conditions of traction, coasting, speed-adjusting control and braking are met by the weight output of the fuzzy decision. The results show that multi-mode train speed control of fuzzy decision-making can achieve good effect under different working conditions and control stage.

## Acknowledgements

This research is financially supported by the technology research and development program of Ministry of Railways, China (Grant NO.2011X008-D) and the Youth Science Foundation of Lanzhou Jiaotong University, China (Grant NO.2012035).

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