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APPLICATION OF PREDICTIVE FUZZY CONTROL TO AUTOMATIC TRAIN OPERATION CONTROLLER

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Abstract

A predictive fuzzy control is applied to an automatic train operation (ATO) controller using a micro-computer. Computer simulations and experiments in practical systems demonstrate that the proposed fuzzy controller can perform robust and energy saving train operations as a skilled human operator does.

Introduction

In recent years, automatic controllers using a micro-computer instead of a human operator have been developed for plants, transportation systems and so on. In many cases, a computer control gives quick response and accurate control, but inferior quality of control than a skilled human operator. A fuzzy logic[1] control method which can make up an algorithm from control know-how of a skilled human operator by fuzzy sets, is proposed by Mamudani[2] (1973), and applied to a plant[2], a traffic junction[3], a cement kiln[4], a water treatment[5] and so on[6]. However, these controllers can't realize operations considering control results which are included in purposes of a system operation.

To solve this problem, we have proposed a predictive fuzzy control which predicts the result of each candidate control command and selects the most likely control rule based on a skilled human operator's experience. The predictive fuzzy control is applied to automatic train operation systems (ATO) by which a train can be started, kept to a limited speed and stopped at a target position of a station.[7]

ATOs have been developed for new transit systems including subway[8], monorail and new public transit systems like PRT.[9,10] In these systems, trains are controlled by a conventional feedback control method such as a PID control. Therefore, it dose not take important performance indices for a train operation such as, safety, riding comfort of passengers, accuracy of the stop gap and energy consumption into consideration.

In this paper, our newly developed fuzzy ATO controller is explained. This controller can realize a skilled human operator's control by evaluating safety, riding comfort, traceability of target velocity, energy saving , running time and the accuracy of a stop gap. By computer simulations, the developed fuzzy ATO controller is compared with the conventional PID ATO controller.

Predictive Fuzzy Control

The fuzzy control applied to a cement kiln by Holmblad (1982) decides a control action u* from the set of control rule Ri, which is described as "If x is Ai and y is Bi, then u is Ui". This fuzzy control evaluates the system state, which is described as "if part : x is A and y is B", and decides u* from these values. "If speed is high and rising, then increase the braking notch a lot" is a typical example of train control rules. However, this method can not evaluate results of a selected control command.

In order to overcome this problem the predictive fuzzy control has been proposed. In the proposed method,
(i) the control rule Ri is described as "If (u is Ci → x is Ai and y is Bi) then u is Ci",
(ii) the control rule Cj is selected if the predictive results (x,y) shows the highest likelihood.
The algorithm of the predictive fuzzy control is as follows:

A fuzzy set A on universe of discourse U is characterized by a membership function μ_A: U ∈(0,1) which associates each element x of U with a number $\mu_A(x)$ in the interval(0,1). A fuzzy set **A** is considered as the union of its constituent singletons. On this basis, **A** may be represented in the form of

$$\mathbf{A} = \int_U \mu_A(x)/x$$

where the integral sign means the union of the fuzzy singletons $\mu_S(x)/x$.

In the predictive fuzzy control, a value of control command is limited to a discrete number u (u=c1,c2,..,cn), and x and y are assumed to be performance indices for control. Evaluations of x and y, for example "good" or "bad", are defined by fuzzy sets which are characterized by membership functions $\mu Ai(x)$, $\mu Bi(y)$. A fuzzy controller periodically evaluates the efficiency of linguistical control rules such as " If the performance index x is Ai and index y is Bi, when a control command u is decided to be Ci at this time, then this control rule is selected and the control command Ci is decided for output of the controller ". The above linguistical control rule is formulated as follows:

Ri:"If(u is Ci → x is Ai and y is Bi) then u is Ci "

The relationship between x and y of Ri's if part is defined by a membership function of $\mu Pi(Ci{:}x,y)$ which is shown as a pyramid of Fig.1.

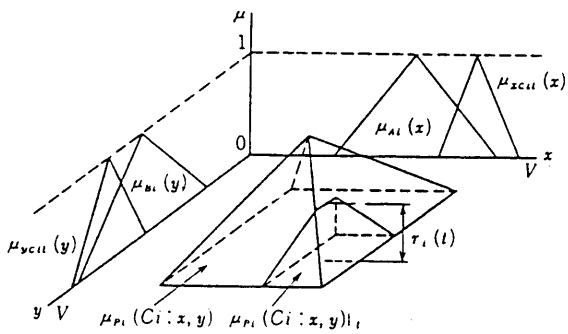


Fig.1 Evaluation of a fuzzy control rule

When u is Ci at this time t, the fuzzy sets of performance indices X(Ci,t), Y(Ci,t) are predicted by a sub-model of the system. Then, the validity of control rule based on the skilled operator's experiments is given by

$$P_i|_t = (A_i \cap X(C_i,t)) \times (B_i \cap Y(C_i,t))$$

and, its value is

$$r_i = \sup_{x,y \in U \times V} \mu_{P_i}(C_i : x,y)|_t .$$

In this way, each control rule is evaluated and the best control rule is selected.

AUTOMATIC TRAIN OPERATION CONTROL AND MODELING

ATO is a subsystem of an automatic train control system(ATC). ATC has two subsystems, namely, ATO and the automatic train protection system(ATP) as shown in Fig.2.

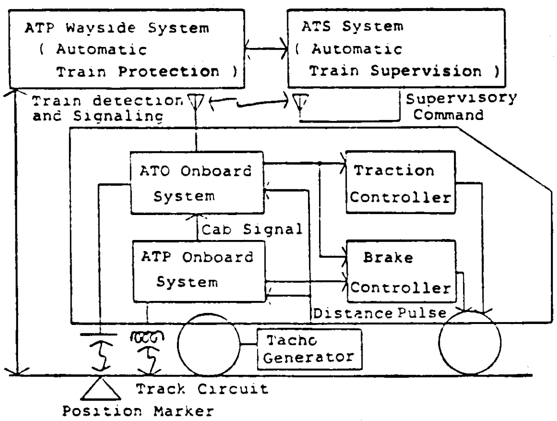


Fig.2 Typical configuration of ATO

The input data of ATO are distance pulses of a tacho-generater, cab signals of the ATP on-board system, position marker detected signals which show that the train has passed a certain position, and supervisory commands from automatic train supervision system (ATS). The output data of ATO are powering and braking commands to a traction controller and a brake controller.

A model of the ATO control system is shown in Fig.3. The ATO controller is formulated as follows.

$$\begin{bmatrix} PN(t) \\ BN(t) \end{bmatrix} = A(t, v(t), s(x,t), SPk(t), DT)$$

,where t is time, v is velocity of train, PN is power notch (acceleration), BN is a brake notch (deceleration), S is ATP signal, SPk is a point signal of k, and DT is a departure time.

The traction controller and the brake controller are controlled by PN and BN, and these generate the actual power by using those notches .

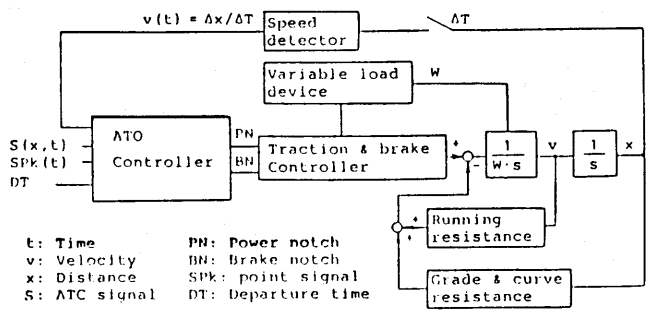


Fig.3 Block Diagram of the ATO Contrl System

Human Operator's strategies of Train Operation

The purpose of this paper is to propose the ATO system which realizes train operation similar to human's operations. As shown in Fig.4, human experts operate trains through evaluating various performance indices such as safety, riding comfort, stop accuracy and so on. The human operator's strategies are divided into two functions. One is the Constant Speed Control (CSC): it starts a train and keeps train speed below the specified one. The other is the Train Automatic Stop Control (TASC) : it regulates a train speed in order to stop the train at a target position of a station. These two functions and a choice of the total control notch are described in the below.

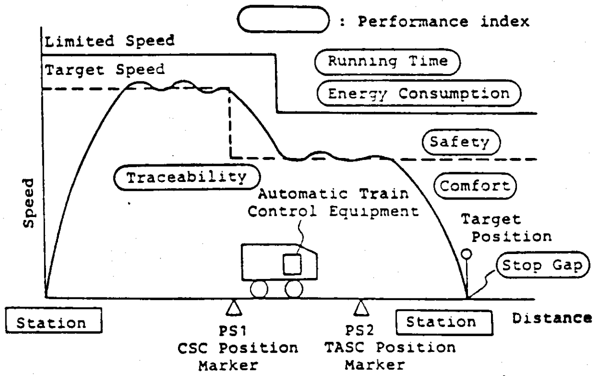


Fig.4 Outline of automatic train operation

CSC operation

With the departure command, the operator generates the target speed within the maximum speed limit. If there is a restricted speed track section in front of the train, the target speed is generated at the beginning of this section. In the CSC operation, the control commands are selected applying experimental control rules in the following way:

(C-1)For safety; if the speed of the train exceeds the speed limit, the maximum brake notch is selected
(C-2)For saving energy; if coasting can keep the scheduled running time, coasting is continued.
(C-3)For shortening running time; if the speed is far below the limited one, the power notch is selected.
(C-4)For riding comfort; if the train speed is in the predetermined allowance range, the control notch is not changed.
(C-5)For traceability; if the notch is kept constant and the train is about to go out of the allowance range, a ± n notch is selected so that the target speed way can be traced accurately. In this case, for riding comfort, notch change frequency is considered.

TASC Operation

An operator starts the TASC operation by detecting the TASC position markers which indicate the distance to the target position of the station. In this control, the control command notch is selected by the following experimental control rules.

(T-1) For riding comfort; when the train is in the TASC zone, the control notch is not changed, if the train stops in the predetermined allowance zone.
(T-2) For running time shortening and riding comfort; the train approaches to the TASC zone, the notch is changed from acceleration to a little deceleration.

(T-3) For the stop gap accuracy; when the train is in the TASC zone, and will not stop within the predetermined allowance zone, a $\pm$ notch is selected so that the train stops accurately at the target position.

Choice of The Total Control Notch

The traction or brake controller is controlled by the total control notch which is chosen from either the CSC notch or the TASC notch.

ATO by Predictive Fuzzy Control

The purpose is to realize an automatic train operation based upon the human operator's experience. Firstly, the fuzzy sets of performance indices such as safety, riding comfort, traceability, energy consumption and running time are defined. Secondly, the control rules using these fuzzy sets are described. The symbols which are used in the below are shown in Table 1.

Table 1 Symbols

t : time (sec) $x(t)$: location of train (m)
$v(t)$: velocity of train (km/h)
$N(t)$: control command notch
$X(t)$: target position of next station (m)
V_t : target speed (km/h)
T_t : predicted running time (sec)
X_d : forward location where the maximum speed limit is lower (m)
t_s : time to reach X_d point (sec)
X_k : ending location of coasting (m)
$X_z(v)$: beginning point of TASC zone (m)
$t_z = (X_z(v)-x(t))/v(t)$: time to TASC zone (sec)
t_c : elapsed time from last notch change (sec)
N_c : degree of last changed notch
N_p : control command notch to be selected
$V_p(N_p)$: predicted speed when N_p notch is selected (km/h)
V_e : velocity allowance range (km/h)
$X_p(N_p)$: predicted stop position if N_p notch is selected (m)
X_e : allowance of stop gap (m)

Fuzzy Sets of Performance Indices

To define the performance indices, the three functions denoted below are used.

$$A(x, a, b) = \begin{cases} b/(a+b-x) & : x < a \\ 1.0 & : a \leq x \end{cases} \quad (b>0)$$

$$A(x, a, b) = \begin{cases} 0.0 & : x < a+2b \\ 1.0+(a-x)/2b & : a+2b \leq x < a \\ 1.0 & : a \leq x \end{cases} \quad (b<0)$$

$$B(x, a, b) = A(2a-x, a, b)$$

$$C(x,a_1,b_1,a_2,b_2) = \min.(A(x,a_1,b_1), B(x,a_2,b_2))$$

(1) Safety performance indices (S)

The safety is evaluated by the time for the train to reach to the lower limited speed (danger) zone.

(a) Danger (SD) : μ_{SD}

$$\mu_{SD}(t_s) = B(t_s, 0.0, -T_s)$$

(b) Safe (SS) : μ_{SS}

$$\mu_{SS}(t_s) = A(t_s, -T_s, -T_s)$$

(2) Comfort performance indices (C)

Riding comfort is evaluated by the degree of the last change and the elapsed time from it.

(a) Good comfort (CG) : μ_{CG}

$$\mu_{CG}(t_c, N_c) = A(t_c, N_c, -N_c+C_b)$$

(b) Poor comfort (CB) : μ_{CB}

$$\mu_{CB}(t_c, N_c) = B(t_c, C_b, -N_c+C_b)$$

(3) Energy saving performance indices (E)

Energy saving is evaluated by running time margin.

(a) Energy saved running (ES) : μ_{ES}

$$\mu_{ES} = B(x(t), X_k, -E_x)$$

(b) Not energy saved running (EN) : μ_{EN}

$$\mu_{EN} = A(x(t), X_k+E_x, -E_x)$$

(4) Traceability performance indices (T) : (Fig.5)

The traceability is evaluated by the difference between the predicted speed and target speed.

(a) Good trace (TG) : μ_{TG}

$$\mu_{TG}(V_p(N)) = C(V_p(N), V_t-V_e, V_e, V_t(t)+V_e, Ve)$$

(b) Accurate Trace (TA) : μ_{TA}

$$\mu_{TA}(V_p(N)) = C(V_p(N), V_t, V_e, V_t, V_e)$$

(c) Low speed (TL) : μ_{TL}

$$\mu_{TL}(V_p(N)) = B(V_p(N), V_t/2, V_t/4)$$

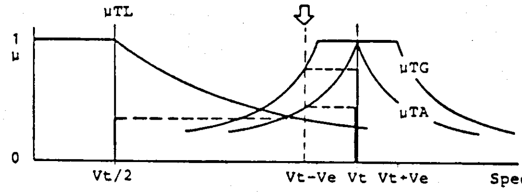


Fig.5 Membership Function of the Traceability

(5) Running time performance indices (R)

Running time performance is evaluated by a start point for TASC based on the train speed.

(a) In TASC zone (RT) : μ_{RT}

$$\mu_{RT}(t_z) = B(t_z, 0.0, -R_t)$$

(b) Not in TASC zone (RF) : μ_{RF}

$$\mu_{RF}(t_z) = A(t_z, 2Rt, -R_t)$$

(6) Stop gap performance indices (G) (Fig.6)

The accuracy of stop gap is evaluated by the difference between the predicted stop position and the target position.

(a) Good stop (GG) : μ_{GG}

$$\mu_{GG}(X_p(N)) = C(X_p(N), X_t-X_e, X_e, X_t+X_e, X_e)$$

(b) Accurate stop (GA) : μ_{GA}

$$\mu_{GA}(X_p(N)) = C(X_p(N), X_t, X_e, X_t, X_e)$$

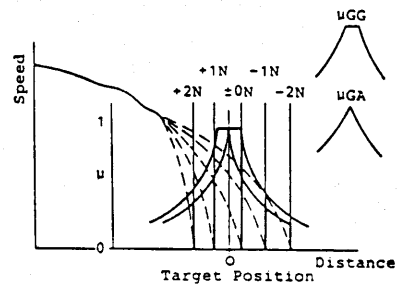


Fig.6 Membership Function of the Stop Accuracy

Predictive Fuzzy Control Rules

The fuzzy control rules have been determined in correspond to the linguistical control rules of human operator's strategies. In the rules, DN is the difference of notches, Pn is the powering notch, and Bn is the braking notch. The maximum members of Pn and Bn are assumed to be 7 and 9.

(1)CSC rules

(C-1)If (N is $(N(t)+B_{max})/2 \rightarrow$ S is SD)
Then N is $(N(t)+B_{max})/2$

(C-2)If (N is 0 → S is SS, C is CG and E is ES)
Then N is 0

(C-3)If (N is P7 → S is SS, C is CG and T is TL)
Then N is P7

(C-4)If (DN is 0 → S is SS and T is TG)
Then DN is 0

(C-5)If (DN is n → S is SS, C is CG and T is TA)
Then DN is N
(n = ±1, ±2, ±3)

(2) TASC rules

(T-1) If (DN is 0 → R is RT and G is GG)
Then DN is 0

(T-2·1) If (N is 0 → R is RF and C is CG)
Then N is 0

(T-2·2) If (N is B1 → R is RT and C is CG)
Then N is B1

(T-3) If (DN is N → R is RT, C is CG and G is GA)
Then DN is n
(n = ±1, ±2, ±3)

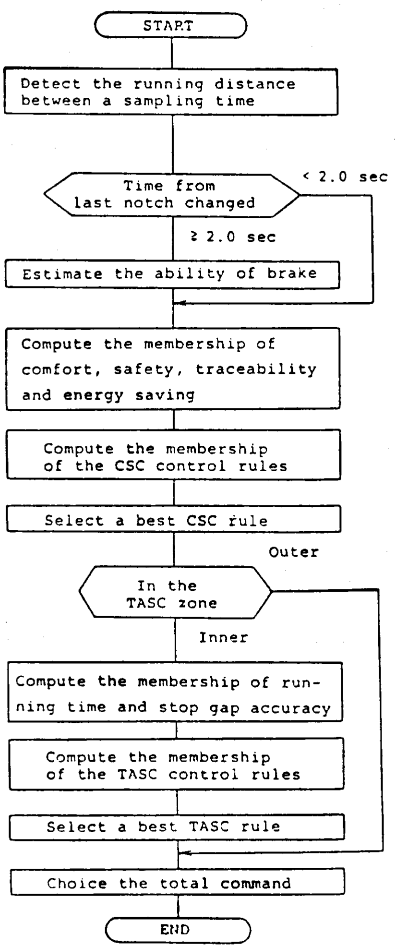


Fig.7 The flowchart of the fuzzy controled ATO algorithm

Realization of the ATO by micro-computer

The computation flow to realize the above fuzzy controlled ATO with a micro-computer is shown in Fig.7. In the ATO system, the control command is selected by evaluating all of the above-mentioned rules every 100 ms.

Simulations

By the simulation using the planning and designing support system for rapid transit systems,[11,12] the developed predictive fuzzy control ATO (Fuzzy ATO) is compared with the conventional PID control ATO (PID ATO). The parameters used in the simulation are described in Table 2. The simulation results are as follows.

Table 2 Values Used in the Simulation

Train length	:	83.5 m
Train weight	:	129.0 ton
Running resistance	:	
$1.97 + 0.016 \times v + 0.00084 \times v^2$ kg/ton		
Number of steps of traction:		7 steps
Maximum acceleration of traction:		3.3 km/h·s
Number of steps of brake:		9 steps
Maximum deceleration of brake B_m:		
nominal = 5.14 km/h·s		
minimum = 3.6 km/h·s		
maximum = 6.68 km/h·s		
Dead time of braking system:		0.2 sec
1st order time lag of braking system:		0.6 sec

(a) Riding comfort and stop gap accuracy

The Fig.8 shows a summary of simulations for a riding comfort and a stop gap accuracy. As the results of the simulation, the number of notch changes in the fuzzy ATO is about a half, and the stop gap accuracy is about a third compared with those of the PID ATO. Therefore, the developed fuzzy ATO is able to control a train with good riding comfort and stop gap accuracy.

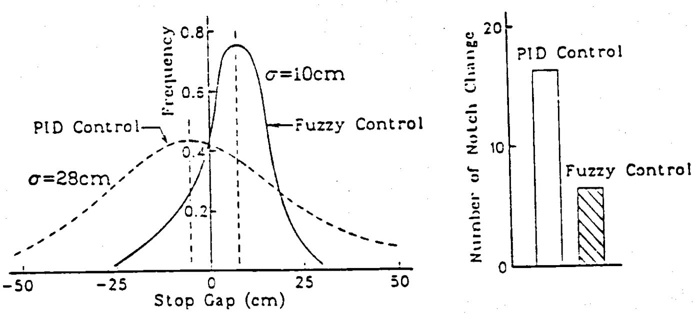
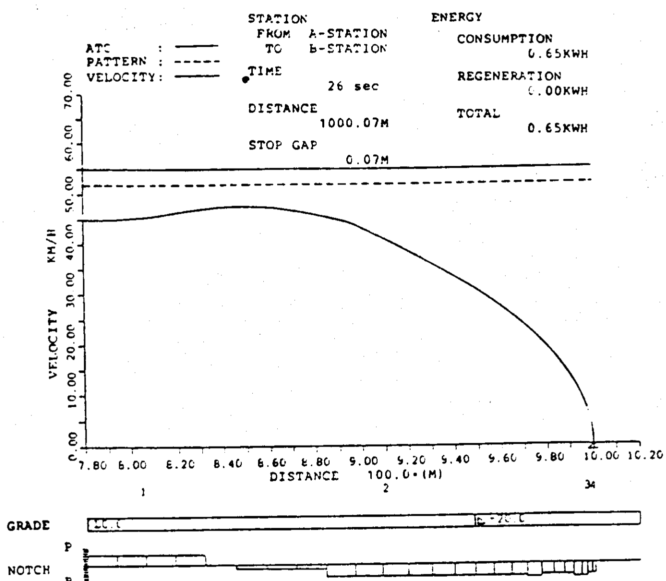
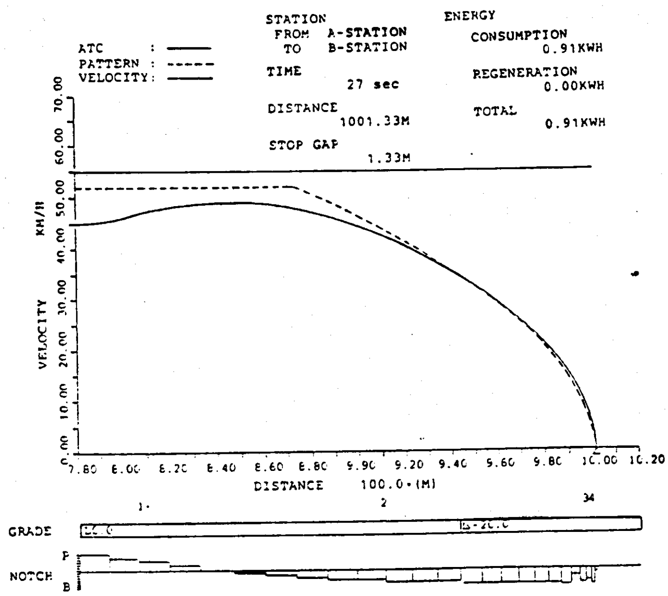


Fig.8 Summary of simulation for riding comfort and stop gap accuracy
- The deceleration to maximum brake notch is 70%, 100% and 130%
- The gradient is $-5^0/oo$, $0^0/oo$ (level) and $+5^0/oo$

In the TASC control, the affection of the environment condition, such as track grade and braking ability, is important in controllability. The simulation results, whose grade change just before the station is $0^0/_{oo}$ to $-20^0/_{oo}$, are shown in Fig.9. The results obtained are that the stop gap of the Fuzzy ATO is 0.03m and the PID ATO is 1.33m. These results show the higher robustness and control accuracy of the Fuzzy ATO.



a) A result by the fuzzy ATO



b) A result of the PID ATO

Fig.9 Simulation for Robust Control

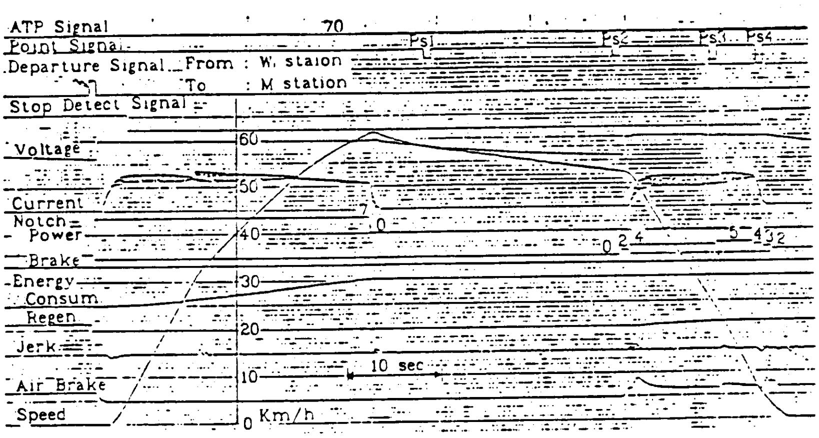


Fig.12 A result of the field experiment

(b) Energy consumption

The Fig.10 shows a summary of simulation results on running time and energy consumption. As the results of the simulation, the fuzzy ATO is able to control trains over 10% of energy saving and/or shorten a running time compared with the PID ATO.

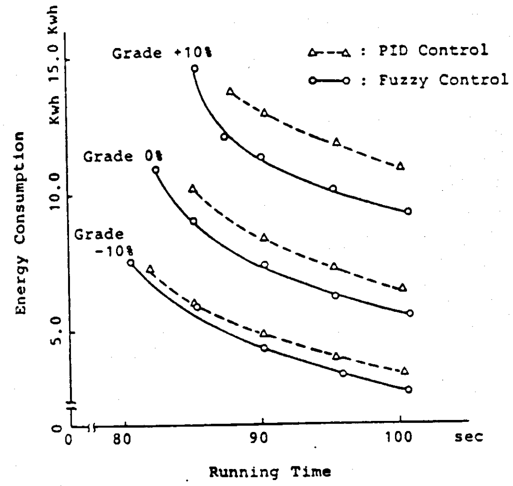


Fig.10 Summary of simulation for energy consumption
- The interval of stations is 1000m
- The gradient is -10⁰/oo,0⁰/oo (level) and +10⁰/oo

Field experiment for a Subway System

The proposed Fuzzy ATO algorithm has been built in an on-board controller, as shown in Fig. 11, and a field experiment was performed at a subway system. Fig. 12 shows a result of the field experiment.

The Fig. 13 shows a running curve of a computer simulation for the system, and the results of field experiment were almost same with these of simulations. The field experiment shows that the developed Fuzzy ATO controller can operate trains as skillfully as human experts do.

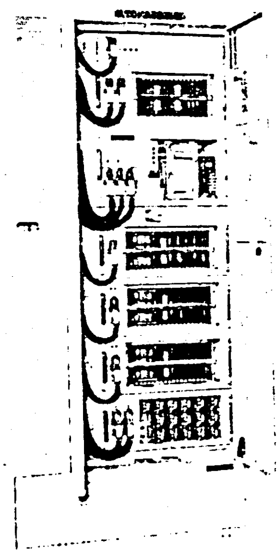


Fig.11 Developed Fuzzy ATO Controller

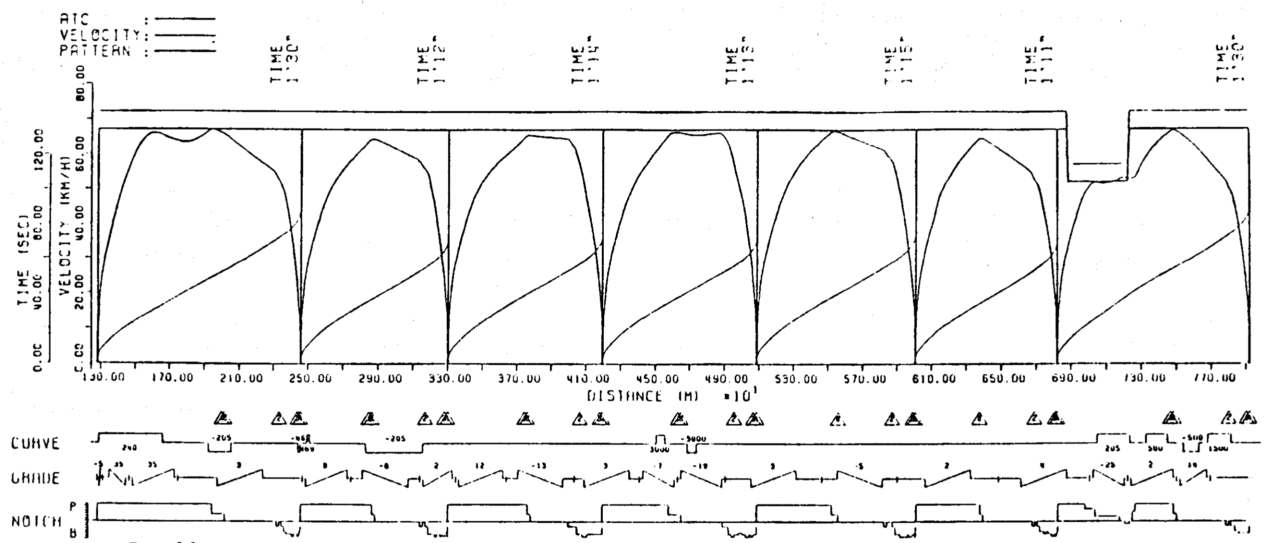


Fig.13 A running curve of the fuzzy ATO for a subway system by a computer simulation

Conclusions

The predictive fuzzy control, which selects the most likely control command based on predictions of control results and direct evaluations on the control objectives, has been proposed. This control method has been applied to ATO systems which control trains by evaluating safety, riding comfort, accuracy of stop gap, running time and energy consumption. The simulation studies have revealed that the Fuzzy ATO extremely improves conventional PID ATO concerning the above-mentioned performence indices. And, it is able to robustly operate under the changing environmental conditions and save over 10% of energy compared with conventional ATO controllers. The proposed Fuzzy ATO algorithm has been built in an on-board controller, and field experiments have shown that the developed Fuzzy ATO controller operate trains as skillfully as a human expert does. Since control quality is strongly required, the proposed predictive fuzzy control becomes more effective method to overcome the problems of conventional control systems.

Acknowledgements

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