Design and Evaluation of an Integrated Vehicle Safety System for Longitudinal Safety and Lateral Stability

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ABSTRACT

This paper describes the design and evaluation of an integrated control strategy for longitudinal safety and lateral stability. The objective of the integrated control strategy is to optimally coordinate independent brake inputs for longitudinal collision-safety and lateral stability in various driving situations such as lane change with braking and circular turning with braking, etc. The proposed integrated vehicle safety system is applied to the vehicle equipped with Smart Cruise Control (SCC)/Collision Avoidance (CA) and Vehicle Stability Control (VSC). The proposed control system consists of a supervisor, control algorithms, and a coordinator. The proposed system has three control modes which are normal driving, integrated safety I, and integrated safety II. According to the corresponding control mode, the longitudinal and lateral control algorithms calculate the desired motion of the subject vehicle. Based on the desired longitudinal force and the desired yaw moment, the coordinator determines the throttle angle and the brake pressures by using optimal distribution. Closed-loop simulations with the driver-vehicle-controller system are conducted to investigate the performance of the proposed integrated vehicle safety system. Finally, the proposed control system was also implemented in a sport utility vehicle and tested in several driving situations.

INTRODUCTION

To improve handling performance and active safety of vehicles, a considerable number of active control systems for vehicle lateral dynamics and longitudinal collision-safety have been developed and utilized commercially over the last two decades. For example, Vehicle Stability Control (VSC), Adaptive Cruise Control (ACC), Stop-and-Go (SG), Lane Keeping Support (LKS), Collision Warning and Collision Avoidance (CW/CA), assisted lane change and automated parking assist have been extensively researched and there has been many development since the 1990's [1-6]. These systems are believed to reduce the risk of accidents, improve safety, and enhance comfort and performance for drivers. These advanced driver assistance and active safety systems open new possibilities in accident prevention [7-9]. With the introduction of these systems, there is the possibility for creating synergies, but also a risk of introducing conflicts. For example, since the ACC/Collision Mitigation Brake (CMB)/CA and VSC systems share the brake, an independent integration of the ACC/CMB/CA and VSC system may result in unexpected behavior of the controlled vehicle and even worse dynamic behavior compared to an uncontrolled vehicle case. Moreover, to obtain both lateral stability and safe clearance to avoid rear-end collisions in severe driving situations, coordinated control of the actuators is necessary.

To solve this problem, this study presents the integrated control strategy with obtaining the ACC/CMB/CA and VSC functions in severe driving situation such as lane change with braking, circular turning with braking. The integrated control algorithm consists of four steps, i.e, a supervisor, control algorithms, decision, and a coordinator. The supervisor determines desired vehicle motions such as a desired yaw rate to improve vehicle lateral stability and a desired longitudinal acceleration to avoid rear-end collisions. The control algorithm calculated a desired yaw moment and longitudinal force to track the desired yaw rate and the longitudinal acceleration, respectively. The decision determines control modes which are normal driving, integrated safety I, and integrated safety II based on a longitudinal and lateral index to illustrate the danger of collision and lateral sliding in the current driving situation. From the control algorithm and the decision, the coordinator distributes brake inputs of each wheel optimally based on the current status of the subject vehicle. Fig. 1 shows the integrated vehicle safety control system scheme.

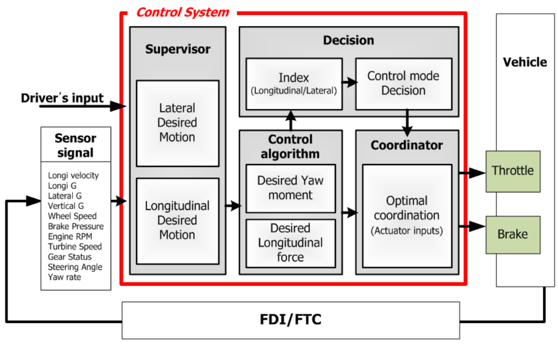


Fig. 1 Integrated vehicle safety system scheme.

The performance of the proposed control system has been evaluated via both simulations and vehicle test. The vehicle tests for a driver-vehicle-controller system have been conducted to prove the improved performance of the proposed control system over individual control systems such as ESC and SCC/CA.

SUPERVISOR

A task of the supervisor is to determine desired vehicle motions such as a desired yaw rate and a desired longitudinal acceleration.

The desired longitudinal acceleration is determined based on the SCC system with a severe braking system. It calculates the desired longitudinal acceleration to improve drivers' comfort during normal, safe-driving situations and to completely avoid rear- end collision in vehicle following situations. As shown in Fig. 2, a relationship between a subject vehicle and the target vehicle can be expressed as following state equation:

$$\begin{aligned}\dot{x} &= Ax + Bu + Gw \\ &= \begin{bmatrix} 0 & -1 \\ 0 & 0 \end{bmatrix} x + \begin{bmatrix} 0 \\ -1 \end{bmatrix} u + \begin{bmatrix} \tau \\ 1 \end{bmatrix} w\end{aligned} \tag{1}$$

where, τ is the linear coefficient, i.e., time gap. The states are x^T=[x_1, x_2]=[$3c_d$-c v_t- v_s], the input, u, is the desired longitudinal acceleration and the disturbance, w, is the target vehicle acceleration. c_d and c are the desired range clearance and actual clearance between the target and subject vehicles and v indicates velocity.

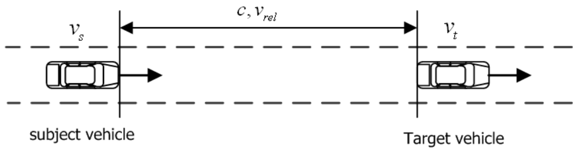


Fig. 2 Relationship between the subject vehicle and the target vehicle.

From (1), the desired longitudinal acceleration considering a ride quality, a driving characteristic of the driver and collision avoidance is determined using a linear quadratic optimal problem.

$$a_* = -k_1(v_s)\cdot(c_d - c) - k_2(v_s)\cdot(v_t - v_s)$$
$$a_{des} = \begin{cases} a_{upper}(v_s) & if \quad a_* > a_{upper}(v_s) \\ a_* & if \quad a_{\min}(v_s) \le a_* \le a_{\max}(v_s) \\ a_{lower}(v_c) & if \quad a_* < a_{lower}(v_s) \end{cases} \tag{2}$$

A detailed description about the desired longitudinal acceleration is provided in the previous research [10].

The desired yaw rate to improve vehicle lateral stability is determined to satisfy maneuverability for steering intention of a driver and lateral stability for a side slip angle. From this goal, the desired yaw rate can be theoretically determined by using the 2-D bicycle model with a linear tire model. Fig. 3 shows the 2-D bicycle model including direct yaw moment:

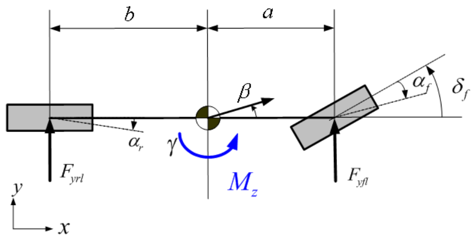


Fig. 3 Bicycle model including direct yaw moment.

From Fig. 3, the dynamic equation can be presented as follows:

$$\begin{bmatrix}\dot{\beta}\\ \dot{\gamma}\end{bmatrix}=\begin{bmatrix}\dfrac{-2(C_f+C_r)}{mV_x} & \dfrac{2(-l_fC_f+l_rC_r)}{mV_x^{2}}-1\\ \dfrac{2(-l_fC_f+l_rC_r)}{I_Z} & \dfrac{-2(l_f^{2}C_f+l_r^{2}C_r)}{I_ZV_x}\end{bmatrix}\begin{bmatrix}\beta\\ \gamma\end{bmatrix}+\begin{bmatrix}\dfrac{2C_f}{mV_x}\\ \dfrac{2l_fC_f}{I_Z}\end{bmatrix}\delta_f+\begin{bmatrix}0\\ \dfrac{1}{I_Z}\end{bmatrix}M_z \tag{3}$$

where, C_f and C_r represent the cornering stiffness at front and rear side, respectively. l_f and l_r are the distance between the CG and front/rear axle. I_z is a moment of inertia about z-axis. The steady state yaw rate of the bicycle model is introduced and the maneuverability of a vehicle is considered to reflect the driver's intention, which is expressed as a function of the vehicle longitudinal velocity and driver's steering input as follows [11]:

$$\gamma_{ref\_yaw}=\frac{1}{1-\dfrac{m(l_fC_f-l_rC_r)v_x^{2}}{2C_fC_r(l_f+l_r)^{2}}}\frac{v_x}{l_f+l_r}\delta \tag{4}$$

Moreover, excessive body sideslip of a vehicle makes the yaw motion of a vehicle insensitive to driver's steer input and threatens the lateral stability. As the sideslip angle of a vehicle increases, the stabilizing yaw moment due to the steer input decreases, and thus, the lateral behavior of a vehicle becomes unstable. Therefore, the other desired yaw rate to maintain body sideslip angle in reasonably small range is required. In this case, the desired yaw rate is determined as follows [7]:

$$\gamma_{ref\_lateral}=K_2\beta+\frac{2F_{yf}\cos\delta+2F_{yr}}{mv_x} \tag{5}$$

Two different reference yaw rates are combined into a single desired yaw rate properly depending on the driving situations as follows:

$$r_d=\sigma_1 r_{ref\_yaw}+\sigma_2 r_{ref\_lateral} \tag{6}$$

A detailed description about the desired yaw rate is provided in the previous research [7].

CONTROL ALGORITHM

Control algorithm calculates a desired longitudinal force and a desired yaw moment to track the desired longitudinal acceleration and desired yaw rate, respectively. Based on the desired longitudinal acceleration from (2), the desired longitudinal force is obtained as follows:

$$F_{x,des}=m\cdot(a_{des}+K_pe_a+K_i\int e_a dt) \quad \text{where, } e_a=a_{des}-a \tag{7}$$

The main goal of the desired yaw moment is to make the actual yaw rate to follow the target yaw rate which is defined from (6). To determine the desired yaw moment, a 2-D bicycle model described in Fig. 3 was used. From (3), the dynamic equation about the yaw rate including the direct yaw moment is presented as follows:

$$\dot{\gamma}=\frac{2(-l_fC_f+l_rC_r)}{I_z}\beta+\frac{-2(l_f^{2}C_f+l_r^{2}C_r)}{I_zv_s}\gamma+\frac{2l_fC_f}{I_z}\delta_f+\frac{1}{I_z}M_z \tag{8}$$

The sliding mode control method is also used to determine the desired yaw moment. The sliding surface and the sliding condition are defined as follows:

$$s_2=\gamma-\gamma_{des}, \qquad \frac{1}{2}\frac{d}{dt}s_2^{2}=s_2\dot{s}_2\le-\eta_2\left|s_2\right| \tag{9}$$

where, η_2 is a positive constant, The equivalent control input that would achieve $\dot{s}_2=0$ is calculated as follows:

$$M_{z,eq}=-I_z\left(\frac{2(-l_f\hat{C}_f+l_r\hat{C}_r)}{I_z}\beta-\frac{2(l_f^{2}\hat{C}_f+l_r^{2}\hat{C}_r)}{I_zv_s}\gamma+\frac{2l_f\hat{C}_f}{I_z}\delta_f\right) \tag{10}$$

Finally, the desired yaw moment for satisfying the sliding condition regardless of the model uncertainty is determined as follows:

$$M_{z,des}=M_{z,eq}-K_2\cdot sat\left(\frac{\gamma-\gamma_{des}}{\Phi_2}\right) \tag{11}$$

where, the K_2 is a sliding gain which satisfies the sliding condition.

The automatic driving and collision safety are achieved by the longitudinal force and the lateral stability is ensured by the yaw moment control.

DECISION

A task of the decision is to determine the control mode based on the index-plane using longitudinal and lateral indexes. The index-plane consists of a normal driving mode, an integrated safety mode I, and an integrated safety mode II. In order to determine the control mode, it is necessary to monitor the reference indexes related with a lateral stability and the collision danger between the subject vehicle and the target vehicle. Fig. 4 shows the index-plane proposed in this paper. If the longitudinal index (lateral index) exceeds unit, the danger of collision (unstable lateral motion) is high. The object of proposed control system is to satisfy both longitudinal safety and lateral stability. However, since both the desired longitudinal force and the desired yaw moment always cannot be satisfied, one of the two control systems should be given off by the control mode. As shown in the Fig. 4, in the case of the integrated safety I mode, the longitudinal safety control to avoid rear end collision has control priority. In contrast, in the case of the integrated safety II mode, the lateral stability control to improve vehicle lateral motion has control priority.

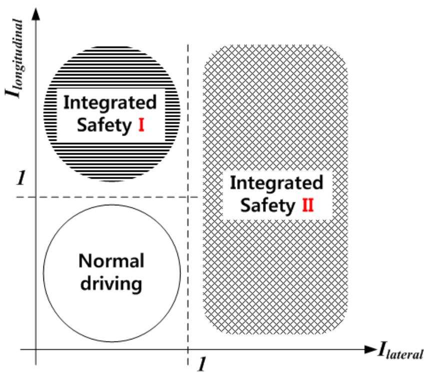


Fig. 4 Control modes in the index-plane.

The longitudinal index to monitor the vehicle-to -vehicle collision can be determined by using a warning index and an inverse TTC which are developed in previous research [2, 3]. The warning index represents the danger of physical collision in the current driving situation. The inverse TTC (TTC^{-1}) which is visual effect for the collision is a well-known parameter in CW/CA systems. The functional equation for the warning index and the inverse TTC is provided in the previous research []. In the case of the warning index beyond a threshold value and the inverse TCC below a threshold value, it indicates that the current driving situation is in a safety region. Otherwise, the current driving situation can be dangerous. Therefore, the longitudinal index is determined using manual driving data for vehicle following. As shown in Fig. 5, the inputs are the warning index and the inverse TTC, and the output is the longitudinal index.

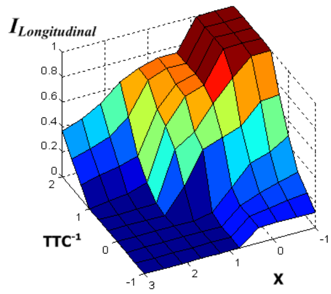


Fig. 5 Longitudinal index of a collision-danger.

The lateral index can be determined by using the desired yaw moment from (11).

$$I_{lateral} = \frac{|M_{z,des}|}{M_{z,th}} \tag{12}$$

Where, $M_{Z,th}$ is threshold value.

COORDINATOR

Based on the desired longitudinal force and the desired yaw moment, the coordinator manipulates a throttle and brake. There are three coordination methods by the control mode. Fig. 6 shows the coordination scheme.

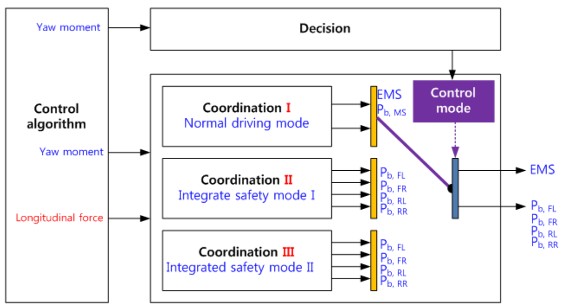


Fig. 6 Coordination scheme

As shown in the Fig. 6, the coordinator calculates the throttle and brake pressures of each wheel based on the coordination methods. In the case of the normal driving mode, since the current driving situation is neither rear-end collision nor unstable vehicle lateral motion, both throttle and brake inputs are determined by coordination I. However in the case of the integrated safety mode I and II, since the current driving situation is rear-end collision or unstable vehicle lateral motion, only brake inputs of each wheel are determined by coordination II or III.

Coordination I

In the case of the normal driving mode, the throttle and brake inputs are determined by the coordination I method. The control principle of the throttle actuator is based on reverse dynamics. Depending on the desired longitudinal force, the coordination I applies throttle or not. If the desired engine torque is larger than a minimum engine torque generated with the closed throttle, the throttle control is necessary. Switching logic with a boundary layer is necessary to avoid frequent switching between throttle control or not. The throttle angle is computed from the desired engine torque using an engine map and a torque-converter map [10].

$$\begin{aligned} &\alpha = EM^{-1}(\omega_e, T_{net,des}) \\ &\quad where,\ \ T_{net,des} = T_p(\omega_e, \omega_t) + K_e(\omega_{e,des} - \omega_e) \end{aligned} \tag{13}$$

where T_p and $T_{net,\ des}$ are the pump torque and the desired net engine torque. ω_e, $\omega_{e,des}$ and ω_t are the engine speed, the desired engine speed and the turbine speed, respectively. EM indicates the engine map. From (13), the throttle angle which is suitable for the acceleration situation from the control algorithm is determined.

The brake pressure is applied when the desired longitudinal force by the control algorithm is negative value. Since the brake torque is proportional to the brake pressure, the desired brake pressure can be obtained by the equation:

$$P_{b,\,i} = \frac{r}{K_b} F_{x,des},\ \ i = FL,\ FR,\ RL,\ RR \tag{14}$$

where, K_b and r are the lumped gain for the entire brake system and radius of wheel, respectively. Since the brake value in the normal driving mode is small, the differential distribution effect for the given braking force is very insignificant in the vehicle lateral motion. Therefore the coordination I do not consider the differential braking.

Coordination II

If the longitudinal index exceeds unit and the lateral index below unit, only brake inputs of each wheel to avoid the rear-end collision are determined by the coordination II. Since the lateral index below unit, the differential braking for vehicle lateral stability is not need. However if the differential distribution for the given brake force is available, the maneuverability of the vehicle will be improved. Therefore, the coordination II determines the brake pressures of each wheel using an optimal algorithm to improve the maneuverability of the vehicle. Due to the danger of rear-end collision, the longitudinal control should have control priority, i.e. the sum of the brake forces of each wheel should be same the desired longitudinal force. For this purpose, in the case of the positive desired yaw moment, the optimal problem for the brake forces of each wheel can be stated as follows:

Minimize:

$$J = \begin{pmatrix} -\frac{t}{2}\left(F_{x,Pb\_FL} - F_{x,Pb\_FR}\right) \\ -\frac{t}{2}\left(F_{x,Pb\_RL} - F_{x,Pb\_RR}\right) - M_{Z,des} \end{pmatrix}^2 \tag{15-a}$$

Subject to:

$$\begin{aligned} &f(x) = \sum_{i=FL}^{RR} F_{x,Pb\_i} - F_{x,des} = 0 \\ &g_1(x) = F_{x,Pb\_FR} \le 0 \\ &g_2(x) = F_{x,Pb\_RR} \le 0 \end{aligned} \tag{15-b}$$

where, F_{x,Pb_FL}, F_{x,Pb_FR}, F_{x,Pb_RL}, and F_{x,Pb_RR} are the brake control inputs of the front-left, front-right, rear-left, and rear-right wheels, respectively.

The cost function of the proposed optimal coordination is the difference between the desired yaw moment and the sum of the generated yaw moment by tire longitudinal forces. This cost function means that since both the desired longitudinal force and the desired yaw moment always cannot be satisfied, the longitudinal control should have a control priority. The tires forces have to satisfy the following constraints: i) the sum of the generated longitudinal forces of each wheel should be equal to the desired longitudinal force, ii) the braking forces as the control input should have a negative value.

Coordination III

If the lateral index exceeds unit regardless of the longitudinal index, only differential brake inputs of each wheel to improve vehicle lateral stability are determined by the coordination III. However, if there is a danger of the rear-end collision, the differential brake inputs considering the collision should be determined by the coordination III. Therefore, in the case of the positive desired yaw moment, the optimal problem for the brake forces of each wheel can be stated as follows:

Minimize:

$$J = \left(\sum_{i=FL}^{RR} F_{x,Pb\_i} - F_{x,des} \right)^2 \tag{16-a}$$

Subject to:

$$f(x) = -\frac{t}{2}\left(F_{x,Pb\_FL} - F_{x,Pb\_FR}\right) - \frac{t}{2}\left(F_{x,Pb\_RL} - F_{x,Pb\_RR}\right) - M_{Z,des} = 0 \tag{16-b}$$

$$g_1(x) = F_{x,Pb\_FR} \leq 0$$

$$g_2(x) = F_{x,Pb\_RR} \leq 0$$

To calculate the control inputs which satisfy the proposed optimal process in (15) and (16), Hamiltonian is defined. Based on first order necessary conditions for the Hamiltonian, six equations with six unknown values can be derived.

EVUALATION

The response of the vehicle with the integrated vehicle safety system was evaluated in simulation. To prove the improved performance of the proposed integrated vehicle safety system, a conventional safety system consisting ESC and SCC/CA systems was used. In the conventional system, the lateral stability control has a control priority than the longitudinal safety control, i.e., if there are both rear-end collision danger and unstable lateral motion of the vehicle in the current driving situation, only the lateral stability control system without the longitudinal safety control system should be operated by the conventional system.

Computer simulations were conducted using vehicle simulation software, CarSim, and Matlab/Simulink. Simulations for a lanechange maneuver and a circular turning maneuver have been conducted.

Lanechange Maneuver

In this test, while following a target vehicle which is driving on a dry road, a single lane change maneuver has been conducted by a sudden deceleration of the target vehicle. Because of the lane change maneuver, the target vehicle is changed to another vehicle which is driving with low speed. This situation needs longitudinal safety control by the changing target vehicle and the lateral stability control by the sudden lane change maneuver simultaneously. Fig. 7 shows the test scenario.

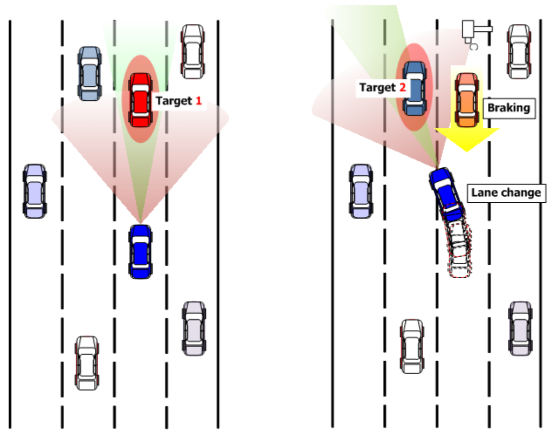
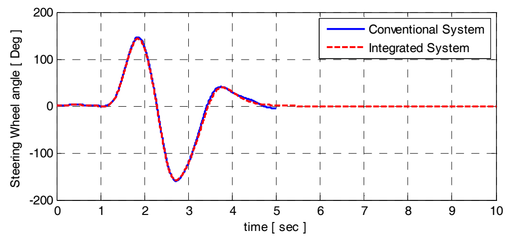
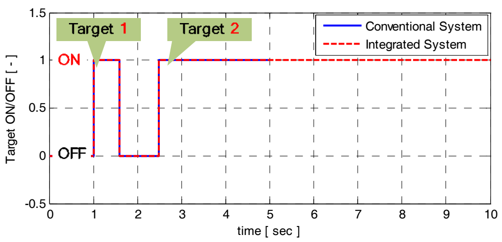


Fig. 7 Test scenario for a single lane change

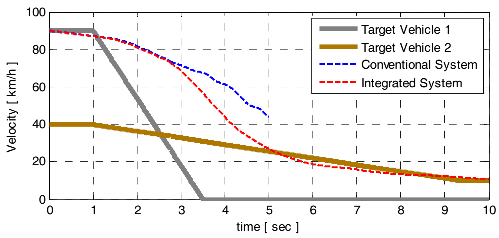
In this simulation, wheel steering angle is determined by a driver steering model [12]. Fig. 8-(a) -(f) show the steering wheel angle, target on/off, vehicle speed profile for the target vehicles and subject vehicle, yaw rate error, and braking pressure which is control input at the front left tire, respectively. As shown in Fig 8-(a) and (b), the target vehicle was changed to another vehicle by the driver's steering angle. From Fig. 8-(e), it is shown that both the integrated system and the conventional system provide good performance with respect to vehicle lateral stability. However, since, to improve vehicle lateral stability, the conventional system gives up a longitudinal safety control, the rear-end collision occurred at 5 sec. This result can be shown from Fig. 8-(d).



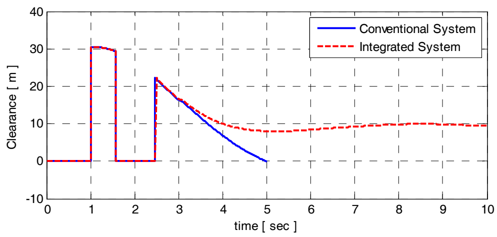
(a) Steering wheel angle



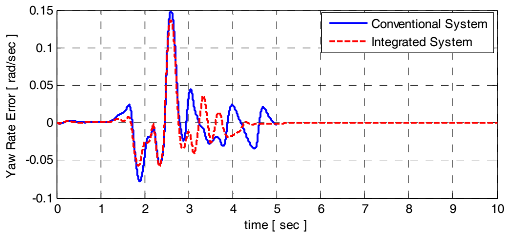
(b) Target On/OFF



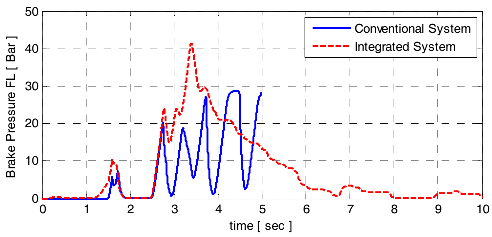
(c) Velocity profile



(d) Clearance



(e) Yaw rate error



(f) Brake pressure Front Left tire

Fig. 8 Simulation results of a lane change with a braking

Circular Turning Maneuver

A circular turning simulation was conducted to evaluate the performance of the integrated system for the improvement of maneuverability. In this simulation, the steering wheel angle is also determined by the driver steering model. The vehicle is simulated on a dry road with 90 km/h to following a target vehicle. While following the target vehicle, the target vehicle starts to decelerate with deceleration level of -5m/sec^2 for cornering. For this situation, braking pressure for the collision avoidance with the target vehicle is applied by the SCC/CA system. Also, the danger of vehicle lateral unstable motion does not exist in this situation. Fig. 9 shows the test scenario.

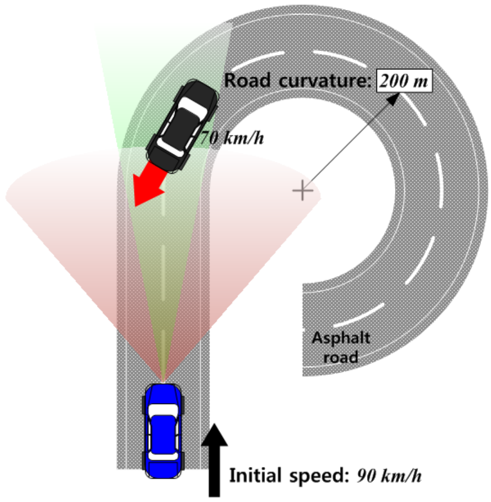
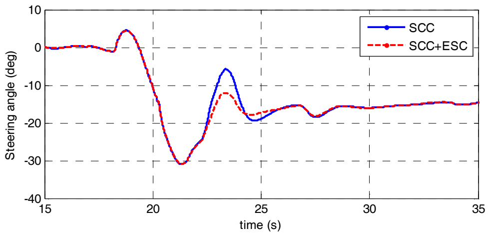
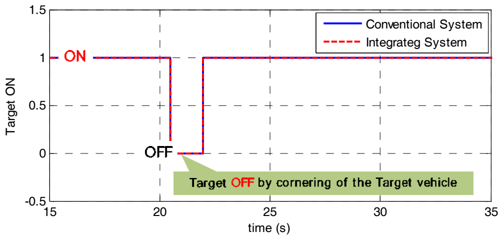


Fig. 9 Test scenario for a circular turning

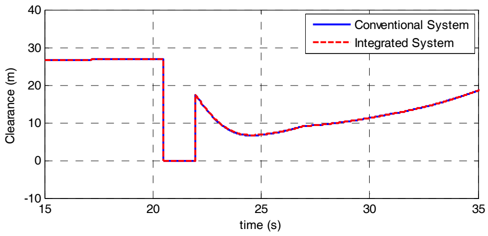
Fig. 10-(a)-(e) show the steering wheel angle, target on/off, yaw rate error, and braking pressure which is control input at the front left tire, respectively. As show in Fig. 10-(b) and (c), a target signal was turned off temporarily by cornering of the target vehicle. While the subject vehicle cornered and neared the target vehicle, a target signal was turned on. Since the scenario needs longitudinal safety control for the collision avoidance without lateral stability control, the conventional system determined a braking pressure considering only the collision avoidance. As shown in the Fig. 10-(c) and (d), both the integrated system and the conventional system provide good performance with respect to vehicle longitudinal safety. However, since, to avoid the rear-end collision, the conventional system gives up a lateral stability control, yaw rate error was increased.



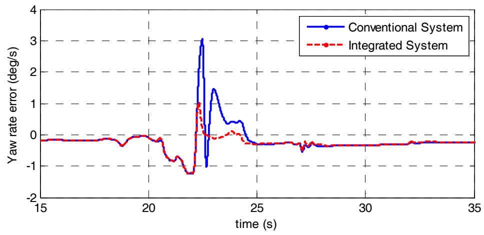
(a) Steering wheel angle



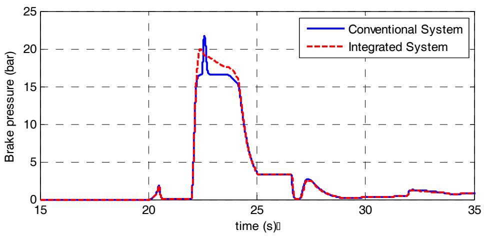
(b) Target On/OFF



(c) Clearance



(d) Yaw rate error



(e) Brake pressure Front Left tire

Fig. 10 Simulation results of a circular turning maneuver

CONCLUSIONS

An integrated vehicle safety control strategy for vehicle longitudinal safety and lateral stability has been proposed. The proposed control strategy is designed to optimally coordinate the brake actuator inputs to obtain both lateral stability and longitudinal safety in various driving situations. Normal driving, integrated safety I, and integrated safety II mode have been defined in the index-based plane. To determine the current control mode, the longitudinal and lateral indices are used. According to the selected control mode, the control algorithms calculate the desired longitudinal force and the desired yaw moment. From the desired longitudinal force and yaw moment, the coordinator determines the throttle angle and the brake pressures by using optimal distribution. The proposed the integrated vehicle safety system has been implemented on a SUV vehicle using a radar sensor, a VSC module and a controller. Simulations have been conducted to investigate the performance of the proposed integrated vehicle safety control system in various driving situations. From the simulation, it has been shown that the proposed system assists the driver in combined severe braking/large steering maneuvering so that the driver can keep maneuverability and prevents the vehicle-to-vehicle collision. Especially the proposed control system improves the vehicle safety in severe driving situations in which both longitudinal and lateral motions are to be controlled simultaneously.

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