Steering-Assist Control System on Curved Road Using Car-to-car Communication*

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Abstract— **Several driver-assist systems have been developed to enhance driver comfort, such as Adaptive Cruise Control (ACC) and Lane-Keeping Assist System (LKAS). Drivers must steer the vehicle even with the current ACC. LKAS manages the vehicle position within the lane in when the road curvature is not very large. The ability of such systems strongly depends on the recognition technology applied to the road environment. A sensor fusion method is one option to increase robustness of environmental recognition. The present study seeks to develop a road-information acquisition method based on a car-mounted sensor and a car-to-car communication system and to explore its application to an automatic steering-control system. In this paper, we assume that there is a lead vehicle in front of the host vehicle within the detection range of the car-mounted sensor and it can detect its relative position. First, a virtual road boundary estimation method is proposed based on measurement of the relative position of the lead vehicle and the lead vehicle status obtained by the car-to-car communication method. A steering-assist control method is then proposed using the estimated virtual road boundary information. Finally, the effectiveness of the proposed steering-assist control method is demonstrated by simulation results.**

I. INTRODUCTION

Several types of driver assistance systems have been successfully developed for reducing driver workload, such as Adaptive Cruise Control (ACC) and Lane-Keeping Assist System (LKAS). Such systems are mainly effective on roads with a relatively large curve radius. Drivers must operate the steering wheel even with the current ACC. LKAS manages the vehicle position within the lane when the road curvature is not very large.

Many research studies have been conducted on steering-assist control methods and driver-assistance systems for lateral control. As a lane-keeping control, a steering torque control law has been proposed [1] [2]. In recent years, many research studies have been conducted on haptic guidance systems for lateral control including curve negotiation [3][4][5]. The main focus of these studies is on the natural interaction between the driver and the assistance system through haptic feedback to keep the driver in the control loop, rather than on automatic control of curve negotiation. Some research studies have proposed methodologies for autonomous driving, including lateral control for collision avoidance, as a driver-assistance system [6]. More recently, fully automated vehicles have been researched based on environmental recognition methods using external sensors such as LIDARs and cameras [7][8][9]. Such advances in automated vehicle control strongly rely on high-performance environmental recognition. A sensor fusion method is one option for increasing the system robustness.

It may be thought that the vehicle-infrastructure system is another effective candidate, but this is presently available only in limited areas. Therefore, the purpose of this research is to develop a road information acquisition method based on a car-mounted sensor and a car-to-car communication system and to explore its application to an automatic steering-control system. We assume that there is a lead vehicle (LV) in front of the host vehicle (HV), that the HV can measure the LV's relative motion by a car-mounted sensor, and that car-to-car (C2C) communication is available between the LV and the HV.

This paper proposes a road-boundary estimation method based on measuring the relative position of the LV and the LV status obtained by the car-to-car communication method. Please note that this method should be used to complement the environmental recognition by a car-mounted sensor in acquiring road-boundary information. In addition, a steering-assist control method for curved roads is proposed. This system judges the necessity of the assist control by detecting the delay in the driver's steering in the curve using the estimated road information and the driver's steering operation model. The effectiveness of the proposed methods are demonstrated by the experiment results obtained using a micro-electric vehicle.

II. AUTOMATIC STEERING-CONTROL METHOD

A. Overview

Assume that there is a lead vehicle in front of the host vehicle within a certain distance so that the HV can measure the relative position of the LV using a car-mounted sensor such as a LIDAR. In addition, assume that the HV and the LV have C2C communication.

The proposed steering-assist control consists of two parts: generating a virtual road boundary and steering-assist control (see Fig. 1).

1) Generation of virtual road boundary

The relative position of the LV, or $\boldsymbol{r}_L$, can be obtained directly from the sensor mounted on the HV. In addition, we assume that the velocity of the two wheels of the LV (V_{WL} , V_{WR}) is obtained by C2C communication and updated at a certain sampling frequency. Based on these variables, the virtual road boundary is generated and stored in the HV's

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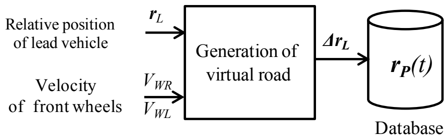
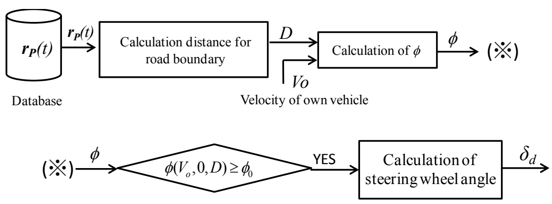
database. In addition, the curve radius is estimated at each road position using the variables above.

2) Steering-assist control

The assist control is designed so that the HV drives along the virtual road generated by the algorithm above whenever the system determines that the assist control is needed. Its necessity is judged based on a calculation involving the distance between the HV and the virtual road boundary and the HV's current velocity. The appropriateness of the steering assist is judged using a driver steering model developed in the present study. If the system judges that the manual steering operation is not sufficient to negotiate the curve, the system calculates the desired steering wheel position.



(a) Generation of virtual road using LV data



(b) Steering-control method

Fig. 1 Overview of steering-assist control

B. Generation of virtual road information

(1) Generation of virtual road boundary

Consider a discrete-time system with sampling time Δt. Let Σ_i be a coordinate system attached to the HV at time t_i (Fig. 2). Its origin is at the HV's center-of-mass (COM). The y-axis coincides with the heading direction, and the x-axis is directed to the right. Vector ${}^i\boldsymbol{r}_L(t_i)$ is the relative position of the LV seen from the HV at time t_i. This is measured by a sensor mounted on the HV as seen in Fig. 2. Note that superscript i on the left side represents a vector that is seen from Σ_i. The displacement of the LV from time t_i, and t_{i+1} is given by Eq. (1).

$$ {}^i\Delta \boldsymbol{r}_L \triangleq {}^i\boldsymbol{r}_L(t_{i+1}) - {}^i\boldsymbol{r}_L(t_i) = {}^iT_{i+1}\,{}^{i+1}\boldsymbol{r}_L(t_{i+1}) - {}^i\boldsymbol{r}_L(t_i) \tag{1} $$

where ${}^iT_{i+1}$ denotes the homogeneous transformation matrix from Σ_{i+1} to Σ_i. Note that ${}^iT_{i+1}$ can be derived easily using the HV's displacement and yaw at times t_i and t_{i+1}.

Assuming that the road boundary at time t_i is known as ${}^i\boldsymbol{r}_p(t_i)$, ${}^i\boldsymbol{r}_p(t_{i+1})$ is calculated by Eq. (2).

$$ {}^i\boldsymbol{r}_p(t_{i+1}) = {}^i\boldsymbol{r}_p(t_i) + {}^i\Delta \boldsymbol{r}_L \tag{2} $$

The virtual road boundary is generated by iterating calculation of Eq. (2) from the initial time t_0. The virtual road boundary could drift, but any such drift is corrected in 500ms using the position of a line marker as measured by external sensors such as a camera or laser sensor.

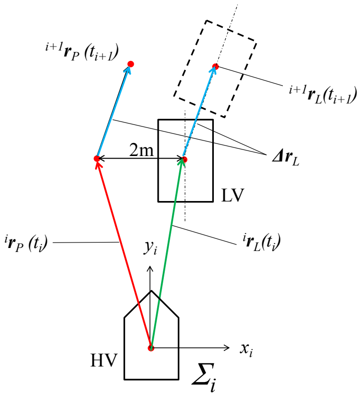


Fig. 2 Relative position of LV and virtual road boundary

(2) Estimating road curvature

The curvature radius can be estimated using the velocity of the two front wheels of the LV, V_{out} and V_{in}, based on kinematics, by assuming LV's steady state cornering as Eq. (3). The curvature radius of the road is calculated by Eq. (3). Equation (3) calculates the curvature radius of a road R_e using the tread of the vehicle d_L and V_{in}, V_{out}.

$$ R_e(t_i) = \frac{d_L(V_{out}(t_i) + V_{in}(t))}{2(V_{out}(t_i) - V_{in}(t_i))} \tag{3} $$

Here, $R_e(t_i)$ denotes the estimated curvature radius, and d_L denotes the tread of the LV.

(3) Estimating the host vehicle position

The vehicle yaw-rate γ can be given by Eq. (4).

$$ \gamma = \gamma_{wh} - \gamma_{sl} \tag{4} $$

Here, γ_{wh} denotes the yaw rate calculated from the difference in front tire velocity given by Eq. (5).

$$ \gamma_{wh} = \frac{V_{out} - V_{in}}{T_L \cos\delta} \tag{5} $$

In addition, γ_{sl} denotes the yaw rate calculated from the slip angle of the front tire β_f given by Eq. (6) [10].

$$ \gamma_{sl} = \frac{1}{1 + AV^2}\frac{V}{l}\beta_f \tag{6} $$

Here, V denotes the host vehicle's velocity, and l denotes the wheel base. Scalar A denotes the stability factor of the vehicle [10].

In addition, β_f, the slip angle of the front tires, is calcu lated by Eq. (7).

$$ \beta_f = \beta + \frac{l_f\gamma}{V} - \delta \tag{7} $$

where β denotes the sideslip angle of the vehicle, and l_f denotes the distance between the body center of the vehicle and the front tire axis. Scalar δ denotes the steering angle. The sideslip angle of the vehicle is given by Eq. (8)

$$\beta = \frac{1 - \frac{ml_f}{2ll_r K_r} V^2}{1 + AV^2} \frac{l_r}{l} \delta \qquad (8)$$

where l_r denotes the distance between the vehicle body center and the rear-tire axis. The yaw rate of the vehicle γ can be calculated using Eq. (4) by substituting Eqs. (5) through (8).

The HV's yaw angle is obtained by integrating the yaw rate γ as in Eq. (9).

$$\theta_{yaw} = \int_0^t \gamma(\tau) d\tau \qquad (9)$$

The HV's position is obtained by Eq. (10).

$$\begin{bmatrix} X \\ Y \end{bmatrix} = V \int_0^t \begin{bmatrix} \cos\theta_{yaw}(\tau) \\ \sin\theta_{yaw}(\tau) \end{bmatrix} d\tau \qquad (10)$$

C. Steering-control method

(1) Detecting steering delay in a curve

The proposed system measures the distance D between the HV and the road boundary P_D along the vehicle direction as indicated in Fig. 3. Note that this calculation can be performed easily by homogenous transformation if all estimated road boundary positions are expressed in the Σ_i-coordinate system. The estimated curvature radius R_e corresponding to point P_D is obtained. Note that the points are defined discretely. Thus, the estimated radius of the nearest point is used as R_e at an arbitrary point on the road boundary.

We assume that the HV drives appropriately without any delay in the center of the lane, and that its direction coincides with that of the tangent of the road as indicated in A in Fig. 5. This is called the appropriate state. B represents the situation in which the HV is directed further to the outside than the tangential direction. C represents the situation in which the HV is located in the outer portion of the lane. B and C can be regarded as delayed. The distance D_a between the HV and the road boundary in the vehicle direction in A is given by Eq. (11).

$$D_a = D_a(R_e(t_i)) = \sqrt{R_e(t_i)^2 - (R_e(t_i) - L)^2} \qquad (11)$$

Here, L denotes the length of a half of the lane. In a delayed situation, such as B and C, Eq. (12) is satisfied, and this is used for steering control.

$$D < D_a \qquad (12)$$

D_a is called the appropriate distance for the road boundary.

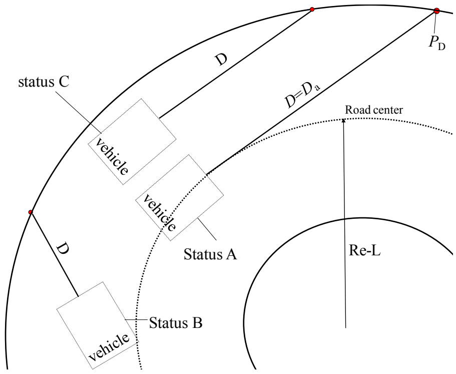


Fig. 3 Definition of appropriate distance for road boundary

(2) Judging the activation of steering control

Let us consider a method for judging the necessity of steering assist based on the driver steering model. Wada et al. successfully modeled the braking timing of drivers based on the drivers' perceptual risk index. A driver's braking timing can be expressed by Eq. (13) [11].

$$\phi(V_r, V_p, D) \equiv 10\log_{10}(|\alpha V_p - V_r|) + \beta \log_{10} D + \gamma = 0 \qquad (13)$$

Here, V_r is the relative velocity of the LV and the HV, and D is the gap between the two vehicles. V_p denotes the velocity of the LV.

The function ϕ is called the risk index because larger values of ϕ denote riskier situations.

Let us consider applying this index to determine the initiation timing of a driver's steering when entering a curve. We assume that point P_D on the road boundary plays the same role as the LV in the car-following situation. Thus, the distance D between the HV and point P_D can also be used in the risk index. In addition, the velocity of P_D is zero. The risk index for steering timing can then be written as Eq. (14).

$$\phi(V_o, 0, D) = 10\log_{10}(|V_o|) + \beta \log_{10} D + \gamma = 0 \qquad (14)$$

where V_o denotes the velocity of the HV.

Experimental verification of the steering model

Steering initiation timing in curves was measured using a fixed-based driving simulator with six participants. The plots in Fig. 4 illustrate the steering initiation timing. The parameters were identified as β= -40.4 and γ= 17.9 using the six participants' results.

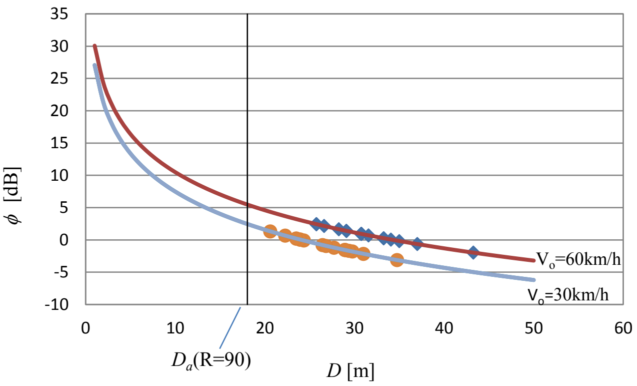


Fig. 4 Distance D when steering is started

The average ϕ at steering initiation is -0.77(SD=1.11) at 30km/h and 0.89 (SD=1.13) at 60km/h. Although there is some variation, steering is started around $\phi = 0$. Thus, ϕ as defined in Eq. (13) is used for determining steering initiation.

Let us consider determining the system's steering activation timing in terms of Eq. (15).

$$\phi(V_o, 0, D) \geq \phi_0 \quad (15)$$

Here, ϕ_o is used as an offset value to account for the individual differences. D_a(R=90m) = 17.7m in Fig.4 represents the appropriate distance. Note that the activation timing in Eq. (15) works when $D > D_a$ upon entering the curve.

(3) Calculating the desired steering angle

Substituting D, the distance between the vehicle and the road boundary along the vehicle direction, into Eq. (12) and solving this by R_e yields the curve radius ρ in Eq. (16), whose appropriate distance from the road boundary is given by D.

$$\rho = D_a^{-1}(D) = \frac{D^2 + L^2}{2L} - L \quad (16)$$

The desired steering wheel angle δ_d for driving along the radius given by Eq. (16) is calculated by Eq. (17).

$$\delta_d = KN(1 + A_O V_O^2)\frac{l_O}{\rho} \quad (17)$$

Here, N denotes the steering gear ratio, V_O denotes the HV's velocity, and l_o denotes its wheelbase. A_O denotes the HV's stability factor. The gain K is defined as Eq. (18).

$$K = \begin{cases} \dfrac{D(t) - D_a(\rho_{in})}{D(t_{str}) - D_a(\rho_{in})} & (t_{str} \leq t < t_{in}) \\ 1 & (t_{in} \leq t < t_{rv}) \\ \dfrac{d(t)}{d(t_{rv})} & (t_{rv} \leq t < t_{out}) \end{cases} \quad (18)$$

where t_{str} denotes the time that steering assist activates. t_{in} denotes the times at the curve entrance, and t_{out} denotes that at the curve exit (Fig. 5). t_{rv} denotes the time when the heading of the HV and a line segment AB at the curve exit begin to intersect. At this time, steering reversal will begin for the curve exit. $D_a(\rho_{in})$ denotes the appropriate distance from the road boundary at t_{str}, where ρ_{in} denotes the curvature radius at the boundary. Scalar $d(t)$ denotes the distance between the vehicle and the line segment AB along the vehicle's heading at time t. This gain suppresses a rapid increase in the steering angle. In straight road, another lane keeping control is activated when $t > t_{out}$.

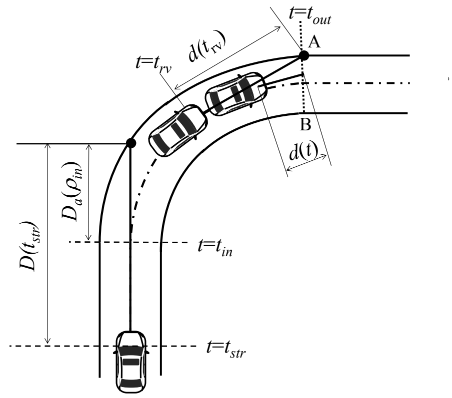


Fig. 5 Parameters defining gain K

III. EXPERIMENTS

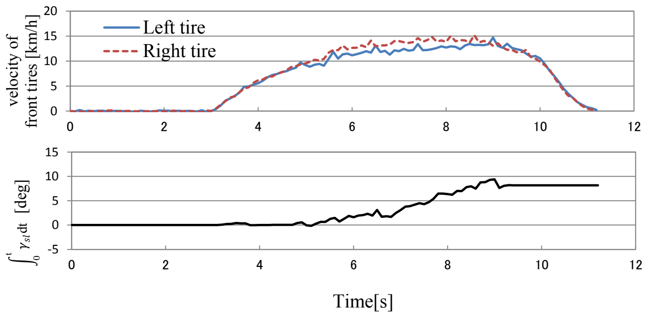
A. *Experiment for estimating HV's position*

The effectiveness of the proposed estimation method for the HV's yaw rate and the resultant vehicle position in Eq. (4) and (10) was investigated using a micro-electric vehicle called COMS (Toyota Auto Body), whose specifications are given in Table 1. The velocity of the two front tires (V_{WL}, V_{WR}) was measured by optical-encoder sensors. The steering wheel angle was measured by a potentiometer attached to the steering shaft.

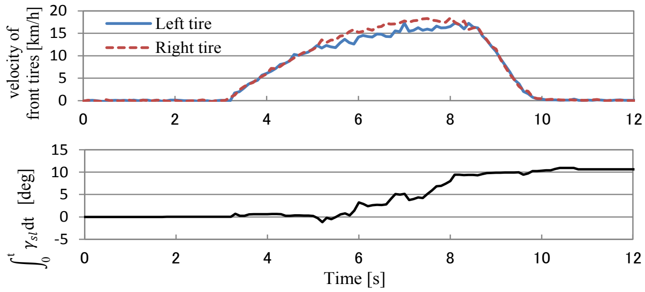
Figure 6 plots the time history velocity of both front tires and the slip angle estimated by integrating Eq. (6). Figure 7 compares the measured trajectory of the vehicle and those provided by estimation methods. The measured trajectory was obtained by attaching a stick of chalk to the center of mass of the vehicle to draw its trajectory on the road, then measuring it manually using a tape measure. The solid line denotes the estimated trajectory using the proposed method with correction by Eq. (6); the dashed line, which is drawn without correction, denotes the case in which γ_{sl} is set to 0. The estimated trajectory with correction was found to agree with the measured trajectory much better than that without correction. The maximum error was 0.17m at 10km/h and 0.13m at 15km/h.

Table 1. Experiment vehicle parameters

M	400[kg]	Vehicle mass
r	0.23[m]	Vehicle tire radius
l_f	0.68[m]	Distance from the center of gravity to front axle
l_r	0.60[m]	Distance from the center of gravity to a rear axle
T_L	0.84[m]	Distance of a right-and-left ring
k_f	30000[N/rad]	Cornering force of a front wheel
k_r	30000[N/rad]	Cornering force of a rear wheel
L	1.28 [m]	Distance of a front-and-near wheel

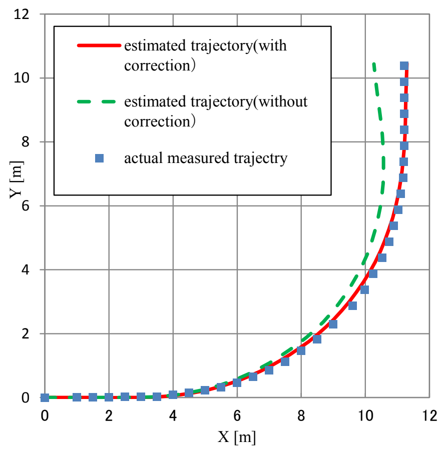


a)10km/h

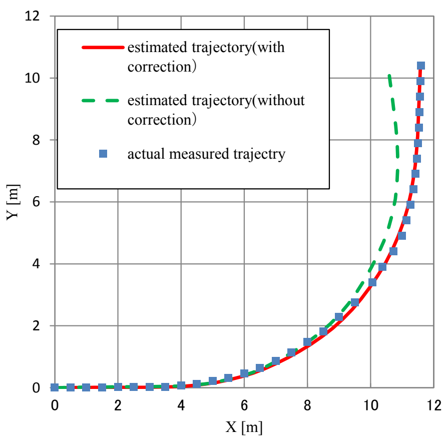


b) 15km/h

Fig. 6 Time history of front-tire velocity and estimated slip angle



a) 10km/h



b) 15km/h

Fig. 7 Estimated trajectories

B. *Verifying the proposed steering-assist control*

Experiment overview

The proposed steering-assist system was installed in the experiment vehicle. In the current version, we assume that the lead vehicle's data was obtained in advance as seen in Fig. 8. The lead vehicle's trajectory and the velocity of both front tires were generated by Carsim (MSC Corp.) by driving on a curve with a 20m radius at 20km/h. A virtual road boundary was then generated using data based on the method in Section II-B. After Eq. (15) with ϕ_0=0 was satisfied, the steering-assist control was activated. The desired steering angle was calculated based on the distance between the HV and the virtual road boundary using the method in Section II-C. The sampling time was set to Δt=0.10s. Finally, the steering wheel angle was controlled by a 200W AC servomotor attached to the steering shaft. The driving velocity was 3 to 5km/h. The experiment vehicle's trajectory was measured by attaching a piece of chalk below its center-of-mass to draw its trajectory on the road.

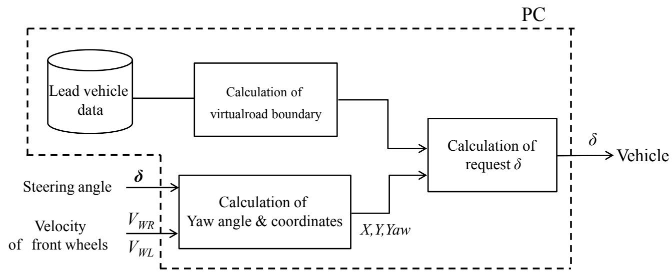


Fig. 8 Experimental system configuration

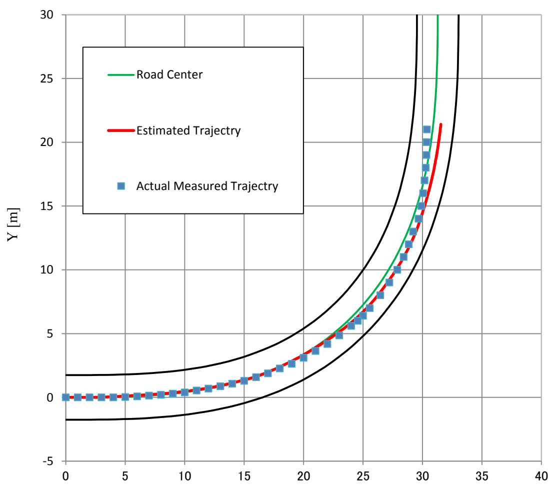


Fig. 9 Trajectory of experiment vehicle

Results

Figure 9 compares the measured trajectory of the vehicle and the estimated one. The solid red line denotes the trajectory estimated using the proposed method, dots denote the measured trajectory based on the chalk drawing, and the solid green line denotes the road center. The measured trajectory agreed well with the road center using our proposed control method. The maximum difference between the experiment vehicle's trajectory and the road center was 0.6m at the center of the curve.

Figure 10 presents the time history of various vehicle states when driving at 6km/h. When $\phi \geq 0$ was satisfied, calculation of the desired steering wheel angle was started. D was controlled around $D_a(\rho = 20\text{m})$=8.18m during the curve.

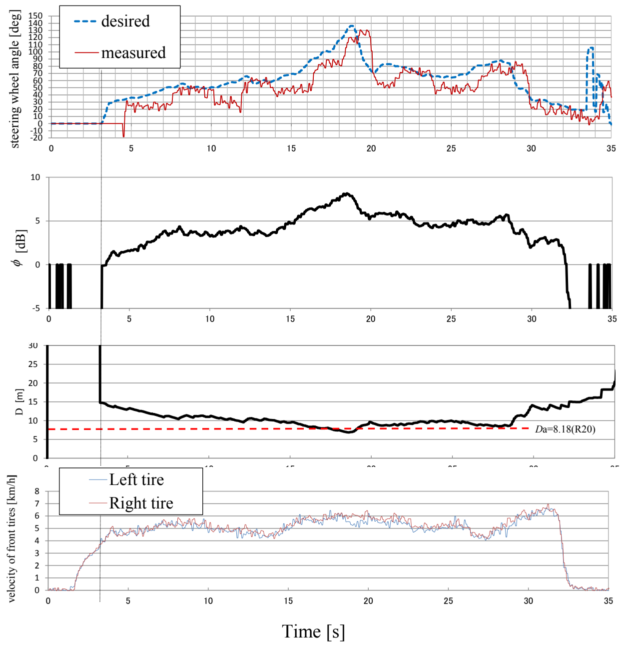


Fig. 10 Time history with various vehicle states

IV. CONCLUSION

A method for generating road boundary information was proposed by combining measurement results of the relative position of the lead vehicle by a car-mounted sensor and the lead vehicle status by C2C communication, as a method complementing the environmental recognition by a car-mounted sensor. A steering-assist control method for curve negotiation was proposed. This method judges the necessity of steering assist by detecting delays in the driver's steering in a curve, using estimated road information and the driver steering model. The experiment results demonstrate that the road-boundary information was accurately generated by taking into account the slip angle of the LV's tires, which is estimated based on their velocity information. A method for judging the activation of steering control was derived based on the driver steering model, which was also first derived in the present paper. Finally, experiments using a micro-electric vehicle demonstrated that the proposed control method enables the vehicle to remain close to the road center at relatively low velocity.

Note that the virtual road estimation method is based on dead reckoning, thus drift can occur. Drift should be removed by lane marker detection and other techniques. As for further studies, experiments in the high-velocity range should be conducted. In addition, experiments using C2C systems will be important in the future because the current study assumed that the lead vehicle's information could be obtained perfectly with no delay.

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