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A Fuzzy Control for Train Automatic Stop Control†

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A predictive fuzzy control system that uses rules based on the experience of a skilled human operator is proposed and applied to achieve automatic stop operation for trains. In recent years, automatic train operation (ATO) systems using microcomputers to replace human operators have been developed for new transit systems, including subways, monorails and new public transit systems. Because the train operation is a typical uncertain nonlinear system, improvement of performance indices such as safety, riding comfort of passengers, and accuracy of the stopgap is great challenge to ATO. Up to now, ATO systems have been developed using linear control of the target pattern. However, it is difficult to control a train automatically in a manner similar to control by a human operator using linear control.

In this paper, we propose a predictive fuzzy control system that selects the most likely control rule from a set of control rules. The system is described as follows: "If (u is C → x is A and y is B) then u is C.". The proposed fuzzy control system is applied to a train automatic stop control system that takes into account passenger comfort, accuracy of a stopgap and running time. Simulation results of this newly developed fuzzy control system indicate that the system can directly adjust system performance as desired in a manner similar to control by a skilled operator and thereby stop the train comfortably and accurately.

Key Words: fuzzy set theory, fuzzy control, transportation system, PID control, automatic train operation, predictive control

1. Introduction

In recent years, automatic controllers using microcomputers have been developed to replace human operators in wide area of applications. The automatic train operation (ATO) system discussed in this paper is a typical example. Using this system, a train can start, run at limited speed, and stop at a target position in the next station. Recently, ATO systems have been applied to subways, monorails and new traffic systems [1),2)].

From a control viewpoint, the ATO system has the following features.

(1) The resolution of input data (speed information) is low.

(2) The characteristics of controlled devices, such as brakes, are time variant.

(3) The route conditions, such as gradients, are a function of location. This means that the applied power must change depending on the position of the train.

(4) The evaluation index of the control system is multi-dimensional and includes the riding comfort of passengers and accurate stops.

Thus, the ATO system is a nonlinear system.

To summarize the above features, automatic train operation has the characteristics of rough input data and time-variant disturbance. It is a nonlinear control system. In the past, PID (proportional-integral-derivative) control method was employed in a practical system. The PID method relies on a target speed pattern. This method applies control to follow a pattern based on an average train model, and to generate a running pattern (the target speed) [3)∼5)]. Application of optimal control theory, such as this pattern-following method, has been proposed and computer simulations have been carried out [6),7)]. Also proposed is a method using an open-loop controller, which outputs the best control instruction to stop the train according to a certain distance, time and speed [8)]. Another proposed method outputs the control instruction according to the target speed of the train, based on a constant pattern and a current speed [9)].

However, these conventional methods do not take into account riding comfort and stop accuracy, both of which are important factors to be considered when determining the evaluation index used for control train movement. In

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conventional control systems, the evaluation index is minimizing the power of the error between train speed and the target speed. The control parameters of the pattern only indirectly address the issue of riding comfort. The stop accuracy is measured experimentally and the distribution is measured using computer simulation and an actual vehicle.

On the other hand, when a skilled operator drives a train carefully, he can control the train so that it stops accurately and comfortably because the change in the brake notch (that is, the control instruction) is smoother than that with an automatic drive. Therefore, if the control method of the human operator can be converted into an algorithm, a control method that satisfies the overall evaluation index of the train operation can be achieved.

In this paper, we propose a predictive fuzzy control method. In this method, the operator's control knowledge is converted into a computer algorithm. By using fuzzy logic control, the control rule that represents the prediction of the future state gained from the experience of operator is evaluated and the best control instruction is selected. The result of this application to a train automatic stop control (TASC), which requires complex control for train operation, is described.

In addition, conventional PID control and the proposed method are compared in a simulation, and the effectiveness of the proposed predictive fuzzy control method is discussed.

2. Train Automatic Stop Control and Human Operator Strategies

2.1 Train automatic stop control

The function of a fuzzy control system is to stop the train at a target position in the next station. This system controls the brake by using the distance pulse from the tacho-generator (TG) and point signal, which indicates that the train has passed a specific point (**Fig. 1**).

The input to the control system is brake notch instruction related to the discrete deceleration. This input is currently used in many train control systems. In this type of system, the braking equipment corrects the deceleration power of an actual vehicle to the brake notch instruction based on the weight of the train, measured by a load device. However, the nominal value reflects an error of about ±30% in actual deceleration of the brake. This error is caused by the change in the friction coefficient of the brake pads, the air pressure in the airbrake, the weight of the train, and so forth. An error of 0.32km/h/s is caused by a 1% gradient condition (a rise of 1m for every 100m),

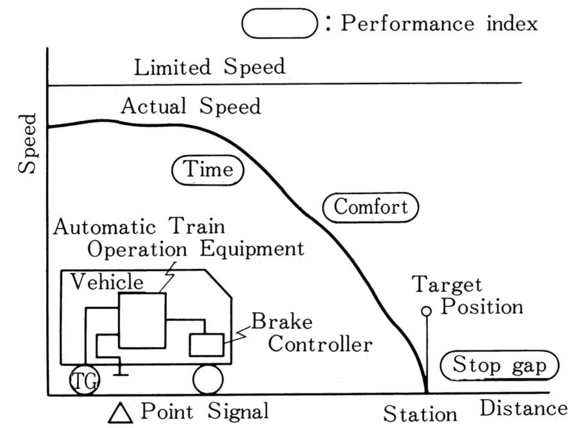


Fig. 1 Train automatic control

relative to the position of the train. The detection of the speed is obtained from the distance pulse generated by the rotation of the wheel. It is a popular assumption that the resolution of the distance pulse is about 1cm. Therefore, if the sampling time is assumed to be 100 msec, the detection accuracy of the speed is 0.36 km/h, which shows rather poor resolution. Under such circumstances, it is difficult to control the object to be stopped at the target station. Because the input and output data are rough, and the system parameter varies depend on the gradient conditions along the route.

2.2 The operator's driving strategy

Train operators are able to describe their control method verbally. The method presented in this paper is based on the experience that we have applied for the automatic train operation system up to now [10)~12)].

The control method using this experience can be described as follows. When the train passes the point signal that shows the start point of the fixed positional stop control (here it is called B-point), the operator begins to apply the brake to achieve a fixed positional stop at the next station. Furthermore, when the brake notch is pulled and the notch is held steady, the train presumably decelerates as a function of the brake notch.

(1) To improve the riding comfort; The notch is maintained while the train is moving at constant speed, and pulled in when passing the B-point according to the current instruction.

(2) To shorten running time and to improve riding comfort; When the train passed the B-point, the brake notch is pulled in further.

(3) To improve the stop accuracy; After passed B-point, that notch which can accomplish an accurate stop

in $\pm n$ notch is selected if present notch is not possible to stop well.

As mentioned above, the operator is applying the train stop control while thinking about the predicted value of (1) the passenger's riding comfort, (2) the running time, and (3) the stop accuracy.

3. Proposal of Predictive Fuzzy Control

Prof. Zadeh proposed fuzzy set theory and fuzzy logic as a method of quantifying human qualitative evaluation indices. Fuzzy control is the result of applying this theory to decision-making [13]. Experimental work was carried out by Mamdani [14]. It is applied to control plants [14], traffic intersections [15] and other complex situation [17].

The method of the fuzzy controls done so far [14), 15), 18)] comes from the input sets $\boldsymbol{R}$=(R_1 ,..., R_i ,..., R_n) of control rule R_i like "If x is A_i and y is B_i, then u is U_i" and "x is A and y is B". The control instruction u is inferred by fuzzy inference (fuzzy reasoning). The fuzzy control of this form is an effective method that accounts for the experience of the human controller to the multi-dimensional state feedback control, by which control instruction u is decided according to sets $\boldsymbol{R}$ of the control rules decided beforehand, based on the multi-dimensional evaluation index. However, it is assumed that the control instruction in the form of human control had been given. The achievement of the control, where the best control instruction for the control purpose was decided while evaluating the control result, was key point in this method.

In order to predict the stop accuracy of the train and to achieve the best control, we propose a predictive fuzzy control. The method has the sets $\boldsymbol{R}$=(R_1 ,..., R_i ,..., R_n) of fuzzy rule R_i: "If(u is $C_i \to x$ is A_i and y is B_i) then u is C_i.". The prediction of each evaluation value (x, y) is based on the following: control instruction C_i includes control rule R_i. The control rule R_i is evaluated. As a result, control instruction C_i of control rule R_i with the maximum evaluation value is selected.

The proposed predictive fuzzy control, as well as the fuzzy control described by Mamdani, has the following features.

(1) The control results are systematically produced, according to the definition of the evaluation index and additional correction of the control rules.

At the same time, the evaluation value is predicted by each control rule while the feature and the control instruction are selected.

(2) The predictive control is based on partial knowledge of the system, which is related to each evaluation function.

3.1 Fuzzy set and fuzzy relation

The fuzzy set used in the predictive fuzzy control proposed here, according to Zadeh [13], is defined as follows. A is a fuzzy subset of universe of discourse U. μ_A: U $\to$ [0,1] is a membership function of A. At this time, the following form defines fuzzy subset A.

$$A = \int_U \mu_A(x)/x \quad (1)$$

In equation (1), x is an element of U, and $\mu_A(x)$ is a membership value of the element x. Moreover, the fuzzy relation, which is the product of the two fuzzy sets A and B, shown by "x is A and y is B", is defined by the next form,

$$A \times B = \int_{U \times V} \mu_A(x) \wedge \mu_B(x)/(x, y). \quad (2)$$

We propose a predictive fuzzy control using the fuzzy sets defined as above.

3.2 Formulation of predictive fuzzy control rules

3.2.1 Fuzzy evaluation of control objective

The sets of values where control instruction u can be taken are assumed to be $\boldsymbol{C}$ $\{u : c_1, \ldots, c_l\}$ and the indices that evaluate the control are assumed to be x and y. Membership functions $\mu_{A_i}(x)$ and $\mu_{B_i}(y)$ evaluate the evaluation indices x and y. "Good" and "Bad" are defined by fuzzy set A_i and B_i. The universe of discourse for evaluation indices x and y are U and V, respectively. These can be shown as follows.

$$A_i = \int_U \mu_{A_i}(x)/x \quad (3)$$

$$B_i = \int_V \mu_{B_i}(y)/y \quad (4)$$

3.2.2 Formulation of control rule

We evaluate the predictive fuzzy control proposed here in every sampling time using control rule R: "At this point, if evaluation index y is B_i (Very good), evaluation index x is A_i(Good). When the control instruction u is assumed to be C_i and this control rule is selected, C_i is the output of the control instruction.". For computer processing, it is stated as follows.

$$R_i : \text{"If } (u \text{ is } C_i \to x \text{ is } A_i \text{ and } y \text{ is } B_i) \text{ then } u \text{ is } C_i\text{"} \quad (5)$$

The premise part (the If part) where this control rule R_i is evaluated is assumed to be P_i with the membership function of fuzzy set $\mu_{P_i}(C_i : x, y)$. In the center of **Fig. 2**, the fuzzy set is shown as pyramidal.

$$P_i = \int_{V\times U} \mu_{P_i}(C_i : x, y)/(x, y) \quad (6)$$

$$= A_i \times B_i : u = C_i \quad (7)$$

In the actual control, some control rules are based on partial knowledge of the system and the control objective. After that, the entire control rules $\boldsymbol{R}$ { $R_1,\ldots,R_i,\ldots,R_n$ } are defined.

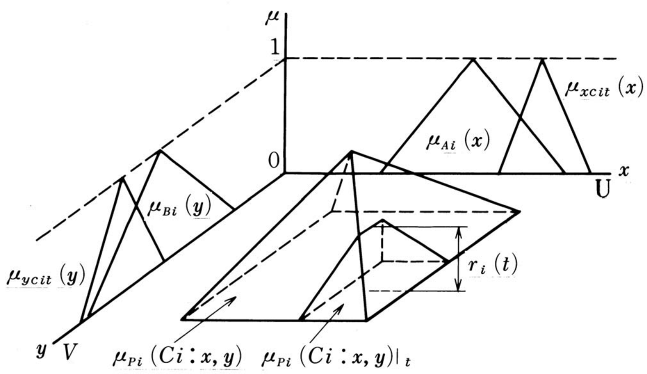


Fig. 2 Evaluation of a fuzzy control rule

3.3 Method for deciding control instruction

3.3.1 Evaluation of individual control

The evaluation indices x and y in control rule R_i shown in equation (5) when a certain control instruction "u is C_i." is executed, are predicted based on partial knowledge of the object system. These predicted results are defined by the following fuzzy set $X(C_i,\, t)$ and $Y(C_i,\, t)$ defined by the membership function $\mu_{xCit}(x)$ and $\mu_{yCit}(y)$.

$$X(C_i, t) = \int_U \mu_{xCit}(x)/x \quad (8)$$

$$Y(C_i, t) = \int_V \mu_{yCit}(y)/y \quad (9)$$

At this time, $P_i|_t$ shows fuzzy sets of the assumption parts according to the control at time t.

$$P_i|_t = (A_i \cap X(C_i, t)) \times (B_i \cap Y(C_i, t)) \quad (10)$$

This becomes part of the pyramid of assumption part P_i of control rule R_i, as shown in **Fig.** 2. Maximum value $Y_i(t)$ of control rule assumption part $P_i|_t$ at this time t is calculated from

$$Y_i(t) = \sup_{x,y\in V\times U} \mu_{P_i}(C_i : x, y)|_t. \quad (11)$$

This is a value that corresponds to the height of the pyramid of fuzzy sets in the control rule assumption part $P_i|_t$, as shown in **Fig.** 2. It becomes the value, which seems more certain in the control rule R_i at the time t.

3.3.2 Selection of the best control instruction

Evaluation value $r(t)$ of the whole control rule $\boldsymbol{R}$ from evaluation value $r_i(t)$ of each control rule R_i at time t is decided by,

$$r(t) = \max_i r_i(t) = r_j(t). \quad (12)$$

Therefore, control rule R_j, which has the evaluation value $r(t)$ in control rules $\boldsymbol{R}$, is chosen. This seems to be the most certain. The control instruction $u(t)$ is assumed to be C_j from "u is C_j" and it is assumed to be the most certain control rule R_j in the predictive fuzzy control proposed here.

4. Train Automatic Stop Control

Fuzzy sets are defined for riding comfort and stop accuracy. First, an evaluation index is defined for the running condition. And then fuzzy control rules are obtained from the operator's experience rules on the train fixed position stop control described in Chapter 2. It is achieved for fuzzy control, as described in Chapter 3.

4.1 Fuzzy sets of evaluation indices

The symbols used in the evaluation function are defined as follows.

t: Time (sec), $x(t)$: Train position (m),
$v(t)$: Speed of train (m/s), $N(t)$: Brake notch,
X_t: Stop target position (m),
$X_z(v)$: Position of B-point corresponding to Speed of train $v(t)$ (m),
$t_z = (X_z(v) - x(t))/v(t)$: Time to B-point (sec),
t_c: Elapsed time after notch changes(sec),
N_c: Number of notch change steps immediately before,
N_p: Brake notch to be selected,
$x_p(N_p)$: Forecast stop position when brake notch N_p is output (m), and,
X_e: Permitted stop error (m).

Next, the evaluation functions are defined and given as follows.
$\boldsymbol{L}$: Triangular function defined by region $(a-b, a+b)$,
$\boldsymbol{F}$: Larger part than value a in function $\boldsymbol{L}$ is 1.0,
$\boldsymbol{A}$: Pyramidal function defined by region $(-\infty, +\infty)$,
and, $\boldsymbol{G}$: Trapezoid function defined by region $(-\infty, +\infty)$.

$$\boldsymbol{L}(x, a, b) = \begin{cases} 0 & : x \le a-b, a+b \le x \\ 1 - |x-a|/b & : a-b < x < a+b \end{cases}$$

$$\boldsymbol{F}(x, a, b) = \begin{cases} 0 & : x \le a-b \\ 1 - |x-a|/b & : a-b < x < a \\ 1 & : a \le x \end{cases}$$

$$\boldsymbol{A}(x,a,b) = b/(|x-a|+b)$$

$$\boldsymbol{G}(x,a,b) = \begin{cases} 1 & : a-b \leq x \leq a+b \\ b/|x-a| & : x < a-b, a+b < x \end{cases}$$

It is assumed that $b > 0$.

(1) Definition of evaluation index of riding comfort **C** (**Fig. 3**)

Changing the notch frequently is assumed to be associated with bad riding comfort. Riding comfort is evaluated at N_c steps, which changes the notch immediately before and after the notch maintained at time t_c.

(a) Riding comfort is good (CG)

$$\mu_{CG}(t_c, N_c) = \boldsymbol{F}(t_c, 1+N_c/2, N_c/2)$$

(b) Riding comfort is bad (CB)

$$\mu_{CB}(t_c, N_c) = 1 - \mu_{CG}(t_c, N_c)$$

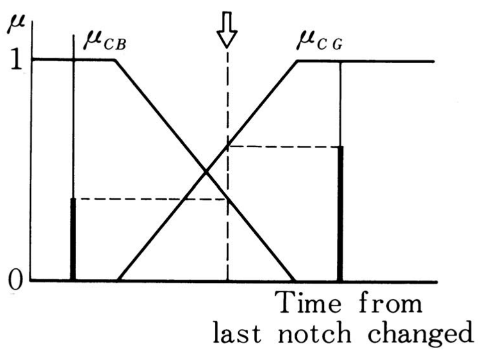


Fig. 3 Membership functions of the comfort

(2) Definition of evaluation index of stopgap accuracy **G** (**Fig. 4**)

The stop accuracy is evaluated by predicting stop position $X_p(N_p)$ relative to the stop target X_t.

(a) Good Stop(GG)

$$\mu_{GG}(x_p(N_p)) = \boldsymbol{G}(x_p(N_p), X_t, X_e)$$

(b) Accurate Stop (GA)

$$\mu_{GA}(x_p(N_p)) = \boldsymbol{A}(x_p(N_p), X_t, X_e)$$

(3) Definition of running time evaluation index **R** (**Fig. 5**)

The departure station is defined as a free zone and the stop target is used from B-point for the evaluation. The running time becomes long when fixed positional stop control begins from the brake start point (B-point).

(a) It is in fixed positional stop control zone (RT)

$$\mu_{RT}(t_z) = \boldsymbol{F}(t_z, 0, 2)$$

(b) It is in a free zone (RF)

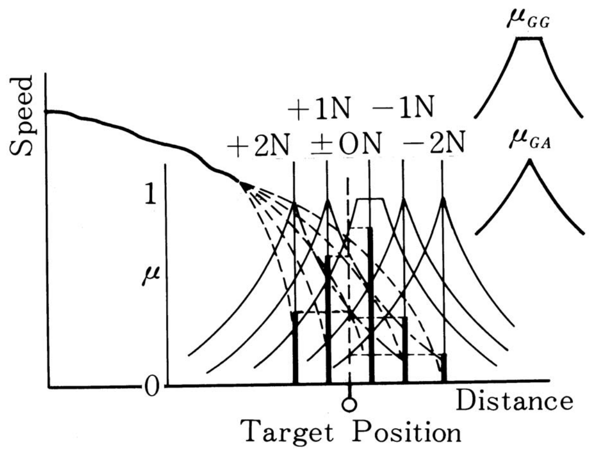


Fig. 4 Membership functions of the stop accuracy

$$\mu_{RF}(t_z) = 1 - \mu_{RT}(t_z)$$

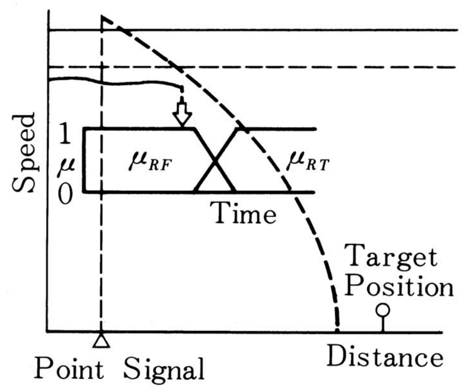


Fig. 5 Membership function of the running time

4.2 Decision of fuzzy control rule

The experience rule for train stop control, qualitatively described in Chapter 2, has been formulated in terms of fuzzy sets, evaluation indices and the fuzzy control rule, as above mentioned. DN shows the change into the value of a present brake notch.

When the experience-based rule used for improving riding comfort, described in Section 2.2, is rewritten, the control instruction of predictive fuzzy control can be described as follows: "When the train passes by B-point, and the brake notch is being maintained, and it is possible to stop well, then maintain the brake notch". Each part of this control rule becomes,

"The brake notch is maintained"	:DN is 0,
"The train passes by B-point"	:R is RT,
and	
"It is possible to stop well"	:G is GG.

So, the linguistic rule is converted to

(1) If(DN is 0 → R is RT and G is GG) then DN is 0.

It becomes fuzzy control rule ***R***. In the same way, another rules are obtained from the experience rules in Chapter 2.

(2-1) If(N is 0 → R is RF and C is CG) then N is 0.

(2-2) If(N is 1 → R is RT and C is CG) then N is 1.

(3) If (DN is n → R is RT and C is CG and G is GA) then DN is n. (n=±1, ±2, ±3)

Following this, it is possible to construct a rule for predictive fuzzy control to control a train automatic stop.

4.3 Presumption of brake performance

In the train system, it is assumed that the control system is changed to a nominal value of ±30% for actual deceleration of the brake to the brake notch. Also, there is the disturbance caused by the inclination of the train on the gradient along the route. Therefore, to achieve accurate control, it is necessary to presume what an actual deceleration of the brake notch is.

The driver's control strategy is used for this purpose. When the brake notch keep on no change more than a fixed time (for example, two seconds), according to the traveled distance in each sampling interval, the actual deceleration can be obtained. With this way, the actual deceleration of each brake notch can be presumed.

4.4 Achievement of fuzzy control

By using the above-mentioned method, the program that can be used to control an actual train (brake notch), and decided each sampling time for a microcomputer equipped in the train has been developed. The flowchart is shown in **Fig. 6**. Control is achieved by starting this program and sampling in 100 msec intervals.

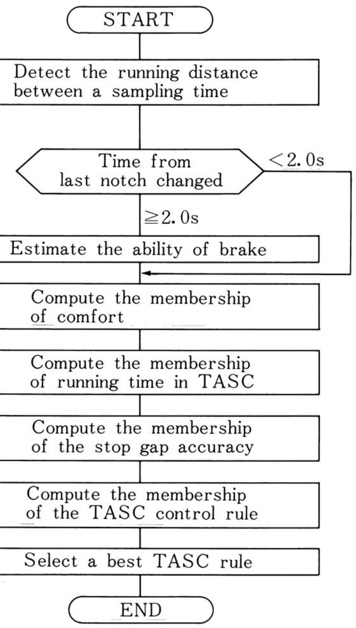


Fig. 6 The flowchart of the fuzzy controlled TASC algorithm

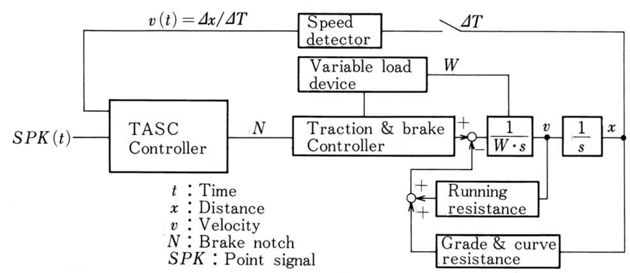


Fig. 7 Block diagram of the TASC control system

5. Evaluation by Simulation

Computer simulations were carried out, using the model shown in **Fig. 7**, to compare and evaluate the new developed fuzzy control method and PID control that is already in use in practical application. A standard subway vehicle, with the parameters shown in **Table 1**, was used for the simulation.

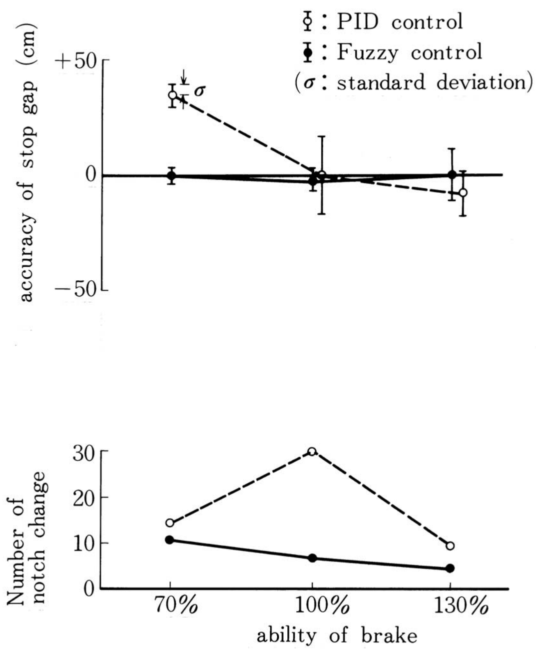
Table 1 Values assumed in the simulation

Train length	:	83.5	m
Train weight	:	129.0	ton
Running resistance	:		
$1.97{+}0.016{*}V{+}0.00084{*}V^2$	kg/ton		
Number of steps of brake notch	:	9	steps
Maximum deceleration of brake Bm	:		
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

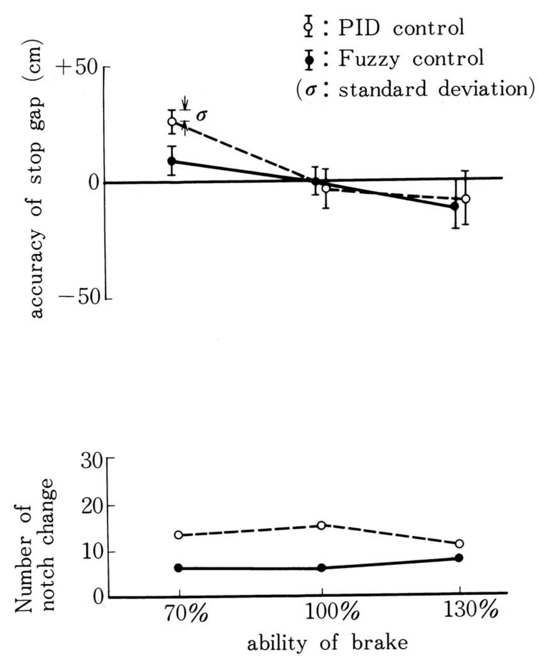
5.1 Simulation and result

Any deviation from the nominal value of an actual deceleration to the brake notch highly influences the control accuracy in fixed positional stop control, as previously described. Simulation about brake performance was also performed on the following route conditions with inclination -0.5% , 0.0% , and +0.5% . In addition, the simulation also included a 30% disturbance of 6.68 km/h/s and 3.6 km/h/s for the nominal value (5.14 km/h/s). The simulation results of frequency change of the mean stop value, standard deviation and the notch are shown in **Fig. 8** (a,b,c).

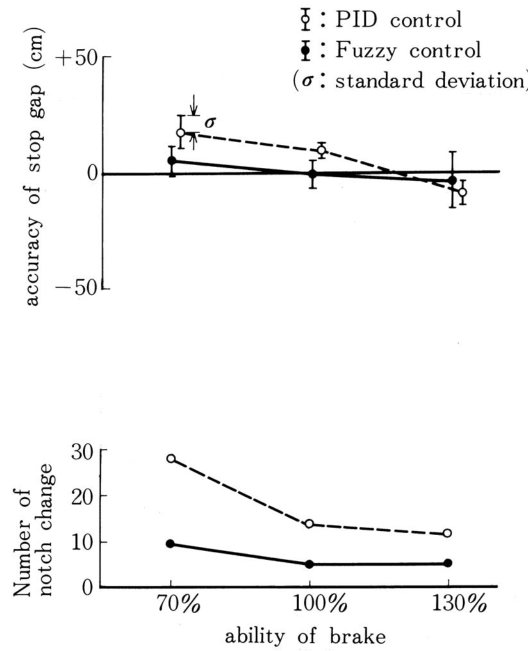
Moreover, the running condition of the train under fuzzy control and PID control, and the condition of the notch change are shown in **Fig. 9** and **Fig. 10**.



(a)Gradient condition is -0.5%



(b)Gradient condition is 0%(Level)



(c)Gradient condition is 0.5%

Fig. 8 Summary of TASC simulation

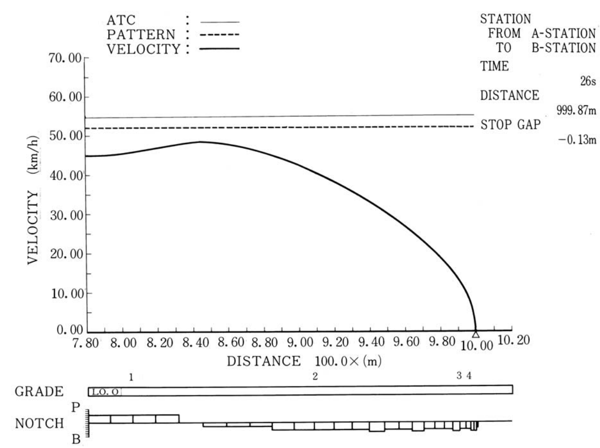


Fig. 9 A result of TASC by the fuzzy control

5.2 Discussion of simulation result

The comparison of the simulation results for fuzzy control and PID control can be seen in Fig. 8.

(1) The change of the mean value of the stop accuracy is small compared to the change of the brake performance and the change of the inclination condition. All fixed positional stop control are done accurately.

(2) The frequency of changes for the notch is reduced by half and shows good control with respect to riding comfort. The control is nearly like that by a human operator.

Thus, the proposed predictive fuzzy control method offers good stop accuracy and notch change frequency for practical applications, compared to PID control, for the following reasons. With constant deceleration, PID algorithm controls the train to follow a target speed pattern with outside power. But the speed pattern and train characteristics are time varying. So the stop accuracy deteriorates and the frequency of the brake notch increases. On the other hand, the proposed method is capable of evaluating the stop accuracy directly. The controller improved riding comfort without changing the notch and the train

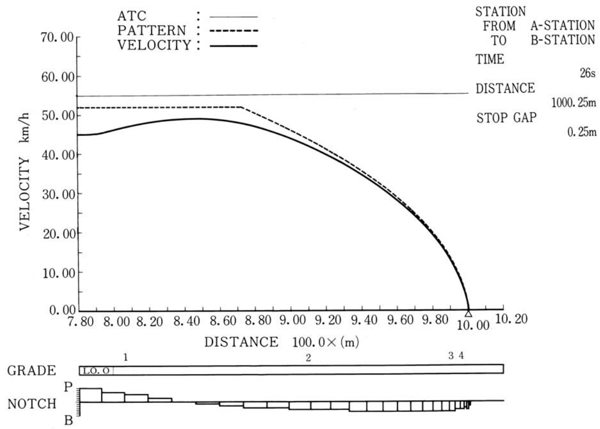


Fig. 10 A result of TASC by the PID control

achieved a stop accuracy of ±10cm. Used in following fixed target speed pattern, even with disturbance, PID control is better than the proposed method. But, this is not an important evaluation index for driving the train.

6. Conclusion

In this paper, we proposed the predictive fuzzy control method that uses a human control strategy based on experience in system operation. And the skilled operator's experience rule was converted into an algorithm. Multi-dimensional fuzzy evaluation indices are used in this control system and applied to the train automatic stop control system. The train was stopped while evaluating (1) riding comfort, (2) stop accuracy, and (3) running time, based on the driver's experiential rule.

In the simulation, although the parameters in train fixed position control system are changing with time, and state and disturbances are random, an accurate fixed position stop control had been archived with the predictive fuzzy control method based on human strategy. The algorithm had satisfied the multi-dimensional evaluation index including the vague human assessment of riding comfort. On the contrary, PID control could not reach that level.

Finally, we wish to express our gratitude to our co-workers, including Dr. Takeo Miura, Director of Hitachi Ltd. computer division, and Dr. Atsushi Kawasaki, Head of the Systems Development Laboratory.

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