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A Longitudinal Control Algorithm for Smart Cruise Control with Virtual Parameters

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ABSTRACT
This paper presents a longitudinal control algorithm for a smart cruise control with virtual parameters in multiple transitions by a driver and traffic conditions. The object is to achieve driver's comfort and smooth transition with collision prevention for safety in various driving situations. The proposed algorithm consists of an in-path target selection, a generation of virtual parameters, and longitudinal controller for smart cruise control. The in-path target selection algorithm selects an important target which moves on the driving direction of subject vehicle. In addition, it provides the information in order to drive a subject vehicle smoothly and improve safety in various traffic transitions. Finally, smart cruise control controller with virtual parameters computes the desired acceleration. In order to reduce effects of discontinuous changes caused by traffic conditions or drivers such as time gap, set speed, and automation switching, the virtual parameters are applied to longitudinal control algorithm for smart cruise control. The performance and safety benefits of the proposed smart cruise control system are investigated via simulations using real vehicle driving data.
Keywords: *Smart cruise control, Virtual parameter, Time gap, Set speed, In-path target*

I. INTRODUCTION

A Driver assistance and active safety technologies have been extensively researched and there have been many developments. For instance, smart cruise control is a common and well known automotive driver assistance system. By using a Radar sensor, it can automatically adjust speed with maintaining a safe headway distance between vehicles in the same lane. These systems use a simple strategy which decides target vehicle as the closest one currently in subject's lane. However, feedback discontinuities are induced when the subject vehicle or a preceding vehicle moves laterally. For example, a cut-in of a second preceding vehicle results in sudden increase of deceleration level. A simple solution for guaranteeing continuous control input would be filtering the output such as a rate limiting control input. However this method has not have to possible disadvantages, such that the deceleration does not have to correspond with actual hazard level or the driver's expectancies, even though contradictory clues could be given to the driver. In addition, when a preceding vehicle appears in front of control vehicle during the smart cruise control driving condition, vehicle is necessary to follow distance control with a desired distance. In this case the desired distance may be either chosen as a constant or based on time headway.

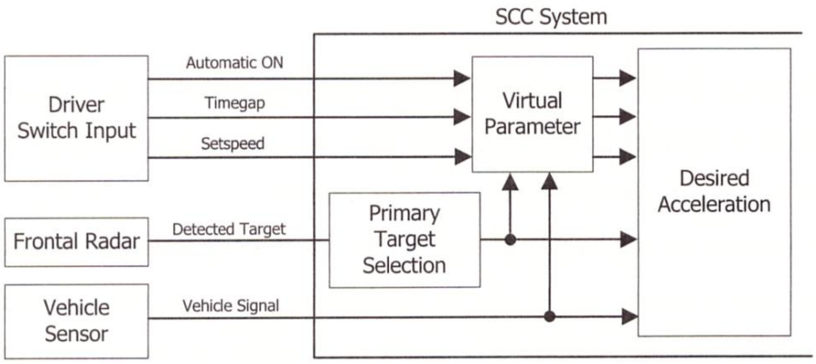


Fig. 1. Smart cruise control system with virtual parameter.

When it is assumed in many papers that the desired velocity and/or the desired time headway is given a prior, a driver may change v_{des}, $T_{h,des}$ arbitrarily in the automatic control mode, respectively. If the desired value is directly fed into the longitudinal controller for smart cruise control, the degradation of performance may occur in a transient period due to its discontinuity. In the worst case of scenario, the actuator may be saturated, thus the system may fail to follow either v_{des} or $T_{h,des}$. In order to minimize the performance degradation due to discrete jump of desired value or change of traffic condition, the longitudinal control algorithm for smart control algorithm for smart cruise control with virtual parameters was proposed. The proposed method reduces degradation of performance in the transient period and to prevent saturation of actuating right after a discrete switching. The overall performance of the proposed controller has been investigated via simulations using experimental data collected from test vehicle in real road.

II. MAIN

2.1 In-path target selection

To select an in-path target, it is necessary to estimate the driving direction of the subject vehicle. In this study, the driving direction is expressed by the curve radius in Fig.2. In addition, the curve radius is calculated by using a yaw-rate and a velocity of the subject vehicle.

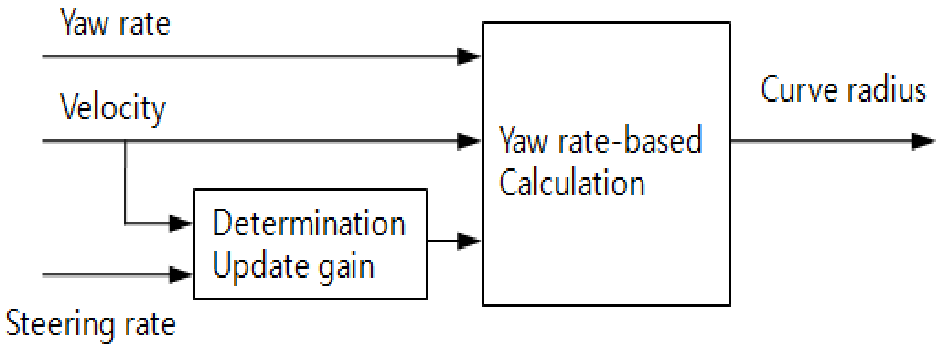


Fig. 2. Estimation of driving direction based on curve radius

To process a yaw-rate signal, the random-walk Kalman filter was introduced as shown in equation (1). According to a steering-angle rate and velocity, process noise, Q, is determined. Thus, an updated Kalman gain is determined depending on the steering-angle rate and velocity of the subject vehicle.

$$\gamma_{k+1} = \gamma_k + W_k \qquad w_k \sim N(0,Q) \qquad (1)$$

$$z_k = x_k + v_k \qquad v_k \sim N(0,R)$$

$$\gamma_{k+1} = \gamma_k + K\,(z_k - \gamma_k)$$

K: constant Kalman gain(Q,R)

When γ_k is the yaw-rate, z_k is the measurement, w_k is the process noise with zero mean and associated covariance R, and v_k is the measure noise with zero mean and associated covariance R.

The in-path target is defined as the closest vehicle detected in the subject vehicle's driving area. The previous vehicle determination in the same lane as the subject is on the basis of a road curvature and positions of the neighboring vehicles. As shown in Fig.3, the in-path target means that a position of the previous vehicle is inside of the shaded area computed with the driving area of the subject vehicle, this target is regarded as the in-path target. As shown in equation (2), $\hat{\rho}$ is the radius of the curved road, which can be estimated by the yaw-rate signal $\hat{\gamma}$, and the velocity of the subject vehicle v_s.

$$\hat{\rho} = \frac{v_s}{\hat{\gamma}_k} \qquad (2)$$

For each neighboring vehicle, the lateral deviation for driving direction of the subject vehicle P_{offset} , is obtained as following equations.

$$dist = \sqrt{(p_{lat} - \hat{\rho})^2 + (p_{long})^2} \qquad (3)$$

$$p_{offet} = dist - |\hat{\rho}|$$

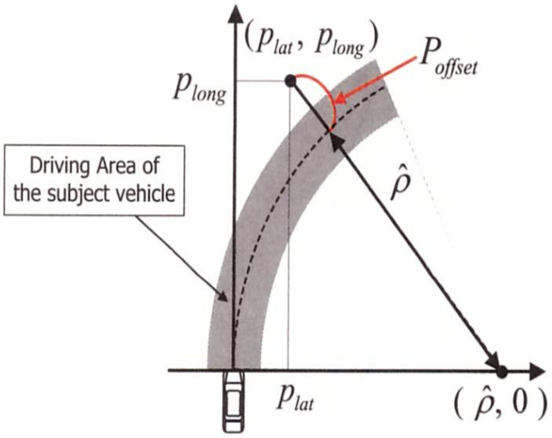


Fig. 3. In-path area reflected the driving direction of the subject vehicle.

Where P_{long} and P_{lat} are the relative longitudinal and lateral distance of each neighboring vehicle, respectively.

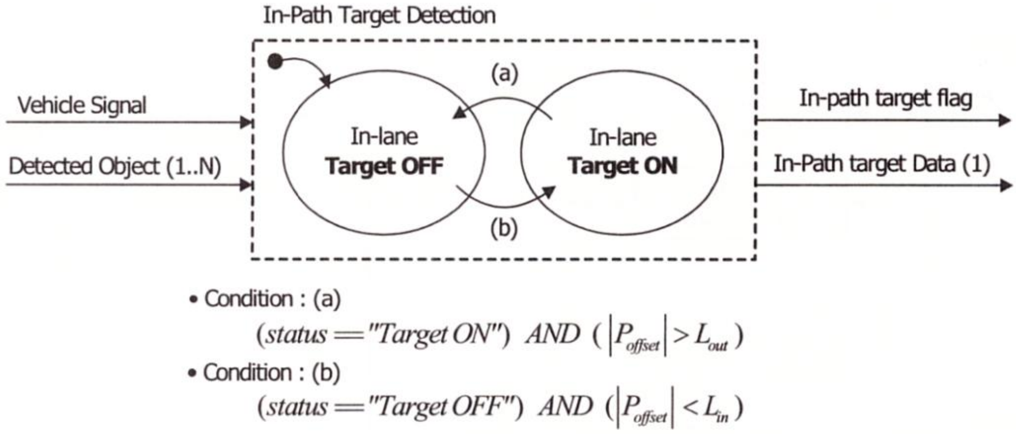


Fig. 4. Determination of an in-path target.

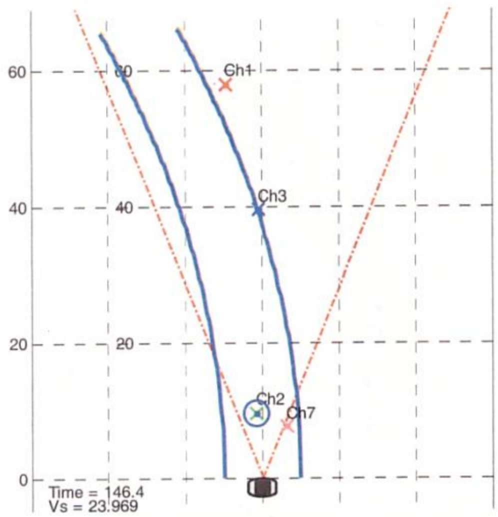


Fig. 5. Result of in-path target selection.

Fig.5 shows the simulation result of in-path target selection. The object of channel 2 was selected to the smart cruise control target. The in-path target is represented "target on" or "target off" as shown in Fig.4. In order to prevent frequent changing of in-path target, a different threshold value is applied to determine the in-path target. When the status of target-off changes to the status of target-on, the threshold L_{in} is applied.

2.2 Virtual parameters

In this study, two virtual parameter, virtual time gap and virtual set speed are introduced. When a driver changes either set speed or time gap manually, a discrete jump of the desired value might occur. In addition, if a driver switches from manual to automatic driving, there is a difference between current value and the desired value in vehicle-to-vehicle distance. Moreover, when the subject vehicle or a preceding vehicle moves laterally, there is a gap between current value and the desired value in vehicle-to-vehicle distance. It is represented the scheme of virtual parameter as shown in Fig. 6. In Fig. 6, τ_{des} , V_{des} are desired time gap and desired set speed by the human driver. $\bar{\tau}(t)$, $\bar{v}(t)$ are the virtual parameters of the time gap and the set speed. When a transition is occur such as a switching from manual to automation and a change of parameters, the virtual parameter changes from $\bar{\tau}(t_0)$, $\bar{v}(t_0)$ to $\bar{\tau}(t)$, $\bar{v}(t)$ respectively.

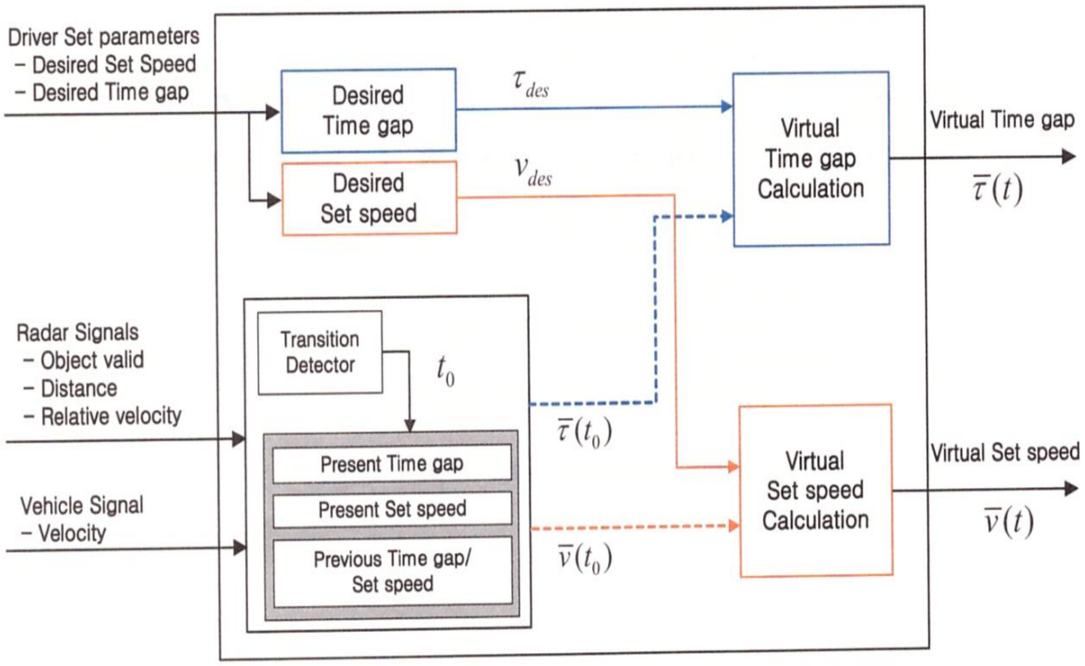


Fig. 6. Scheme of a virtual parameter.

In order to reduce the discontinuities mentioned above, it is necessary to calculate the virtual time gap and virtual set speed. If the new desired time gap is chosen as $\tau_{des(new)}$ or an operating mode is switched from manual to automatic as shown in Fig. 7(a), (b), the virtual time gap is defined as

(i) $\bar{\tau}(t_0) < \tau_{des}$

$$\bar{\tau}(t) = \begin{cases} \bar{\tau}(t_0) + T(t - t_0) & \text{if } \bar{\tau} < \tau_{des} \\ \tau_{des(new)} & \text{otherwise} \end{cases}$$

(ii) $\bar{\tau}(t_0) > \tau_{des}$

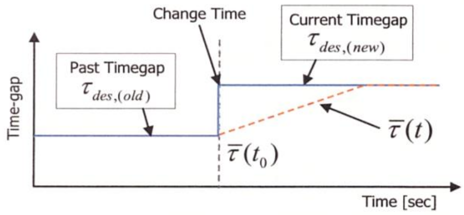
$$\bar{\tau}(t) = \begin{cases} \bar{\tau}(t_0) - T(t - t_0) & \text{if } \bar{\tau} > \tau_{des} \\ \tau_{des(new)} & \text{otherwise} \end{cases} \qquad (4)$$

$\bar{\tau}(t_0) = \tau_{des(old)}$ (changing the desired value)

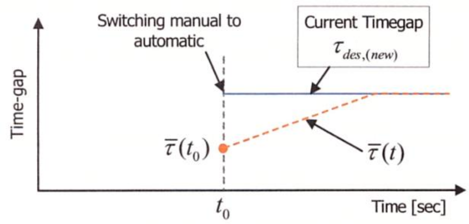
$\bar{\tau}(t_0) = \tau_{current}$ (switches from manual to automatic)

t_0= switching or changing time

where t_0 is the initial time right after the desired values is changed or operating mode is switched from manual to automatic driving. Then this value is applied to calculate the desired clearance in equation (7)



(a) In case of changing time gap value



(b) In case of switching manual to automatic driving

Fig. 7. Operation of a virtual time gap

Similarly, if the desired set speed is changed by a driver or an operating mode is switched from manual to automatic as shown in Fig. 8(a), (b), the virtual set speed is derived as

(i) $\overline{v}(t_0) < v_{des}$

$$\overline{v}(t) = \begin{cases} \overline{v}(t_0) + T(t - t_0) & \text{if } \overline{v} < v_{des} \\ v_{des(new)} & \text{otherwise} \end{cases}$$

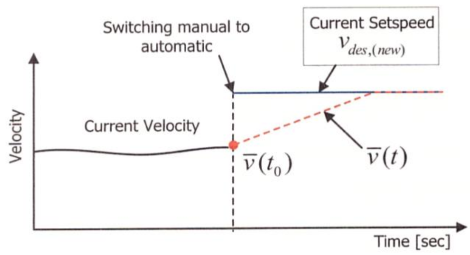
(ii) $\overline{v}(t_0) > v_{des}$

$$\overline{v}(t) = \begin{cases} \overline{v}(t_0) - T(t - t_0) & \text{if } \overline{v} > v_{des} \\ v_{des(new)} & \text{otherwise} \end{cases} \quad (5)$$

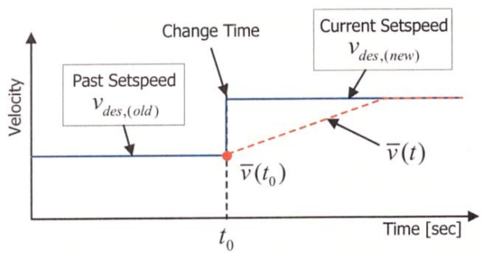
$\overline{v}(t_0) = \tau_{des(old)}$ (changing the desired value)

$\overline{v}(t_0) = \tau_{current}$ (switches from manual to automatic)

v_0= switching or changing time



(a) In case of switching manual to automatic driving



(b) In case of changing set speed value

Fig. 8. Operation of a virtual set speed.

2.3. longitudinal control for smart cruise control

Since the smart cruise control system is controlled by a relative velocity and distance to the target vehicle, the information of in-path target and driver's parameter such as a time gap and set speed are indispensable. As high level controller of the smart cruise controller determines the desired acceleration in general. In safe driving, the smart cruise controller generates command for smooth naturalistic vehicle's behavior similar to normal driving of a human driver. In dangerous situation or in unexpected events, the smart cruise control controller generates large deceleration command to maintain safe range of vehicle-to-vehicle. A low level controller manipulates the throttle-brake actuators such that the vehicle acceleration tracks the desired acceleration. The throttle-brake control algorithm is based on the reverse dynamics. Basically, linear optimal control theory has been used to design the desired acceleration in normal preceding vehicle following situation. By applying integrators to model the vehicles, a state space model for the controlled and preceding vehicles can be written as follows:

$$\dot{x} = Ax + Bu + \Gamma w = \begin{bmatrix} 0 & -1 \\ 0 & 0 \end{bmatrix} x + \begin{bmatrix} 0 \\ -1 \end{bmatrix} u + \begin{bmatrix} \tau \\ 1 \end{bmatrix} w \qquad (6)$$

Where τ is the linear coefficient, i.e., time gap, and the defined states are

$x^T = [x_1 \ - \ x_2] = [c_d - c \ \ v_t - v_s]$, input u is the controlled vehicle acceleration and disturbance, w is the preceding vehicle acceleration. c_d and c are desired clearance and actual clearance between the preceding and controlled vehicles and v indicates velocity. Subscripts t and s indicate the preceding and the subject vehicles, respectively. The gains for the state feedback law, $u = -kx$ are chosen to minimize the cost function.

$$J = \int_0^x (x^T Q\,x + u^T R u)\,dt = \int_0^\infty \left\{ x^T \begin{bmatrix} q_1 & 0 \\ 0 & q_2 \end{bmatrix} + u^T r u \right\} dt \qquad (7)$$

The weighting factors q_1 , q_2 , r have been chosen to achieve naturalistic behavior of the controlled vehicle that would feel natural to the human driver in normal driving situation. In this study, alterative weighting factors have been used for low, medium and high speed ranges. Therefore, desired acceleration is represented by

$$a_{des} = -k_1(v_s)(c_d - c) - k_2(v_s)(v_t - v_s) \qquad (8)$$

The control gains, k_1 and k_2 have been obtained by tuning the weighting matrices Q and R. In this study, the desired clearance defined by equation (9) has been used.

$$c_d = c_0 + \tau_{vir,time\,gap}\, v_t \qquad (9)$$

where c_0 is the minimum clearance, and $\tau_{vir,time\,gap}$ is the virtual time gap,. Where there is no primary target, set speed control is applied. In this case, the desired acceleration is defined as follows:

$$a_{des}(t) = \ -k_3(v_{vir,set} - v_s \qquad (10)$$

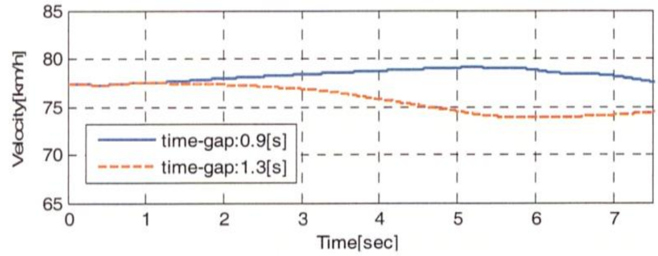
where k_3 is control gain of setspeed and $v_{vir,set}$ is the virtual setspeed.

2.4. Simulation results

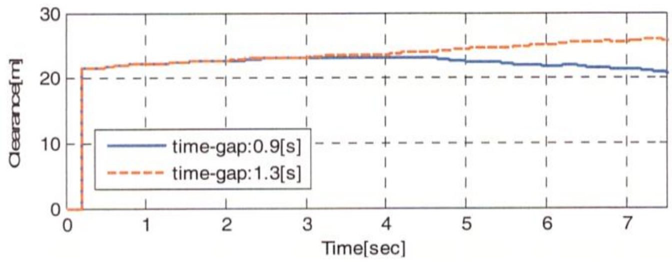
The smart cruise control algorithm with virtual parameters has been tested via simulations using real road driving data. With the speed of the simulated subject vehicle being controlled by the smart cruise control system with virtual parameters in a close-loop simulation, the raw data of vehicles has been manipulated with observer algorithm hence fed into simulation. To overcome this problem, the raw data was transformed to a global frame reference prior to the simulation and calculate measurements between surrounding vehicles and the subject vehicle as the simulation progress.

2.4.1 Transition by driver: Switching from manual to automatic driving

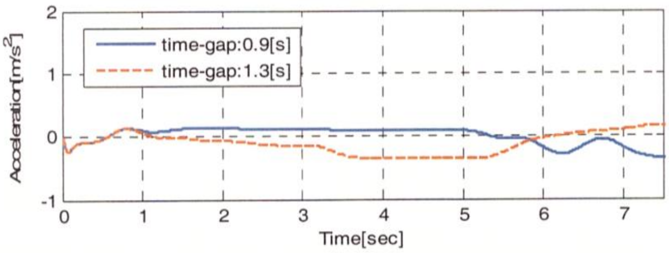
While a driver is maintaining the specified distance with the preceding vehicle which is corresponds to time gap 0.9, manual driving is switched to automatic driving at 0.5 (sec). The case that the desired time gap is 1.3, the current time gap is needed to change from 0.9 to 1.3 that shows smooth transition with virtual parameter as shown in Fig. 9.



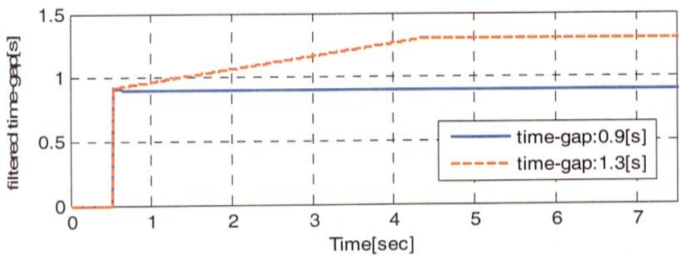
(a) velocity



(b) clearance



(c) acceleration

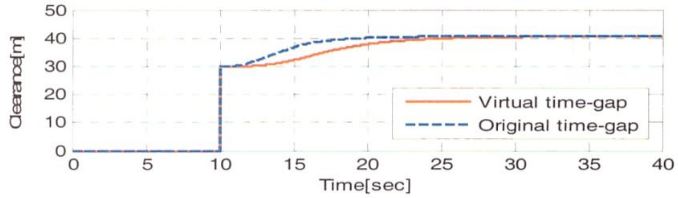


(d) virtual time gap

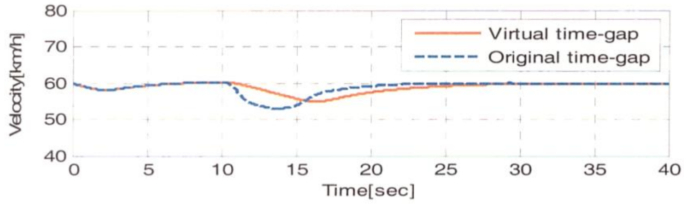
Fig. 9. Simulation results for switching from manual to automatic driving.

2.4.2 Traffic-Transition: A Cut-in Situation

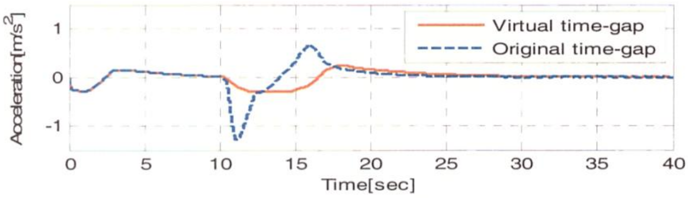
Fig. 10 shows a comparison between smart cruise control with an original desired time gap and smart cruise control with a virtual time gap. The initial vehicle velocity is 60 km/h and a cut-in vehicle, at a velocity of 60 km/h, appears in front of the subject vehicle after a time-lapse of 10 seconds. The initial clearance between the subject and cut-in vehicles is about 30 meters. A time gap of 2.0 seconds and 5m of minimum clearance are used in the cut-in simulations. The vehicle velocities, clearances, and accelerations are compared in Fig. 10 (a), (b), (c) respectively. When the in-path target is detected, there is a difference between the current time gap and desired time gap as shown in Fig. 10. The virtual parameter enables the current time gap to increase the desired time gap smoothly. Thus, it can be shown that the acceleration command of smart cruise control with the virtual parameter is smoother than that of smart cruise control with the original parameters in case of traffic condition change.



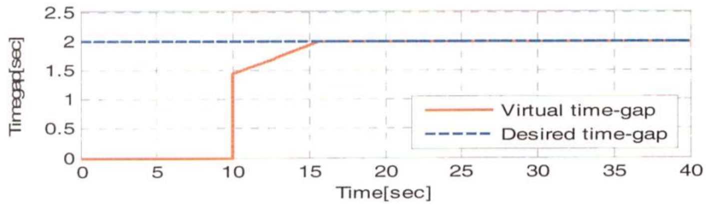
(a) clearance



(b) velocity



(c) acceleration



(d) time gap

Fig. 10. Simulation results for a normal cut-in.

III. CONCLUSION

A longitudinal control algorithm for smart cruise control with the virtual parameters has been presented. The proposed control algorithm consists of an in-path target detection, a generation of virtual parameters, and the longitudinal controller for smart cruise control. The in-path target selection algorithm selects a primary target which drives on the driving direction of the subject vehicle. In addition, it provides the information in order to drive a subject vehicle smoothly and to improve safety in various traffic transitions. Finally, the smart cruise control system with virtual parameters computes the desired acceleration. The overall performance of the proposed control system has been investigated via close loop simulations. The test scenarios such as cut-in and an automation switching are used. It has been shown that the proposed control strategy can provide a smooth transition in various transitions of a driver and traffic conditions. This algorithm has only been tested by the simulation. It will be applied to real vehicle with smart cruise control and the trade-off relationship of comfort and performance will be studied in next research.

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