Capturing and Modeling of Driving Skills Under a Three Dimensional Virtual Reality System Based on Hybrid System

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Abstract: This paper has develops a new framework to understand the human's driving maneuver based on the expression as HDS focusing on the driver's stopping maneuver. The driving data has been collected by using the three-dimensional driving simulator based on CAVE, which provides three-dimensional visual information. In our modeling, the relationship between the measured information such as distance to the stop line, its first and second derivatives and the braking amount has been expressed by the PWPS model, which is a class of HDS. The key idea to solve the identification problem was to formulate the problem as the MILP with replacing the switching conditions by binary variables. From the obtained results, it is found that the driver appropriately switches the 'control law' according to the following scenario: At the beginning of the stopping behavior (just after finding the stopping point), the driver decelerate the vehicle based on the acceleration information, and then switch to the control law based on the distance to the stop line.

Keywords: CAVE, Virtual Reality, Three-dimensional Visual Information, PWPS, MILP, Driving Skill

1. INTRODUCTION

Recently, a great deal of attention has focused on the modeling of driving skill by many researchers with Driving Simulator[1][2][3]. Numerous approaches in various driving situations have been taken to realize driving skill. Especial1y, in [2], the modeling of human driving skill for the driving task was conducted by a three-dimensional driving simulator (DS) that uses CAVE, which the projected image varies according to the viewpoint and motions of the driving examinee.

In modeling of driving skill, several techniques such as nonlinear and linear regression model, neural network–fuzzy system, GMDH (Group Method of Data Handling) and HDS (Hybrid Dynamical System) has been proposed.

One of these techniques adopts the viewpoint of HDS to propose a model of driver's stopping maneuver, which stop in front of a stop line at intersection.

HDS (Hybrid Dynamical Systems) are systems with both continuous and discrete dynamics, the former typically associated with differential equations, the latter with logic devices. Most literature of hybrid systems has deal with modeling, stability analysis, control, verification, and fault detection. The different tools rely on a model of the hybrid system. Getting such a model from data is an identification problem, which does not seem to have received enough attention in the hybrid systems community [4][5][6]. On the other hand, in other fields there has been extensive research on identification of general nonlinear black-box models [6]. A few of these techniques lead to piece-wise polynomial (PWP) model, and thanks to the equivalence between PWPS (Piece-Wise Polynomial System), which includes continuous dynamics and logical (discrete) switching, and several classes of hybrid systems, they can be used to obtain hybrid models.

In this paper, we adopt PWPS to formulate Human's driving maneuver because (1) three sub-maneuvers Appearing in driver's stopping maneuver can be transformed to the form of PWPS by introducing logic variables and (2) PWPS can be easily combined with various mathematical programming techniques (in many cases, it can be formulated by Mixed Integer Linear Programming (MILP), and (3) the optimal solution with both continuous and logical variables under objective function can be found by solving the identification problem.

This paper, first, tries to formulate modeling of the human's driving maneuver based on PWPS theory. Secondly, it is shown that the PWPS based on the problem of identification of hybrid dynamical systems can be regarded as one of the hybrid systems, which consists of systems with both continuous and logical variables, since the interactive dynamics between the physical meaning of the driving skill and the decision-making in the driving behavior varies according to the sensory information and braking amount.

This paper is organized as follows.

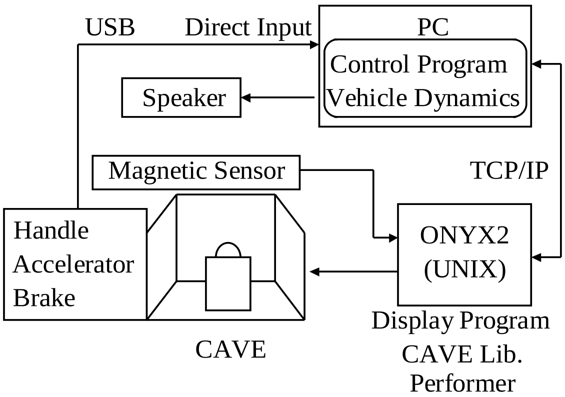
In Section Ⅱ, configuration of the developed DS based on CAVE is introduced. In Section Ⅲ, the scenario of our examination is described. In Section Ⅳ, based on the setup described in Section Ⅲ, driver's stopping maneuver to model Human's driving behavior is analyzed. In Section Ⅴ, the problem of identification for the modeling of driver's driving behavior based on PWPS can be found by solving Mixed Integer Linear Programming(MILP).

2. CONFIGURATION OF DRIVING SIMULATOR

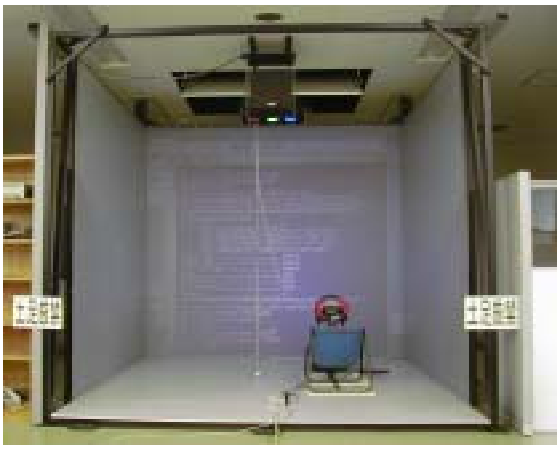
T The configuration and appearance of our DS based on the CAVE are shown in Figs. 1(a) and (b).

The display unit in the CAVE system provides the 3D virtual environment, and it is controlled by ONYX2. The display program was developed by making use of the CAVE library and the Performer. The cockpit is built by installing a handle, an accelerator and a brake in the CAVE system. The information on the driver's output to the handle, accelerator and brake is transferred to the PC through the USB terminal, and the vehicle position and motion are calculated based on these inputs and vehicle dynamics implemented on the PC using the CarSim software.

The results of the calculation are transferred to ONYX2 through the Internet (TCP/IP), and the 3D visual image based on the position and motion of the vehicle is displayed.



(a)



(b)

Fig. 1. The developed driving simulator. (a) Configuration of the DS. (b) CAVE system.

3. CAPTURING DRIVING BEHAVIOR

3.1 Road environment and investigated task

Generally speaking, most traffic accidents occur at intersections [7][8]. In this paper, we focus on a stopping maneuver in front of the stop line because this maneuver strongly depends on the distance to the stop line, and our DS has clear advantage over other 2D virtual environment based DS [2].

In order to model the stopping maneuver, the following sensory information is captured as the inputs:

① Distance from the vehicle to the stop line [$x_{1,k}$]

② First time derivative of ① (velocity) [$x_{2,k}$]

③ Second time derivative of ① (acceleration)[$x_{3,k}$]

The outputs of the driver are also specified as follows:

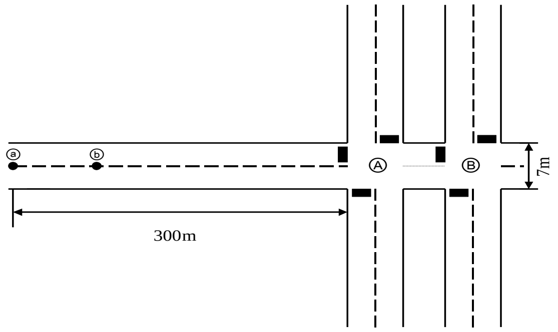
① Acceleration [$y_{1,k}$]

② Braking [$y_{2,k}$]

Note that no steering operation is necessary in the stopping maneuver.

Since it is reported that the velocity $x_{2,k}$ does not play an important role in the stopping maneuver [2] [9] [10], ① and ③of the sensory information and ②of the output of the driver are used for the modeling.

The configuration of the intersection and its projected image are shown in Figs. 2(a) and (b) with some geometric parameters.



(a)

(b)

Fig. 2. Approaching an intersection. (a) Model of intersection. (b) Sample of projected image.

The road is 7m wide and the pedestrian way is 2m wide. There are two intersections in this environment (Ⓐand Ⓑ). The driver is supposed to stop in front of the stop line at the intersectionⒶ. The vehicle is supposed to start moving at position ⓐ or ⓑ.

3.2 Driving conditions

The vehicle used in the simulator is a large-size passenger car whose engine displacement is 3000cc. Eight male drivers, ranging in age from 22 to 25 years, are selected as examinees. The maximum velocity is set to be 50km/h, and the selected starting point is 0m or 100m as shown in Figure 2(a).

Each driver takes a number of preliminary trials to get used to the DS, and then begins the test, which is made up of numerous trials. The number of trials for each driver is listed in Table 1.

Table 1 Experimental Conditions.

Notation	Driving conditions (Maximum steady running velocity [km/h], start point[m])	
	50km/h 0m	50km/h 100m
Preliminary drive	Ten times	Ten times
Test drive	Three times	Three times

3.3 Experimental procedures

Both preliminary trials and test trials are carried out twenty times and six times, respectively. These trials consist of two different driving situations.

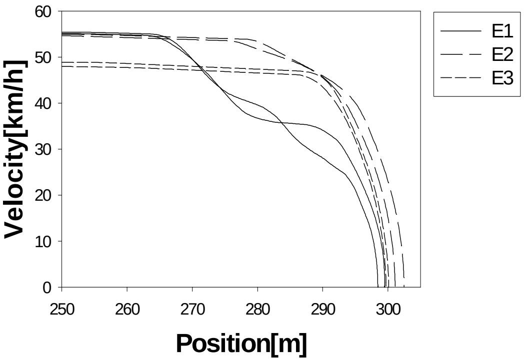
1. Velocity restriction of 50km/h, starting point of 0m.
2. Velocity restriction of 50km/h, starting point of 100m.

The experiments are executed in the sequence shown in Table I. After the preliminary trials, the driver rests for 10 minutes, and answers a questionnaire in which he record his impressions of his driving behavior, driving preferences, SSSQ [11], and so on. The SSSQ schedule is a way to find a driver who is likely to suffer from simulator sickness. If the driver wants to quit the experiment due to the simulator sickness, the experiment is suspended. Each driver takes about 30 minutes to complete all of the trials.

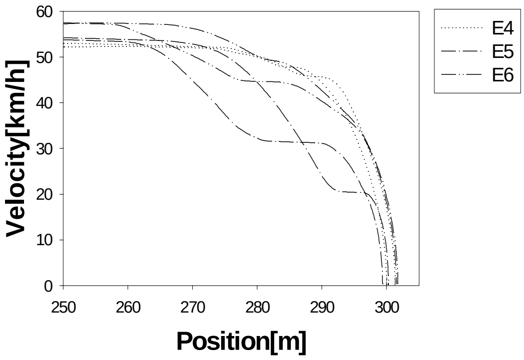
4. EXPERIMENTAL RESULTS AND PROPOSED MODELING FRAMEWORK

Based on the setup described in section 3, eight drivers carried out the experiment under virtual environments.

Firstly, the stopping maneuver, which is characterized by the profile between the beginning of the deceleration and the stopping point, were measured and analyzed. The profiles of the driving data of the six drivers in the case that the velocity restriction is 50km/h are depicted in Fig. 3 (the data of third and fourth trials with 50km/h, 0m and 50km/h, 100m, respectively).



(a)



(b)

Fig. 3. Behavior at stopping

The data of the driver who has shown high levels of simulator sickness in our questionnaires were not used for the modeling. The personal information of six examinees is listed in Table 2. The horizontal and vertical axes in Fig.3 denote the position (stop line is located at 300m) and the velocity of the vehicle, respectively.

Table 2. Individual Information of Examinees

Examinee	Age [Years old]	Mileage per year [km]	Driving Career [Years]
E1	22	2500	3
E2	22	15000	2
E3	21	5000	3
E4	22	5000	4
E5	22	5000	3
E6	22	25000	3

When we look at profiles in Fig.3, roughly speaking, the stopping maneuver can be regarded as the series of the following three sub-maneuvers: (1) deceleration, (2) running with constant velocity and (3) re-deceleration. This sequence of sub-maneuvers is often observed in the driving pattern in real cars. In Fig.3 (a), however, the drivers E2 and E3 show different maneuver from one described above. From the answer to the questionnaire, we could find the reason of this as follows: The driver (E2) often makes 'sudden stopping' in his real driving situation. Also, the driver (E3) has found the optimal beginning point for the deceleration by investigating the building and the electric pole around the stop line instead of taking a look at the stop line in this experiment.

In the following, we call the duration corresponding to above three sub-maneuvers 'Interval A', 'Interval B' and 'Interval C'.

The more formal expression based on the polynomial model is introduced in the following.

The interval A (deceleration)

$$y_{2,k} = a_0 x_{1,k} + a_1 x_{3,k} + a_2 x_{1,k}^2 + a_3 x_{3,k}^2 \quad \text{if} \quad d_1 > x_{1,k} \tag{1}$$

The interval B (running with constant velocity)

$$y_{2,k} = b_0 x_{1,k} + b_1 x_{3,k} + b_2 x_{1,k}^2 + b_3 x_{3,k}^2 \quad \text{if} \quad d_2 > x_{1,k} \geq d_1 \tag{2}$$

The interval C (re-deceleration)

$$y_{2,k} = c_0 x_{1,k} + c_1 x_{3,k} + c_2 x_{1,k}^2 + c_3 x_{3,k}^2 \quad \text{if} \quad x_{1,k} \geq d_2 \tag{3}$$

In eq. (1) to (3), $x_{1,k}$ and $x_{3,k}$ denote the position and acceleration, respectively. d_1 and d_2 are parameters to specify the switching between intervals. Since the structure of this model contains both the continuous dynamics (polynomials) and the logical conditions (switching o f polynomials), the proposed model belongs to a kind of Hybrid Dynamical Systems (HDS).

As alternative ways of modeling the driving maneuver, for example, nonlinear regression models, neural network and fuzzy system can be used. If we use these techniques, however, the obtained model often results in too complicated model, and this makes it impossible to understand the physical meaning of the driver's behavior. On the contrary, the HDS model proposed in this section enables us to capture not only the physical meaning (polynomials), but also the decision-making aspect (logical conditions) in the driving maneuver.

Note that the switching conditions between each interval are not specified in advance in our model. The parameter specifying switching condition (d_1 and d_2) and coefficients appearing in each polynomial (a_i to c_i) must be found simultaneously from the measured data. In the next section, the strategy to solve this simultaneous identification problem is developed.

5. MODELING OF DRIVER'S BEHAVIOR BASED ON PIECEWISE POLYNOMIAL SYSTEMS (PWPS) EXPRESSION

5.1 Expression as PWPS

PWPS is one of classes of hybrid system, in which logic, dynamics and constraints are integrated. PWPS is formulated by (4).

$$y_{2,k} = \begin{cases} a_0 x_{1,k} + a_1 x_{3,k} + a_2 x_{1,k}^2 + a_3 x_{3,k}^2, \\ \quad \text{if } d_1 > x_{1,k} \\ b_0 x_{1,k} + b_1 x_{3,k} + b_2 x_{1,k}^2 + b_3 x_{3,k}^2, \\ \quad \text{if } d_2 > x_{1,k} \geq d_1 \\ c_0 x_{1,k} + c_1 x_{3,k} + c_2 x_{1,k}^2 + c_3 x_{3,k}^2, \\ \quad \text{if } x_{1,k} \geq d_1 \end{cases} \tag{4}$$

where $k \in Z$ is a discrete time. Thus, the PWPS form includes both continuous dynamics (polynomials) and logical conditions. The goal of our modeling is to find not only coefficients in the polynomials a_i, b_i and c_i but also parameters in the 'switching conditions' d_i from the measured driving data. Although this identification problem is not straightforward to handle, the idea developed in the Mixed Logical Dynamical Systems framework [4] makes it tractable. The key ides is to transform the logical condition into some inequalities by introducing auxiliary binary variables $\delta \in \{0,1\}$ and auxiliary continuous variables *z*, and to formulate the problem as the Mixed Integer Linear Programming.

5.2 Useful tools to transformation from logical condition into inequalities

In this section, some useful tools to transform the logical condition into inequalities are introduced. Firstly, the logical relationship given by

$$[f(x) \geq a] \Leftrightarrow [\delta = 1] \tag{5}$$

can be transformed into inequalities (6) and (7).

$$-f(x) + (a - m)\delta + m \leq 0 \tag{6}$$

$$f(x) - (M - a + \varepsilon)\delta - a + \varepsilon \leq 0 \tag{7}$$

where $M = \max_x f(x)$, $m = \min_x f(x)$, and $\varepsilon > 0$ is a small tolerance. Also, in our setup, the product term of binary and continuous variables such as $\delta f(x)$ often appear. Since it is undesirable to handle this nonlinear term, we secondly introduce another auxiliary variable $z = \delta f(x)$, which satisfies the following two logical relationships.

$$[\delta = 0] \Rightarrow [z = 0], [\delta = 1] \Rightarrow [z = f(x)] \tag{8}$$

These relationships can be transformed into the following equivalent inequalities.

$$z \leq M\delta \tag{9}$$

$$-z \leq -m\delta \tag{10}$$

$$z \leq f(x) - m(1 - \delta) \tag{11}$$

$$-z \leq -f(x) + M(1 - \delta) \tag{12}$$

5.3 Identification of PWPS model by Mixed Integer Linear Programming (MILP)

In order to transform the three logical conditions involved in (4) into the equivalent inequalities, binary variables $\delta_{1,k}, \delta_{2,k}$ are introduced as follows:

① $[d_1 > x_{1,k}] \Leftrightarrow [\delta_{1,k} = 0, \delta_{2,k} = 0]$

② $[d_2 > x_{1,k} \geq d_1] \Leftrightarrow [\delta_{1,k} = 1, \delta_{2,k} = 0]$

③ $[x_{1,k} > d_2] \Leftrightarrow [\delta_{1,k} = 0, \delta_{2,k} = 0]$

By applying the transformation rules and introducing the auxiliary variables, eq. (4) can be reformulated by the following linear equation.

$$\begin{aligned} \mathrm{y}_{2,k} &= a_0 x_{1,k} + a_1 x_{3,k} + a_2 x_{1,k}^2 + a_3 x_{3,k}^2 \\ &+ x_{1,k} z_{1,k} + x_{3,k} z_{2,k} + x_{1,k}^2 z_{3,k} + x_{3,k}^2 z_{4,k} \\ &+ x_{1,k} z_{5,k} + x_{3,k} z_{6,k} + x_{1,k}^2 z_{7,k} + x_{3,k}^2 z_{8,k} \end{aligned} \tag{13}$$

where, the auxiliary variables, $z_{i,k}$, are defined as follows.

$$z_{i,k} = \delta_{j,k} f_{i,k} = \delta_{j,k}(b_r - a_r) \text{ (i=1〜4,r=0〜3,j=1)} \tag{14}$$

$$z_{i,k} = \delta_{j,k} f_{i,k} = \delta_{j,k}(c_r - a_r) \text{ (i=5 ˜ 8,r=0 ˜ 3,j=2)} \tag{15}$$

$$z_{i,k} = \delta_{j,k} f_{i,k} = \delta_{j,k} d_r \text{ (i=9 ˜ 10,r=1 ˜ 2,j=1)} \tag{16}$$

$$z_{i,k} = \delta_{j,k} f_{i,k} = \delta_{j,k} d_r \text{ (i=11 ˜ 12,r=1 ˜ 2,j=2)} \tag{17}$$

Also, as stated in the previous section, some linear inequalities that come up with the introduction of $\delta_{1,k}, \delta_{2,k}$ and $z_{i,k}$ must be accompanied with (13) to (17).

Now, the problem to find the parameters in the switching condition and coefficients in the polynomials is formulated as the following MILP.

$$\textit{known} \quad y_{2,k}, x_{1,k}, x_{3,k}$$

$$\textit{find} \; \{a_0, a_1, a_2, a_3, b_0, b_1, b_2, b_3, c_0, c_1, c_2, c_3, d_1, d_2, \delta_{1,k}, \delta_{2,k}\}$$

$$\textit{which minimize } J = \sum_k^N \left| y_{2,k} - \hat{y}_{2,k} \right| \tag{18}$$

subject to

$$z_{i,k} \leq M_i \delta_{j,k} \tag{19}$$

$$-z_{i,k} \leq -m_i \delta_{j,k} \tag{20}$$

$$z_{i,k} \le f_{i,k} - (1-\delta_{j,k})m_i \tag{21}$$

$$-z_{i,k} \le -f_{i,k} + (1-\delta_{j,k})M_i \tag{22}$$

$$0 \le \delta_{1,k} \le 1 \tag{23}$$

$$0 \le \delta_{2,k} \le 1 \tag{24}$$

$$0 \le \delta_{1,k} + \delta_{2,k} \le 1 \tag{25}$$

$$\delta_{2,k} \le \delta_{2,k+1} \tag{26}$$

$$x_{1,k} \le d_1 - z_{9,k} + z_{10,k} - z_{11,k} - \varepsilon + \delta_{2,k}(M_d + \varepsilon) \tag{27}$$

$$x_{1,k} \ge (1-(\delta_{1,k} + \delta_{2,k}))m_d + z_{9,k} + z_{12,k} \tag{28}$$

where, M_i and m_i (i=1～12) are the maximum and minimum values of $z_{i,k}$, and M_d and m_d represent the maximum and minimum values of d_1 and d_2, respectively. ε is a small tolerance.

There are several ways to solve the MILP. One of the most efficient algorithms is a branch-and-bound method. Although it requires some heuristic rules in the decision of the branching variable, it can guarantee the optimality, and can reduce the computational burden with assistance of appropriate heuristic rules.

Note that the computational burden strongly depends on the number of binary variables since this specifies the size of the search space. In our case, the number of the measurement points affects the computational burden significantly.

5.4 Identification results of stopping behavior based on PWPS model

Based on the formulation of the identification of the PWPS model described in the previous section, the identification of parameters in the switching conditions and coefficients in the polynomials in the stopping behavior is carried out.

The profile between the beginning of the deceleration and the final stopping point of each driver shown in Fig. 3 was used for the modeling.

The fifteen sampling data of the third trial of six drivers were used for the identification of the stopping behavior. These data were selected by culling from the measured data between the beginning of the deceleration and the final stopping point. Before applying the MILP to the measured data, the input and output data were normalized as follows:

$$\bar{x}_i = \begin{cases} \dfrac{x_i}{x_{i\max}} & (x_i \ge 0) \\ -\dfrac{x_i}{x_{i\min}} & (x_i < 0) \end{cases} \tag{29}$$

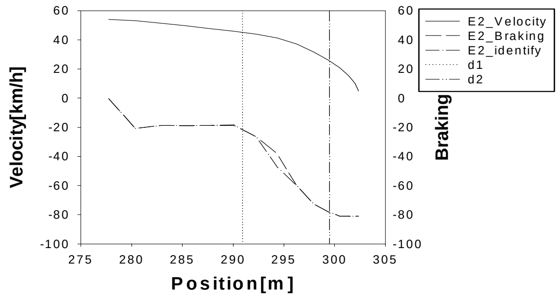
$$x_i \in [x_{i\min} \quad x_{i\max}]$$

$$\bar{y}_i = \begin{cases} \dfrac{y_i}{y_{i\max}} & (y_i \ge 0) \\ -\dfrac{y_i}{y_{i\min}} & (y_i < 0) \end{cases} \tag{30}$$

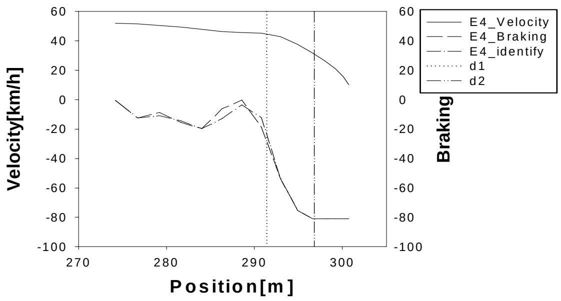
$$y_i \in [y_{i\min} \quad y_{i\max}]$$

All numerical experiments have been performed by PC (CPU 4 3.06[GHz] and Memory 1024[MB]). It took about two hours to find the solution of the MILP.

In order to verify the validity of the obtained PWPS model, the reproduced braking amount found by MILP is plotted together with the measured braking amount and the velocity of the vehicle in Fig. 5.



(a)



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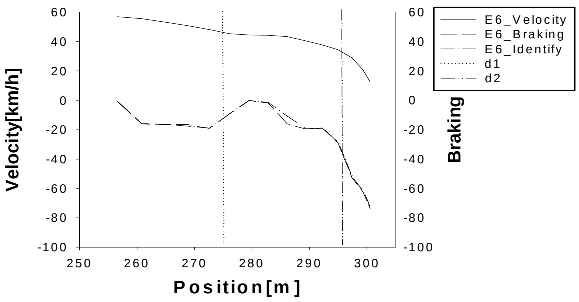

(c)

Fig. 5. Comparison of actual brake input and estimated brake input

In Fig.5, Horizontal axis represents the distance from the starting point. The stopping line is located at 300[m]. Note that the braking amount takes negative values, and zero braking implies 'no braking'. Also, the switching points between polynomials are designated by vertical lines. As shown in Fig. 5, the measured braking amount and reproduced braking amount based on the PWPS model agree well with each other. These results verify the effectiveness of the modeling based on the PWPS. The switching points, however, vary from driver to driver. In order to understand the common characteristics in the stopping behavior, the identified parameters for three examinees (E2, E4 and E6) are listed in Table 3.The coefficients in the polynomials a_i, b_i, c_i and the parameters in the switching conditions d_i in (13) and (18) are listed in Table 3.

As shown in Table 3, the most dominant input information in the intervals B and C were the distance $x_{1,k}$ to the stop line, and the acceleration $x_{3,k}$ did not play an important role in the stopping maneuver. On the other hand, the acceleration information $x_{3,k}$ was found to be dominant input information, and played a crucial role in the interval A. Similar tendency has been found in the identified results of other drivers.

Table 3. Identified parameters and values by a PWPS form of E2, E4 and E6 examinee

Parameters	Values (E2)	Values (E4)	Values (E6)
a_0	-0.4619	-0.1501	0.9824
a_1	2.3118	1.1358	1.2932
a_2	0.54747	0.1834	-1.1310
a_3	4.4584	0.8705	1.8747
b_0	26.810	24.200	1.7534
b_1	1.6844	-20.660	0.4065
b_2	-27.578	-34.404	-1.8845
b_3	1.2212	-12.058	-0.6546
c_0	-2.0241	-2.005	11.220
c_1	-0.0233	0.0039	-20.663
c_2	1.0130	1.0067	-20.854
c_3	-0.0122	0.0023	-10.029
d_1	290.900	291.360	274.739
d_2	299.477	296.776	295.222

From these observation, we can conclude that the driver appropriately switches the 'control law' according to the following scenario: At the beginning of the stopping maneuver (just after finding the stopping point), the driver decelerate the vehicle based on the acceleration information, and then switch to another control law based on the distance to the stop line. Although the switching points depend on the driver's characteristics, qualitatively speaking, the scenario described above can be found as common characteristics in all drivers.

These results highly demonstrate the usefulness of the modeling based on the expression as an HDS.

6. CONCLUSIONS

This paper has developed a new framework to understand the human's driving maneuver based on the expression as HDS focusing on the driver's stopping maneuver. The driving data has been collected by using the three-dimensional driving simulator based on CAVE, which provides three-dimensional visual information. In our modeling, the relationship between the measured information such as distance to the stop line, its first and second derivatives and the braking amount has been expressed by the PWPS model, which is a class of HDS. The key idea to solve the identification problem was to formulate the problem as the MILP with replacing the switching conditions by binary variables. From the obtained results, we could find that the driver appropriately switches the 'control law' according to the following scenario: At the beginning of the stopping behavior (just after finding the stopping point), the driver decelerate the vehicle based on the acceleration information, and then switch to the control law based on the distance to the stop line. Thus, our proposed approach enables us to capture not only the physical meaning of the driving skill, but also the decision-making aspect (switching conditions) in the driving behavior. The application to more complicated task and the integration with mental aspects of the driver are our future works.

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