Development of a Combined Steering Torque Overlay and Differential Braking Control for Side Crash Prevention

Dongwook Kim, Junyung Lee, Kyongsu Yi
School of Mechanical and Aerospace Engineering, Seoul National University
Seoul, Korea
Mechar04@snu.ac.kr

Abstract— **This paper presents an algorithm for side crash prevention systems using a combined steering torque overlay and differential braking control. This system prevents lane changes when a driver attempts to lane change despite existence of a neighboring vehicle in the blind spot. For this purpose, the system needs some technologies for detecting a vehicle in blind spot, judging driver's lane change intention and controlling a vehicle to avoid side crash. In this paper, we focus on judging driver's intention and controlling a vehicle. The proposed system was evaluated via human driver model-in the loop simulation.**

Keywords-component; Side Crash Prevention; Active Safety System; Risk Monitoring; Integrated Control; Blind spot

I. Introduction

According to a research in USA by NHTSA(2006), lane change caused about 28% of the fatal vehicle accidents[1]. The large number of lane change accidents is due to inattention of the driver. To prevent this type of accidents, a number of systems that provide a prior warning to the driver who attempt to lane change despite of other vehicles in the blind spot by giving auditory or haptic feedback have been developed. However, these systems can not guarantee that a driver excutes the appropriate action to avoid a side crash. Therefore the system that provides active assistance to avoid the side crash is needed and developed widely.

In developing driver support systems, it is important to prevent the system from intervening with the driver in the middle of corrective action because the driver support system requires a cooperative operation between drivers and controllers. To avoid the absence of maneuverability due to the unnecessary intervention against driver's intention, the side crash prevention system is required to determine a driver's intention to distinguish whether the driver wants to change the lane or not. There have been many researches about the driver behavior recognition[2-7]. Hidden Markov Models, driver models and head motion detection modules are used in many previous works. To identify the driver's intention simply using vehicle sensor and vision sensor, the method of recognition of the driver's intention of lane change with steering behavior is proposed in this paper. To recognize the intention of driver with steering behavior, driving data is collected on the road with the test vehicle in the case of lane change and lane keeping separately.

There are so many ongoing studies about the side crash prevention systems. Most of these researches use a steering input as the only variable[1,8,9] and use a DC motor similar to the electrical power steering (EPS) assistance[10]. This approach has difficulties and limits because the steering wheel is controlled by the interaction between drivers and controllers. The steering torque imposed by the driver could be affected as disturbance input to the controller and it can cause the decrease of the control performance. Also, the overlay torque imposed by the controller could make the driver uncomfortable. Thus, the work presented in this paper aims to design a combined control strategy with overlay steering torque and differential braking for side crash prevention. The main objective of this research is to develop a lateral control strategy that prevents a side crash.

The side crash prevention system proposed in this paper was investigated via human driver model-in the loop simulation. The rest of this paper is organized as follows: Section 2 introduce our strategy of side crash prevention. The detection method of lane change intention is introduced in Section 3. Section 4 contains the controller design side crash prevention. The performance and results of simulation are shown in Section 5. Conclusions in Section 6 summarize the most important results and introduce future works.

II. Control Strategy

The control strategy of side crash prevention system is to prevent lane changing when a driver attempts to lane change despite existence of a neighboring vehicle in the blind spot. For this purpose, our algorithm consists of two parts: one that determine time to intervene (Lane Change Intention Decision), and the other that determine the controlled variable for avoiding side crash (SCP Controller). The overall architecture of the proposed side crash prevention system is organized as shown in Figure 1.

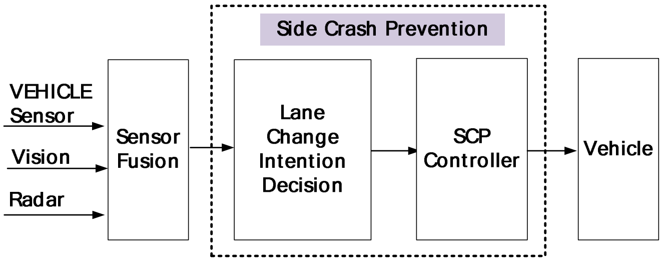


Figure 1. Architecture of the proposed Side Crash Prevention System.

III. LANE CHANGE INTENTION DECISION

In order to make a decision of the time to operate the side crash prevention system, it is needed to determine driver's intention and measure a probability of side crash. The architecture for the lane change intention decision is shown in figure 3.

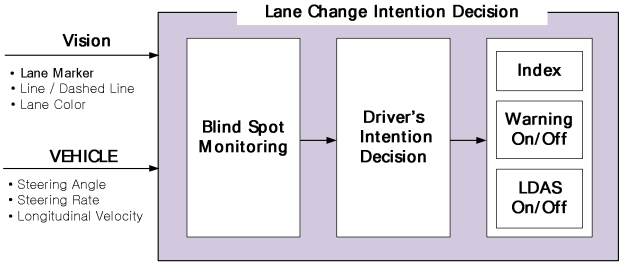


Figure 2. Architecture for the lane change intention decision

A. Blind Spot Monitoring

Blind spots are defined as the areas in adjacent lanes of traffic that are blocked by various structures in the automobile or other indirect areas not visible to the driver. For monitoring this spot, we suppose that side radar is provided. Since radar has relatively high angular uncertainty, the system that considers long range can cause unnecessary interventions. So our system is only operated when blind spot zone is occupied by neighboring vehicles. Blind spot zone is described in figure2.

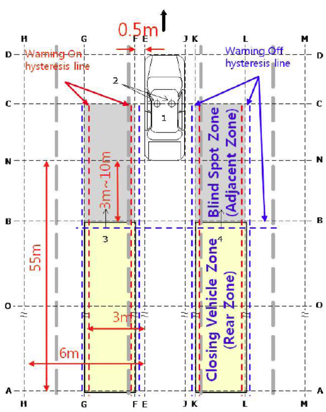
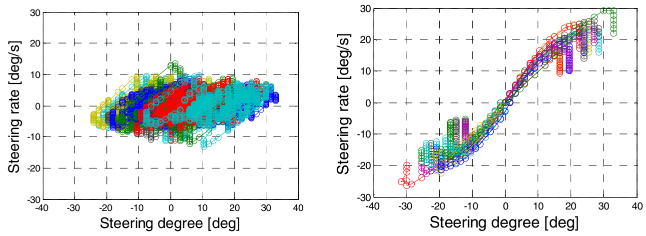


Figure 3. Operation Range of Side Crash Prevention.

B. Driver's Intention Decision

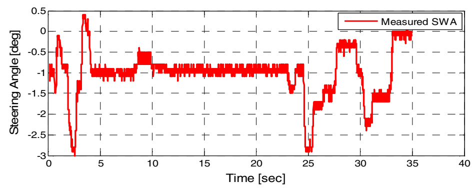
To accomplish an identification of the driver's intention with steering behavior, the driving data of drivers were collected on the real road and test track with a vehicle in which motor driven power steering (MDPS) module is installed. The driving data in the case of lane keeping situation and lane change situation were collected separately. Then the lateral driving characteristics of drivers were analyzed with driving data to compare the lane change situation with the lane keeping situation[11]. Normal driver's steering characteristic in the lane keeping situation is shown in figure. 4-(a) and that in the lane change situation is shown in figure. 4-(b).



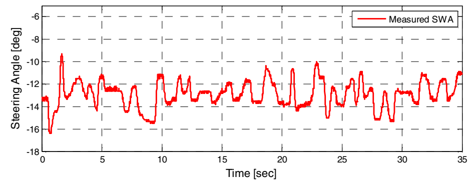
(a) (b)

Figure 4. Driver's Steering Characteristics

As shown in Figure 2, the steering behavior characteristic in lane change situation is different from that in lane keeping situation. When the driver has an intention to change the lane, the steering angle and the steering rate change more rapidly than when the driver has no intention to change the lane. It can be concluded based on the analyzed results that the driver's intention to change the lane can be decided by monitoring a steering behavior. To monitor and determine the intention of the lane change with a steering behavior, the steering behavior index is proposed in [11] and it presents a brief way to recognize the intention. Based on the driver's steering characteristic analyzed above, the index should be defined to reflect a tendency of a steering behavior. Furthermore the intention of driver should be detected regardless of the road shape. To develop the index which accomplishes a high performance regardless of the road shape, the characteristic of the steering behavior on straight road and curved road was analyzed.



(a) Steering Characteristic on straight road



(b) Steering Characteristic on curved road (R = 300 m)

Figure 5. Driver's steering characteristic in lane keeping situation (80kph)

As can be comprehended from a common sense, when the driver has an intention to keep the lane, the steering angle on the straight road is close to zero and that on the curved road is close to some nonzero value as shown in figure. 3. If the curvature of the road can be estimated or provided, the default value of the steering angle for negotiating a circular road can be calculated with a bicycle model. The steady state steering angle δ_{ss} for negotiating a circular road of curvature κ is given as follows(1);

$$\delta_{ss} = \left(l_f + l_r + \frac{mV_x^2 \left(l_r C_{\alpha r} - l_f C_{\alpha f} \right)}{2C_{\alpha f} C_{\alpha r} \cdot \left(l_f + l_r \right)} \right) \cdot V_x \cdot \kappa \tag{1}$$

When the driver has an intention to change the lane, the difference in steering angle between driver's steering angle and the steady state steering angle for negotiating a circular road of curvature κ is evident. The curvature κ is estimated by kalman filter using a yaw rate signal measurement[11].

Based on the above consideration, the steering behavior index to monitor the intention of driver can be defined as follows;

$$\begin{aligned} I_{LC}(k+1) &= \rho \cdot I_{LC}(k) + \left(\delta_k - \delta_{ss} \right) \cdot \dot{\delta}_k \cdot T \qquad (0 < \rho < 1) \\ I_{LC}(k) &= T \cdot \sum_{p=1}^{p=k} \rho^{k-p} \cdot \left(\delta_p - \delta_{ss} \right) \cdot \dot{\delta}_p \end{aligned} \tag{2}$$

where, I_{LC} is the steering behavior index at k-th step and ρ is the forgetting factor and T is the sampling time and δ_k is the steering angle at k-th step. The steering angle rate signal is obtained by kalman filter using a steering angle measurement.

IV. CONTLOLLER DESIGN

When the driver's lane change intention is detected, the vehicle should be controlled to prevent an side crash. In order to avoid an side crash, electrical stability control (ESC) module and MDPS module are used as actuators in this paper. The objective of this research is to develop a lateral control strategy to prevent an side crash.

A. Desired Dynamics

The desired dynamics is to reduce a relative lateral velocity to zero while the vehicle avoid hitting the neighboring vehicle as shown in Eq.(3)

$$V_{y,rel} = v_T \psi_T - v_S \psi_s \;\rightarrow\; 0 \quad while \quad C_y > C_{d,y} \tag{3}$$

where, ε_{lat} is the minimum guarantee of the distance between the ego vehicle and neighboring vehicle.

If the relative lateral velocity is determined as Eq(3), then desired yaw rate is determined as Eq(4).

$$\frac{d}{dt} V_{y,rel} = v_T \dot{\psi}_T - v_S \dot{\psi}_s = -k \cdot V_{y,rel} \tag{4}$$

$$\gamma_{des} = \frac{k}{v_S} V_{y,rel} + \frac{v_T}{v_S} \gamma_T \tag{5}$$

Where υ_T, υ_S are velocities of target vehicle and subject vehicle, and ψ_T, ψ_S are yaw rates of them. In this equation, we suppose that lateral velocity of neighboring vehicle can be ignored. The relative lateral distance which is needed to reduce a relative lateral velocity to zero at that moment can be calculated easily as Eq.(6).

$$C_y(T_1) = C_y(0) + \int_0^{T_1} V_{y,rel}\, dt \tag{6}$$

$$C_y(T_1) = C_y(0) + \int_{V_{r,y}(0)}^{0} -\frac{1}{k} \cdot dV_{y,rel} = C_y(0) + \frac{V_{y,rel}(0)}{k} \tag{7}$$

Since relative later distance (C_y) calculated by Eq (6) satisfy the condition in Eq (3), control gain (k) satisfy the condition in Eq(8).

$$k = -\frac{V_{y,rel}(0)}{C_y(0) - C_d} \cdot k_{safety} \tag{8}$$

The yaw rate should be limited to guarantee a lateral stability of the vehicle while the lane departure avoidance system operates. Therefore the desired yaw rate is limited as follows.

$$\begin{gathered} m \cdot A_y \le \mu \cdot m \cdot g \;\Rightarrow\; m \cdot V_x \cdot \gamma \le \mu \cdot m \cdot g \\ \therefore \gamma_{des} = \begin{cases} \gamma_{des} & if \;\; (\left| \gamma_{des} \right| < \dfrac{\mu \cdot g}{v_x}) \\ \dfrac{\mu \cdot g}{v_x} sign(\gamma_{des}) & elsewhere \end{cases} \end{gathered} \tag{9}$$

Then the sliding mode control method is used to calculated the required yaw moment for tracking the desired yaw rate. The sliding surface is defined as follows;

$$s = \gamma - \gamma_{des} \tag{10}$$

The control objective is to keep the sliding surface at zero. This can be achieved by choosing the control law such that;

$$\frac{1}{2} \cdot \frac{d}{dt} \cdot s^2 = s \cdot \dot{s} = -\eta \cdot |s| \tag{11}$$

where, η is a positive constant. From the bicycle model, the dynamic equation about the yaw rate can be represented as follows;

$$\begin{aligned} \dot{s} = &\frac{2\left(-l_f C_f + l_r C_r \right)}{I_z} \beta + \frac{-2\left(l_f^2 C_f + l_r^2 C_r \right)}{I_z V_x} \gamma \\ &+ \frac{2 l_f C_f}{I_z} \delta_f + \frac{1}{I_z} M_{z,des} - \dot{\gamma}_{LDAS} = -\eta \cdot \mathrm{sgn}(s) \end{aligned} \tag{12}$$

By substituting equation (12) into equation (11), the desired yaw moment can be determined as follows;

$$M_{z,des} = -2\cdot\left(-l_f\cdot C_f + l_r\cdot C_r\right)\cdot\beta - 2\cdot l_f\cdot C_f\cdot\delta_f + \frac{2\left(l_f^2\cdot C_f + l_r^2\cdot C_r\right)}{V_x}\cdot\gamma + I_z\cdot\dot{\gamma}_{LDAS} - I_z\cdot\eta\cdot\mathrm{sgn}(s) \tag{13}$$

To cope with the chattering phenomenon, the saturation function with boundary, Φ, is used to determine the desired yaw moment input as follows;

$$M_{z,des} = -2\cdot\left(-l_f\cdot C_f + l_r\cdot C_r\right)\cdot\beta - 2\cdot l_f\cdot C_f\cdot\delta_f + \frac{2\left(l_f^2\cdot C_f + l_r^2\cdot C_r\right)}{V_x}\cdot\gamma + I_z\cdot\dot{\gamma}_{LDAS} - I_z\cdot\eta\cdot\mathrm{sat}\left(\frac{s}{\Phi}\right) \tag{14}$$

B. Strategic Control Input Distribution

As mentioned above, the torque imposed on the steering wheel by the driver could be affected as a disturbance input to the controller. Therefore, the torque input imposed by the controller could not guarantee the tracking performance of desired steering angle for lane departure avoidance. Hence, ESC module was used to obtain the desired dynamics calculated above for lane departure avoidance and MDPS module was used to overlay the additional torque to induce driver to reduce steering angle in order to avoid a side crash[11]. The architecture of the proposed lane departure avoidance algorithm is shown in figure 6.

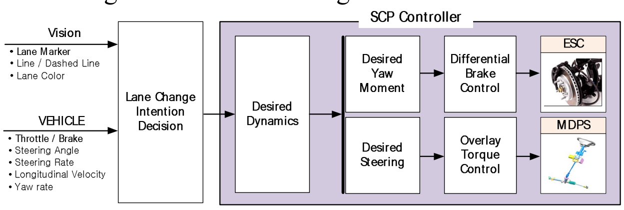


Figure 6. Architecture of Side Crash Prevention controller

The desired yaw moment calculated in above section is a virtual input. It can be made by differential braking. To distribute each tire's braking force to yield the desired yaw moment with a consideration of actuator's control input constraints, the control allocation method was used. The desired yaw moment and actual control inputs are related as follows;

$$\underbrace{M_{z,des}}_{v(t)} = B\cdot\underbrace{\left[\Delta F_{x1}\quad \Delta F_{x2}\quad \Delta F_{x3}\quad \Delta F_{x4}\right]^T}_{u(t)}$$
$$B = \left[l_f\cdot\sin\delta_f - t_f\cdot\cos\delta_f \quad l_f\cdot\sin\delta_f + t_f\cdot\cos\delta_f \quad -t_f \quad t_f\right] \tag{15}$$

A common approach to solve these control allocation problem is to formulate an optimization problem that minimize the allocation error, $\|B\cdot u(t) - v(t)\|$ subject to actuator constraints. The linearly-constrained quadratic problem can be formulated as a weighted least square method. The cost function for the decision of the actual control inputs is defined as follows;

$$J(u) = \left\{\|W_1 u\| + \tau^2\cdot\|B\cdot u(t) - v(t)\|^2\right\} \tag{16}$$

The weighting factor, τ is typically chosen with very large value to emphasize to minimize the allocation error. The diagonal weighting matrix, W_1 should be defined with a consideration to minimize the unnecessary brake input to reduce an inconvenient feel. As a result, the weighted least square problem for optimum distribution of the actuator commands can be formulated as follows;

$$u(t) = \arg\min_{\underline{u}\le u\le\bar{u}}\left[\|W_1\cdot u\|^2 + \tau^2\cdot\|B\cdot u - v\|^2\right]$$
$$= \arg\min_{\underline{u}\le u\le\bar{u}}\left\{\left\|\begin{matrix}\tau\cdot B\\ W_1\end{matrix}\right\|\cdot u - \left\|\begin{matrix}\tau\cdot v\\ 0\end{matrix}\right\|\right\}^2 = \arg\min_{\underline{u}\le u\le\bar{u}}\left\{\|A\cdot u - b\|^2\right\} \tag{17}$$

To decide the amount of the overlay torque, the desired steering angle which is needed for lane departure avoidance is calculated by bicycle model using the desired yaw rate obtained above section. The desired steering angle can be represented as follows;

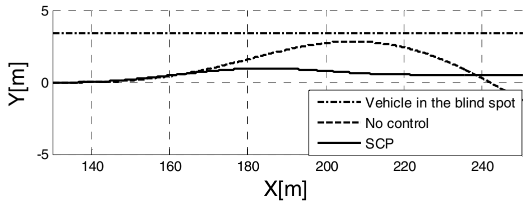
$$\delta_{SCP} = \left(l_f + l_r + \frac{m\cdot V_x^2\cdot\left(l_r\cdot C_{\alpha r} - l_f\cdot C_{\alpha f}\right)}{2C_{\alpha f}\cdot C_{\alpha r}\cdot(l_f + l_r)}\right)\cdot\gamma_{des} \tag{18}$$

Then the amount of the overlay torque is determined by a linear feedback control method as follows;

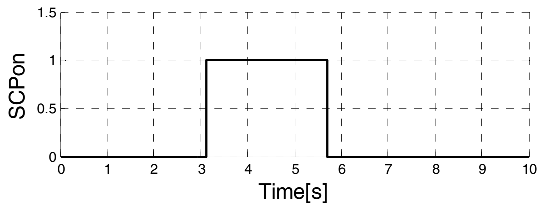
$$T_{overlay} = -K_{overlay}\cdot\left(\delta_{Actual} - \delta_{SCP}\right) \tag{19}$$

V. SIMULATION RESULT

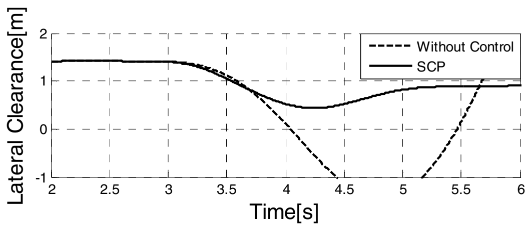
To verify a performance of a proposed side crash prevention controller, it was evaluated via human driver model-in the loop simulation conducted using the vehicle dynamic software CARSIM and Matlab/Simulink under the condition : driver is assumed to change the lane, the velocity of the vehicle is 80 kph in the straight road. As mentioned before the actuators composed by ESC module and MDPS module get activated when controller detected lane change intention. The human driver model is going to change the lane from 2.5 second to 3 second in the simulation. The side crash prevention system is operated from 3.1 second to 5.7 second. Simulation results are shown in figure 7. The lateral clearance between outer body of two vehicles(ego vehicle and vehicle in blind spot) is represented in figure. 7-(c). As shown in figure. 7-(c), the proposed side crash prevention algorithm provides an efficient assistance and prevents side crash



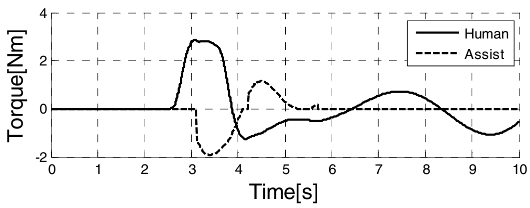
(a) Trajectory of vehicles



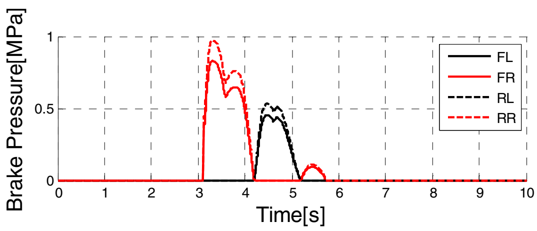
(b) SCP On



(c) Lateral clearance



(d) Steering wheel torque



(e) Brake pressure at each wheel

Figure 7. Simulation Result

VI. CONCLUSION

In this paper, side crash prevention system has been proposed. The side crash prevention algorithm supports driver to avoid collision using differential braking and steering torque overlay. The controller prevents the lane change when a driver attempts to lane change despite existence of vehicle in the blind spot. To reduce unnecessary intervention by this system, lateral driving characteristics of drivers and driving data collected on a real road were used. The analyzed characteristics are used to detect the lane change intention with steering behavior index. When the lane change is detected, the MDPS and ESC module are controlled strategically to prevent a side crash. Steering torque overlay and differential braking are operated to reduce a relative lateral velocity to zero while the vehicle avoids hitting the neighboring vehicle. The performance of the algorithm has been investigated via computer simulations conducted using the vehicle dynamic software CARSIM and Matlab/Simulink. A side crash prevention system can be extended to more complex system using all-around detection system and advanced actuators like AFS or 4WD. The development of the new algorithms for the variable combination of actuators and sensors is topics of present research.

ACKNOWLEDGMENT

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