LONGITUDINAL CONTROL OF PLATOON FOR ELECTRIC VEHICLE USING ADAPTIVE NEURAL NETWORKS

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Abstract: In AHS(Automated Highway Systems) project which is one of the ITS (Intelligent Highway Systems), the platoon control is developed. In this paper, a platoon control law based on Adaptive Neural Network (ANN) to lower level and Semi-Autonomous Adaptive Cruise Control (SAACC) to upper level is proposed. Moreover, there is "Delay" with the communication and the sensor. We design their compensators, and did stability analysis that takes those error into consideration. We confirmed that the closed loop system is stable, and confirmed the effectiveness in the numerical simulation.

Keywords: Adaptive control,Neural networks,Follow-up control,Nonlinear controlsystems,Inverse dynamics control,Electric vehicles

1. INTRODUCTION

While it will enter in the 21st century and the world of traffic also goes into a new stage, the social role of automobile traffic is still larger. Also in Japan, the Intelligent Transport Systems (ITS) project is advanced mainly by the Road Bureau, the Ministry of Land, Infrastructure and Transport. The purposes of ITS are improvement in safety, reduction of traffic congestion, reduction of environmental load, creation of a new industry, etc. ITS does not remain only in Japan but is actively performed in the area in EU, the U.S., and other Asia. Smart Cruise Systems (SCS) are in one of the development fields of ITS (the U.S. Automated Highway Systems: AHS). SCS consists of Advanced Cruise-assist Highway Systems (AHS), Advanced Safety Vehicle (ASV), and Association of Radio Industries & Business (ARIB).

Generally the control system of a platoon in SCS is divided roughly into a position follow-up control and a vehicle follow-up control. By the former system, since each vehicles are controlled nothing with regards to the position of other vehicles, the collision of the vehicles in an emergency is not avoided. On the other hand, although the position and velocity information on the preceding car are needed as a feedback signal by the vehicle follow-up control, there is little danger of a collision. The way of the vehicle follow-up control is suitable also from a viewpoint of "string stability" (D.V.A.H.G.Swaroop, 1997) later mentioned also from the above thing. Moreover, by the traditional method, the absolutely position information is indispensable. The absolutely position information had been acquired by integrating with speed or measuring the magnet embedded by the road. However, by the technique, there is a problem at the reliability of data, and it is difficult to realize.

In the design of longitudinal control of a platoon of vehicles, it is important to acquire the exact information on a physical parameter that each car has. However, in practice, change of the dynamic characteristics that cannot be predicted arises because of various factors, or various kinds of indefinite phenomena arise. Moreover, the nonlinear nature of the parameter that cannot be disregarded exists in many cases. By the conventional method, since it has ignored for simplification of the slip modeling of a tire, the control according to change of slip ratio by the weather etc. is not securable with robustness. In such a case, according to change of the dynamic characteristic of a plant, introduction of the adaptive control that adjusts a controller with an on-line automatically can be considered. Even when a parameter is unknown or it changes, adaptive control maintains the optimal performance. On the other hand, a neural network (NN) is in one of the effective means in nonlinear control, and research on it is done briskly. Then, the system called adaptive neural network that combined adaptive control and NN is studied (S.S.Ge *et al.*, 1999), and it is applied to many examples. Then, adaptive neural network that combined adaptive control and NN is studied, and it is applied to many examples.

The concept of string stability is shown below. String stability refers to a property in which spacing errors, that is the error between the desired distance between two vehicles and the real distance between two vehicles, are guaranteed not to amplify as they propagate towards the tail of the platoon (Rajamani and Zhu, 2002). The reason for defining string stability is that it is vehicle follow-up control of not one set but two or more vehicles.

In this paper, we deal with electric vehicle becouse its accuracy model is easy to get. We let a lower level be an motor model and a model that includes air resistance and rotation resistance and propose the technique of using ANN for platoons in the model. By this technique, even in case a slip phenomenon happens, string stability can be secured. Also, in an upper level, Semi-Autonomous Adaptive Cruise Control (SAACC) scheme which computes desired acceleration which follows the desired distance between two vehicles which changes distance according to speed is used, compensating the time lag by the lower level. In this technique, since there is no absolute position in the information needed in each control, a possibility of realizing is high. However, to need the communication between vehicles, time delay is generated in this technique. Then, the compensators for time delay by the measurement is designed, and this problem is solved. In addition, it is proven to set up a useful Lyapunov function as a stability analysis on the nonlinear control system, for the signal of the system to be bounded, and to settle within the arbitrary range (uniformly ultimately bounded). Finally, The numerical simulation confirmed the effectiveness of the proposed technique.

2. VEHICLE FOLLOW PROBLEM

Consider vehicle model in a platoon control (Fig.1). The j-th vehicle model consists of lower level model and upper level model. Lower level considers its motor input voltage v_{m_j} as a ninput and its acceleration $\ddot{x}_j$ as an output. Upper level considers its acceleration $\ddot{x}_j$ as an input and its position x_j as an output.

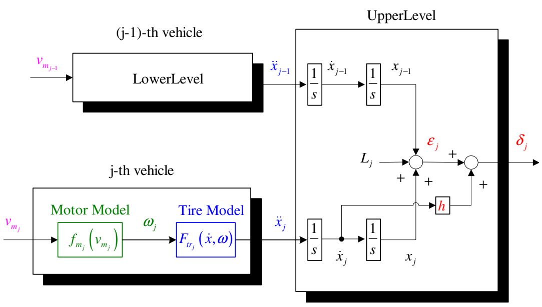

Fig. 1. Structure of the longitudinal vehicles model

2.1 Upper level model

For the upper level model, spacing error that is the error between the desired distance between two vehicles and the real distance ε_j and $\delta_j$is defined as follow (Fig.2).

$$\varepsilon_j \triangleq L_j - \left(x_{j-1} - x_j\right) \quad (1)$$

$$\delta_j \triangleq \left(L_j + h_j\dot{x}_j\right) - \left(x_{j-1} - x_j\right) \quad (2)$$

where L_j[m] is the desired distance and h_j[s] is called “headway time”(D.Swaroop *et al.*, 1994). It is a margin for “string stability” detailed later.

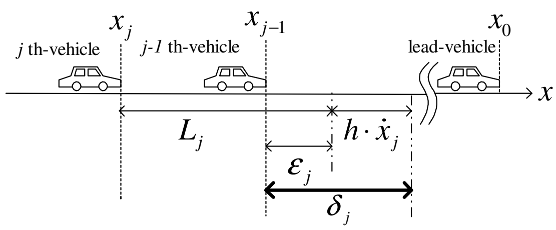

Fig. 2. Notation of vehicles in a platoon

2.2 Lower level model

Lower level model consists of Tire model and Motor model. Note that affixing character j that shows vehicle’s number is omitted because of simple.

The Tire model is written as follow.

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = F_T(\mathbf{x}, \omega, \dot{\omega}) \end{cases} \quad (3)$$

$$x_1 = \dot{x}, x_2 = \ddot{x}, \mathbf{x} = [x_1, x_2]^T \quad (4)$$

$$F_T(\mathbf{x}, \omega, \dot{\omega}) = -2\frac{c_l}{M}x_1x_2 + \frac{1}{M}\frac{\partial F_{tr}(x_1,\omega)}{\partial x_1}\ddot{x} + \frac{1}{M}\frac{\partial F_{tr}(x_1,\omega)}{\partial \omega}\dot{\omega} \quad (5)$$

where M[kg] is vehicle weight, c_l[kg/m] is coefficient ratio of aerodynamic efficiency ω[rad/s] is wheel rotational speed and $F_{tr}(x_2, \omega)$ is the nonlinearity for tire's frictional force limit as follow.

$$F_{tr}(x_2, \omega) = K_r sat\left(\frac{\lambda}{\lambda_{\max}}\right) \quad (6)$$

$$\lambda = \frac{\dot{x} - r\omega}{\dot{x}}, \dot{x} > r\omega \quad (7)$$

$$= \frac{\dot{x} - r\omega}{r\omega}, \dot{x} < r\omega \quad (8)$$

K_r[N] is the longitudional tire stiffness, and λ is the slip ratio.λ_{max} is the slip ratio that the frictional force of the tire becomes the maximum.

The Motor model is written as follow (Y.Hori *et al.*, 1998)

$$T_m = K_T i_m \quad (9)$$

$$v_e = K_e \omega = K_e \dot{\theta} \quad (10)$$

$$v_m = L_a \frac{d}{dt} i_m + R_a i_m + v_e \quad (11)$$

$$J\dot{\omega} + B\omega = T_m - T_{tr} \quad (12)$$

$$T_{tr} = rF_{tr} \quad (13)$$

where T_m[Nm] is a motor torque, K_T[N · m/A] is a torque constant, i_m[A] is a motor current, v_e[V] is a counter electromotive force, K_e[V/rpm] is a counter electromotive force constant, L_a[H] is an armature inductance, R_a[Ω] is an armature resistance. J_j[kgm^2] is an inertia, B_{m_j}[N · m/rad] is a viscous friction, and T_{tr}[Nm] is a load torque. The transmission is disregarded.

The block diagram of lower level model is shown in Fig.3.

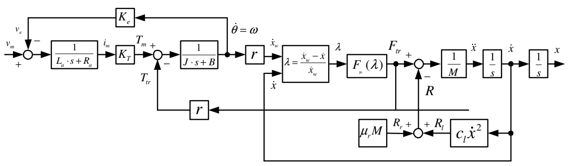

Fig. 3. Block diagram of lower level model

3. VEHICLE FOLLOW-UP CONTROLLER DESIGN

First of all, string stability(D.V.A.H.G.Swaroop, 1997) is defined.

Definition (string stability) The transfer function $H_j(s) \triangleq \frac{\delta_j(s)}{\delta_{j-1}(s)}$ is defined. It is said to string stability about spacing error δ_j between vehicles if the following expressions consist for all $H_j(s)$

$$|H_j(j\omega)| \leq 1, \quad \forall\omega \quad (14)$$

The objective of controller design is the following.

(1) $\lim_{t\to\infty} \delta_j(t) \to 0 \qquad \forall j$
(2) string stability (14)

3.1 Upper level controller

Semi-Autonomous Adaptive Cruise Control(SAACC (Rajamani and Zhu, 2002)) is used as upper level controller. The objective of upper level controller is that the controller calculates a desired acceleration that satisfies the above-mentioned objective, compensating first order lag that generated in engine model. The algorithm is showed as follow.

As a problem fomulation, the engine model in the jth vehicle is considered as follow

$$\tau_j x_j^{(3)} + \tau_j \ddot{x}_j = \ddot{x}_{d_j} \quad (15)$$

The next control input is given to this acceleration input $\ddot{x}_{d_j}$

$$\ddot{x}_{d_j} = -\kappa_1 \ddot{x}_{j-1} - \kappa_2 \ddot{x}_j - \kappa_3 \dot{\varepsilon}_j - \kappa_4 \varepsilon_j - \kappa_5 \dot{x}_j \quad (16)$$

$\kappa_1, \cdots, \kappa_5$ are determined as follow

$$\begin{cases} \kappa_1 h_j = \tau_j \\ \kappa_4 h_j = \kappa_5 \\ -\kappa_1 - \kappa_2 + \kappa_3 h_{w_j} = 1 \end{cases} \quad (17)$$

Substituting from (15), (16), (17) into (15) and rearranging, we obtain

$$\kappa_1 \delta_j - \kappa_3 \dot{\delta}_j - \kappa_4 \ddot{\delta}_j = 0 \quad (18)$$

If $\kappa_1 < 0, \kappa_3, \kappa_4 > 0$, then the poles of the closed-loop dynamics (18) are in the negative left half plane. we choose κ_3 as follow

$$\kappa_3 = \frac{1}{h_j}(1 - \kappa_1 \kappa_4) \quad (19)$$

τ_j changes with j, and in almost all cases, differs from nominal model. Consequently, we prove string stability in case determination of κ_1 is not made. It is contained in this when determination of κ_1 is made. Substituting from (17), (2),into (16) and rearranging, we obtain the transfer function as follow

$$H_{\delta_j \varepsilon_j}(s) \triangleq \frac{\varepsilon_j(s)}{\delta_j(s)} = \frac{\tau s^2 + h_j \kappa_3 s + \kappa_5}{\left(\tau_j + k_1 h_j\right) s^2} \quad (20)$$

From (1), (2), we obtain,

$$\delta_j - \delta_{j-1} = \varepsilon_j - \varepsilon_{j-1} + h_j \dot{\varepsilon}_j \quad (21)$$

Substituting from (21) into (20), we obtain

$$H_j(s) = \frac{1}{1 + h_j s \left\{ \frac{\tau_j s^2 + h_j \kappa_3 + \kappa_5}{-\kappa_1 h_j s^2 + h_j \kappa_3 + \kappa_5} \right\}} \quad (22)$$

Also we obtain next equation from (19), (22)

$$||H_j(j\omega)||^2 = \frac{h_{nj}(j\omega)}{h_{dj}(j\omega)} \quad (23)$$

$$h_{nj}(j\omega) = (\kappa_5 + \kappa_1 h_j \omega^2)^2 + (1 - \kappa_1\kappa_5 h_j)^2\omega^2$$

$$h_{dj}(j\omega) = (\kappa_5 + \kappa_1 h_j\omega^2 - h_j\omega^2 + \kappa_1\kappa_5 h_j^2\omega^2)^2 + (1 - \kappa_1\kappa_5 h_j - \tau_j h_j\omega^2 + \kappa_5 h_j)^2\omega^2$$

then, we obtain

$$(14) \Leftrightarrow\ 0 \leq 2(1 - \kappa_1\kappa_5 h_j)(-\kappa_1 h_j - \tau_j)\omega^2 + h_j(1 - \kappa_1\kappa_5 h_j)^2\omega^2 + h_j(\kappa_5 + \kappa_1 h_j\omega^2), \quad \forall\omega \quad (24)$$

κ_1 that satisfies (24) is chosen like

$$-\kappa_1 h_j \geq \tau_j \quad (25)$$

Note that information required for this algorithm is acceleration of precedence vehicle $\ddot{x}_{j-1}$, acceleration of "my" vehicle $\ddot{x}_j$, velocity of "my" vehicle $\dot{x}_j$, relative distance between $j-1$th and jth $x_{j-1} - x_j$, and relative velocity between $j-1$th and jth $\dot{x}_{j-1} - \dot{x}_j$ and is not absolute position of "my" vehicle x_j.

3.2 Lower level controller

The controller for actual acceleration $\ddot{x}_j$ to follow to the desire acceleration $\ddot{x}_{d_j}$(16) is designed according to the following algorithm. The composition of the controller referred to (Selmic and Lewis, 2001). The error dainamics and the control rule are as follows.

$$e_{v_j} \triangleq x_{1_j} - \dot{x}_{d_j} \quad (26)$$

$$\hat{x}_{2_j} = -K_v e_{v_j} + \ddot{x}_{d_j} \quad (27)$$

$$e_{a_j} \triangleq \hat{x}_{2_j} - x_{2_j} \quad (28)$$

$$\hat{\phi}_j = K_a e_{a_j} + \xi_j - y_{nn_j} + \zeta_j \quad (29)$$

where ξ_j is the filter output introduced to achieve derivative. ζ_j is a signal introduced to make the system robustness of the following description. y_{nn_j} is an output of NN shown by the following expression.

$$y_{nn_j} = \hat{\boldsymbol{W}}_j^T \boldsymbol{S}_j(\boldsymbol{z}_j) \quad (30)$$

$\boldsymbol{S}_j(\boldsymbol{z}_j)$ is a radial base network(Chen and Kawaji, 1999), and In this paper, the Volterra polynomial basis function is used. The NN input vector $\boldsymbol{z}_j$ is chosen as

$$\boldsymbol{z}_j = \left[1\ e_{v_j}\ \dot{x}_{d_j}\ e_{a_j}\ \hat{x}_{2_j}\ y_{nn_j}\ \left\|\hat{\boldsymbol{W}}_j\right\|\right]^T \quad (31)$$

Moreover, the following assumption is put for NN.

Assumption 1 (Boundedness of neural net approximation error) NN approximation error $\eta_N(\boldsymbol{z})$ is $|\eta(\boldsymbol{z})|| \leq \eta_N(\boldsymbol{z})$ for $\boldsymbol{z} \in \Omega$. In this paper, we consider $\boldsymbol{z}$ restricted to a compact set. and in that case these bounds are constant, i.e.$\eta_N(\boldsymbol{z}) = \eta_M$ $\boldsymbol{z}$. Therefore, the following expressions consist.

$$||\eta(\boldsymbol{z})|| \leq \eta_M \quad (32)$$

Here, it is assumed that η_M is known.

Assumption 2 (Boundedness of ideal target weight) The approximating weight $\boldsymbol{W}$ is an ideal target weight, and it is assumed that it is bounded so that

$$||\boldsymbol{W}|| \leq W_M \quad (33)$$

where $\boldsymbol{W}_M$ is known.

4. TIME DELAY COMPENSATOR

Time delay by the communication is caused because the communication between car cars is necessary in the technique for proposing it. Moreover, time delay for the measurement time exists though the millimeterwave radar is assumed as a sensor used. They have the possibility of making the faction unstable. Therefore, the amends machine of time delay to have used 0 counterbalances in the pole by the Taylor development approximation is designed for those signals. The transfer function of the proposed amends machine is as follows.

$$C_d(s) = 1 + \tau s + \frac{1}{2}(\tau s)^2 \cdots \quad (34)$$

The errors with time delay compensators is defined as follows.

$$\begin{cases} \Delta_{\ddot{x}_{j-1}}(t) \triangleq C(s)\ddot{x}_{j-1}(t-\tau_1) - \ddot{x}_{j-1}(t) \\ \Delta_{\varepsilon_j}(t) \triangleq C(s)\varepsilon_j(t-\tau_2) - \varepsilon_j(t) \\ \Delta_{\dot{\varepsilon}_j}(t) \triangleq C(s)\dot{\varepsilon}_j(t-\tau_2) - \dot{\varepsilon}_j(t) \end{cases} \quad (35)$$

Here, $\tau_1 and \tau_2$sis time delay by the communication and time delay respectively by the measurement time of the millimeterwave radar. The error with the amends machine of time delay can be arbitrarily reduced by raising the degree of the Taylor development. The following assumption is put for the error with the amends machine of time delay.

Assumption 3 (Boundedness of error with time delay compensators) It is assumed time delays of the communicated between vehicles and the millimeterwave radar, and these are already-known constant respectively. The errors with time delay compensators $\boldsymbol{\Delta} = [\Delta_{\ddot{x}_{j-1}}(t), \Delta_{\varepsilon_j}(t), \Delta_{\dot{\varepsilon}_j}(t)]^T$ is bounded so that

$$||\boldsymbol{\Delta}|| < \Delta_M \quad (36)$$

where Δ_M is a known constant.

5. STABILITY ANALYSIS OF CLOSED-LOOP SYSTEM

The boundedness of the signals in closed-loop system is considered in the following theorem and, and, the influence of the error of the amends machine of useless time is considered.

Theorem 1 (Boundedness of closed-loop) Robustifying signal ζ_j is chosen as follows.

$$\begin{cases} \zeta_j = K_{\boldsymbol{W}_1}\|e_{v_j}\| \cdot \frac{e_{a_j}}{\|e_{a_j}\|} + K_{\boldsymbol{W}_2}\left\|\hat{\delta}_j\right\| \cdot \|e_{v_j}\| \cdot \frac{e_{a_j}}{\|e_{a_j}\|^2} \\ \quad +K_{\boldsymbol{W}_3}\left\|\hat{\delta}_j\right\| \cdot \frac{e_{a_j}}{\|e_{a_j}\|} + K_{\boldsymbol{W}_4}\left\|\hat{\delta}_j\right\| \cdot \left\|\ddot{x}_{d_j} - \ddot{x}_{j-1}\right\| \cdot \frac{e_{a_j}}{\|e_{a_j}\|^2} \\ \quad +K_{\boldsymbol{W}_5}\|e_{v_j}\| \cdot \frac{e_{a_j}}{\|e_{a_j}\|^2} + K_{\boldsymbol{W}_6}\frac{e_{a_j}}{\|e_{a_j}\|} + K_{\boldsymbol{W}_7}\left\|\hat{\delta}_j\right\| \cdot \frac{e_{a_j}}{\|e_{a_j}\|^2} \\ \quad +K_{\boldsymbol{W}_8}\left\|\hat{\ddot{x}}_{d_j} - \hat{\ddot{x}}_{j-1}\right\| \cdot \frac{e_{a_j}}{\|e_{a_j}\|^2} & : e_{a_j} \neq 0 \\ \zeta_j = 0 & : e_{a_j} = 0 \end{cases} \quad (37)$$

Here, $K_{\boldsymbol{W}_1} > 1$, $K_{\boldsymbol{W}_2} > K_v|1+\kappa_1|$, $K_{\boldsymbol{W}_3} > |1+\kappa_1|$, $K_{\boldsymbol{W}_4} > -\kappa_1$, $K_{\boldsymbol{W}_5} > K_v|1+\kappa_1|\Delta_M$, $K_{\boldsymbol{W}_6} > |1+\kappa_1|\Delta_M$, $K_{\boldsymbol{W}_7} > (\kappa_3+\kappa_4)\Delta_M$, $K_{\boldsymbol{W}_8} > \kappa_1\Delta_M$is assumed to be a positive constant. NN weight presumption value $\hat{\boldsymbol{W}}$ is adjusted by the following NN adjustment algorithms.

$$\dot{\hat{\boldsymbol{W}}} = -\Gamma \boldsymbol{S}(\boldsymbol{z})e_a - k\Gamma\|e_a\|\hat{\boldsymbol{W}} \quad (38)$$

where $\Gamma = \Gamma^T$ is an arbitrary, positive constant symmetric matrix, $k > 0$ is a small scalar design parameter. The first term is corresponding to error back propagation, and second term is corresponding to the $\sigma-$ modification often used by the robust adaptive control. Then spacing error δ between cars, the filtered tracking error e_v error e_a and NN weight estimate $\hat{\boldsymbol{W}}$ are Uniformly Ultimately Bounded (UUB).

Proof : The candidate of the Lyapunov function is chosen as follows.

$$V_j = \frac{1}{2}e_{v_j}^2 + \frac{1}{2}e_{a_j}^2 + \frac{1}{2}\tilde{\boldsymbol{W}}_j^T\Gamma^{-1}\tilde{\boldsymbol{W}}_j + \frac{1}{2}\kappa_3\delta_j^2 \quad (39)$$

Taking derivative

$$\begin{aligned} \dot{V}_j =& e_{v_j}\dot{e}_{v_j} + e_{a_j}\dot{e}_{a_j} + \tilde{\boldsymbol{W}}_j^T\Gamma^{-1}\dot{\tilde{\boldsymbol{W}}}_j + \kappa_3\delta_j\dot{\delta}_j \\ =& -\kappa_4\delta_j^2 - K_v e_v^2 - K_a\left\{\|e_a\| - \frac{1}{2K_a}\left(\frac{kW_M^2}{4} + \eta_M\right)\right\}^2 \\ & - k\|e_a\|\left(\|\tilde{\boldsymbol{W}}\| - \frac{W_M}{2}\right)^2 \\ & + \frac{1}{4K_a}\left(\frac{kW_M^2}{4} + \eta_M\right)^2 \\ & + \{|1+2\kappa_1|(-\kappa_1+\kappa_3+\kappa_4) - \kappa_1\}\Delta_M^2 \end{aligned} \quad (40)$$

Therefore, it can be said that it is UUB. □

6. NUMERICAL SIMULATIONS

Vehicle parameters are given in Table 1. This value referred to Electric vehicle "MC-1 EV" made in Mitsuoka Motor Co., Ltd.

The desired distance is assumed to be $L_j = 5$. Time delays is assumed to be $\tau_1 = \tau_2 = 0.1$. Moreover, the controller gain parameters in upper and lower are given in Table 2.

In this simulation, the six vehicles consisting of a lead vehicle and five following vehicles are considered.

Table 1. Vehicle parameters

M_j	Vehicle weight	320kg
r_j	Radius of a tire	0.27m
K_{r_j}	Tractional force	$210 * 9.8$N
$\lambda_{\max_j}$	max slip coefficient	0.1
c_{l_j}	Air resistance coefficient	0.3kg/m
μ_{r_j}	Rolling resistance coefficient	0.005
J_j	Motor inertia	0.67kgm^2
B_{m_j}	Viscous friction	0.040N · m/rad
K_{e_j}	Counter electromotive force constant	4.7V/rpm
K_{T_j}	Torque constant	42.0N · m/A
L_{a_j}	Armature inductance	$6.0 * 10^{-3}$H
R_{a_j}	Armature resistance	7.9Ω

Table 2. Controller gain parameters

κ_1	-35	$K_{\boldsymbol{W}_1}$	2
κ_2	2.235	$K_{\boldsymbol{W}_2}$	10
κ_3	2.35	$K_{\boldsymbol{W}_3}$	11
κ_4	4.5	$K_{\boldsymbol{W}_4}$	12
κ_5	0.45	$K_{\boldsymbol{W}_5}$	0.5
h	0.1	$K_{\boldsymbol{W}_6}$	11
K_{v_j}	0.1	$K_{\boldsymbol{W}_7}$	32
K_{a_j}	5000	$K_{\boldsymbol{W}_8}$	11
k	0.001	Γ	$100I_{35}$

The lead car slams on the brakes by 20s as shown in Fig.4 while the platoon is running by 100km/h The spacing error δ_j without delay compensators and with delay compensators is shown in Fig.5 and Fig.6. These simulation is a similar condition except for delay compensator. Moreover, the acceleration of each vehicle with time delay compensator is shown in Fig.7. Only the 1st, 3rd, and 5th result are put like being comprehensible the change.

The spacing error δ_j without delay compensators diverges in the vicinity of 48s as understood from Fig.5. Therefore, it is understood not to be able to achieve the platoon when the lead vehicle slams on the brakes. It is thought that it is because transmitting stopping of the lead car a rapid brake in the vicinity of 38s for time delay in this cannot correspond late.

When there is time delay compensator, it is understood to settle to 0 afterwards though the spacing error between vehicles increases when the acceleration of the lead vehicle changes from Fig.6. Moreover, the peak of the spacing error between vehicles is more small in the fifth vehicle than the first vehicle from Fig.6 in the vicinity of 34s and 39s. Therefore, it can be confirmed to fill string stability from the simulation.

The appearance of the slipping parameter of the 1st, the 3rd, the 5th, and the lead car is shown in Fig.8. It is understood that the 1st, the 3rd, and the 5th from Fig.8 run as both correspond to the limit of the tire power.

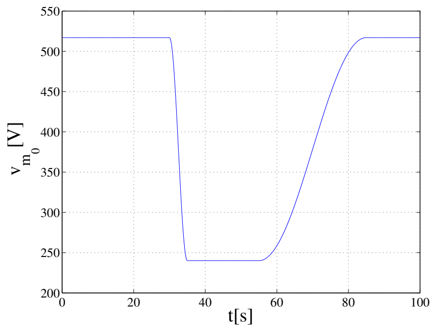

Fig. 4. lead vehicle input v_{m_0}

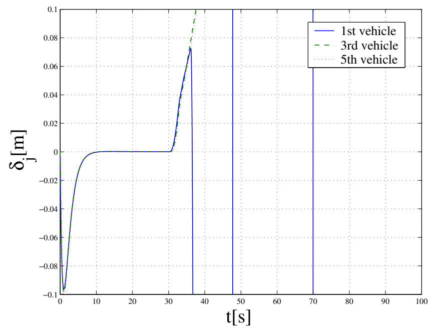

Fig. 5. Spacing error δ_j (without delay compensator)

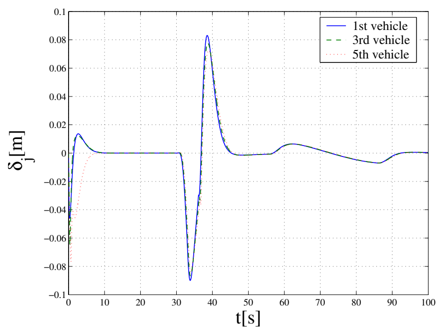

Fig. 6. Spacing error δ_j (with delay compensator)

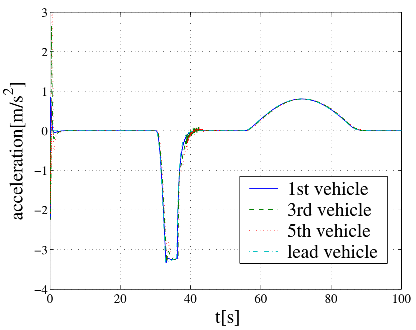

Fig. 7. Acceleration of vehicles (with delay compensator)

7. CONCLUSION

In this paper, for the electric vehicle which is easy to model compared with the engine car platoon control law is proposed. The control law is using ANN for saturation characteristic of tire force and guaranteeing string stability. Moreover, time delay of the sensor signals was considered and their compensator is designed. In addition, the stability of the closed-loop system is proven. Finally, the effectiveness is confirmed by the simulation. The experiment by real vehicles is future reseach.

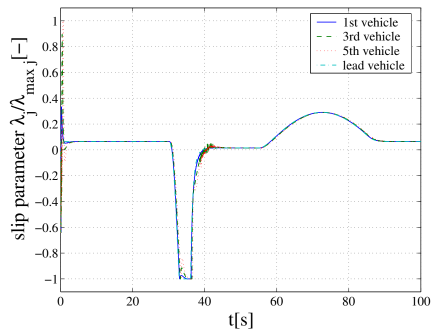

Fig. 8. Slip parameter λ/λ_{max}

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