

Design and Evaluation of Emergency Driving Support Using Motor Driven Power Steering and Differential Braking on a Virtual Test Track

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ABSTRACT

This paper presents the design and evaluation of an emergency driving support (EDS) algorithm. The control objective is to assist driver's collision avoidance maneuver to overcome a hazardous situation. To support driver, electrically controllable chassis components such as motor driven power steering (MDPS) and differential braking and surrounding sensor systems such as radar and camera are used. The EDS algorithm is designed for 3 parts: monitoring, decision, and control. The proposed EDS algorithm recognizes a collision danger using minimum lateral acceleration to avoid collision and time-to-collision (TTC) and driver's intention using sensor systems. The control mode is determined using the indices from monitoring process and the collision avoidance trajectory is derived with trapezoidal acceleration profile (TAP). Using the collision avoidance trajectory, the MDPS overlay torque is determined to support the driver's response of collision avoidance and differential braking is determined to maximize minimum vehicle-to-vehicle distance. Vehicle behavior and the interactions between the vehicle, the controller, and the human driver are investigated through a full-scale driving simulator on the virtual test track (VTT) which consists of a real-time vehicle simulator, a visual animation engine, a visual display, and suitable human-vehicle interfaces. The success rate of collision avoidance is investigated with test drivers and it has been increased for all test drivers.

CITATION: Choi, J. and Yi, K., "Design and Evaluation of Emergency Driving Support Using Motor Driven Power Steering and Differential Braking on a Virtual Test Track," *SAE Int. J. Passeng. Cars - Mech. Syst.* 6(2):2013, doi: 10.4271/2013-01-0726.

1. INTRODUCTION

Intelligent vehicles and driver support systems have been an issue to enhance the safety of drivers and passengers. In recent years, automakers are trying to help drivers to avoid or mitigate collision with active safety system instead of passive safety system which focuses on protecting vehicle occupants in case of accidents. The practical applications have become possible due to recent advances in the areas of exterior sensors such as radar, lidar and vision and of electronically controllable actuators such as motor driven power steering (MDPS), active suspension and differential braking. These advances have opened up many possibilities for active safety systems like lane-keeping assistance system (LKAS), or collision warning and collision avoidance system (CW/CA).

In recent researches, several algorithms have been proposed for collision avoidance system related to steering control. It tends to control the vehicle autonomously with steering angle control using active front steering (AFS) as an actuator [1]. It can make additional steering angle even if

driver holds the steering wheel strictly. However the most of vehicles uses motor driven power steering (MDPS) system instead. The steering angle cannot be controlled autonomously if driver holds it [2]. The control input using MDPS is not an additional steering angle, but an overlay torque which is additional torque for steering wheel.

In previous researches, several methods for collision avoidance trajectory generation have been proposed. The lane change trajectories have been researched and compared: the circular trajectory, cosine trajectory, polynomial and trapezoidal acceleration profile (TAP) [3]. The lane change trajectories are not designed for collision avoidance, however it is useful for collision avoidance. Sinusoidal function is used in many researches for steering avoidance support system design [2, 4]. Trapezoidal acceleration profile and a sigmoid function are also used for collision avoidance research [5, 6]. Recently several researches propose the optimal trajectory generation method and trajectory generation considering uncertainty for collision avoidance [7, 8, 9].

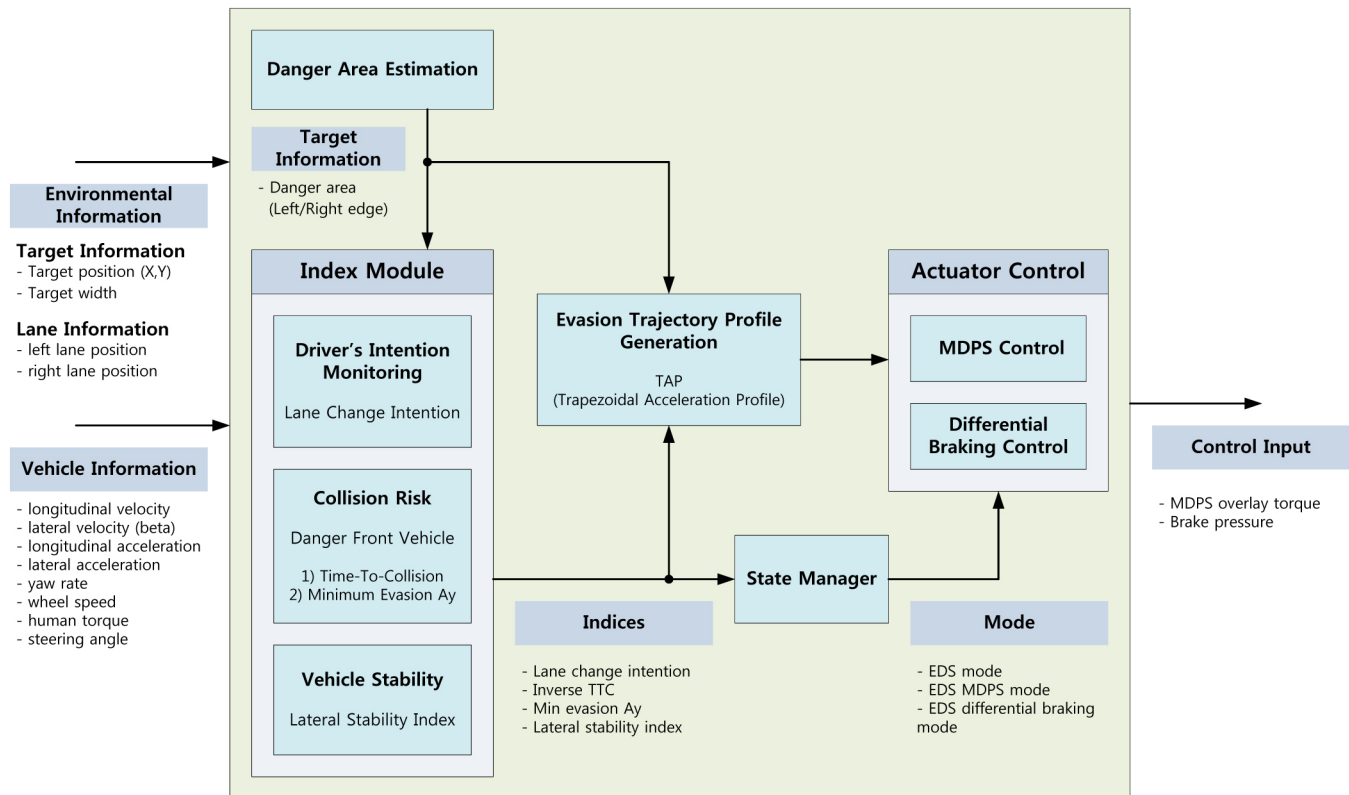


Figure 1. Schematic diagram of emergency driving support algorithm

For actuator control, trajectory following control algorithms has been proposed [1, 4, 10]. Instead of automated collision avoidance, a support based algorithm using yaw moment control has been proposed and tested with simulator [2, 5].

The EDS algorithm is designed to assist driver's collision avoidance maneuver. If the intention of collision avoidance is confirmed, it can be interpreted that the appropriate yaw motion of vehicle is desired by driver. Therefore the additional yaw moment is adjusted and used for collision avoidance using differential braking and MDPS torque overlay can be adjusted to assist driver's steering input. A deceleration is not considered to assist driver that it cannot assist yaw motion of vehicle.

In this research, the TAP is modified and proposed to derive collision avoidance trajectory. Present lateral acceleration and lateral velocity can be considered to design collision avoidance trajectory using TAP. MDPS overlay torque and differential braking control is designed to cooperate with driver. Considering driver's uncertainties and limitation of sensors, the controller should be designed that driver to have control priority. The sensor fusion algorithm and state estimation algorithm is not designed in this paper. It is another important issue for driver assistance system. We assume that environmental information and vehicle information is given in this research.

From the motivations, this paper is organized as follow 7 chapters. First chapter is about the overview of emergency

driving support algorithm. Second chapter introduces danger area estimation. Third chapter is about used indices in emergency driving support (EDS) algorithm. Fourth chapter is about state manager. Fifth chapter explains collision avoidance trajectory generation. Sixth chapter is about control methods for actuators and final chapter describes evaluation using virtual test track (VTT).

2. OVERALL CONTROL ARCHITECTURE OF EMERGENCY DRIVING SUPPORT

An emergency driving support (EDS) system is developed to support driver's collision avoidance behavior. In order to assist the driver in avoiding collisions, the controller is designed to do not control the vehicle autonomously. The algorithm only works when the driver's intention of collision avoidance using steering input is confirmed. The algorithm is designed to use radar and camera for sensor system to detect front vehicle and lane and MDPS overlay torque and differential braking are used as actuators to control vehicle.

Fig. 1 shows the schematic diagram of emergency driving support algorithm. The environmental and vehicle information are obtained from radar, vision and vehicle sensors. The sensor fusion and state estimation algorithm should be adjusted to obtain organized information. Danger area estimation algorithm returns danger point which should be avoided by subject vehicle. It should be back side edge of

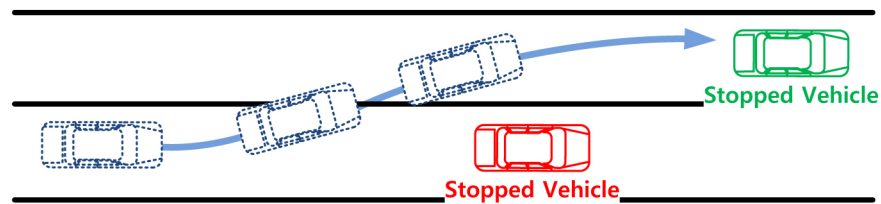
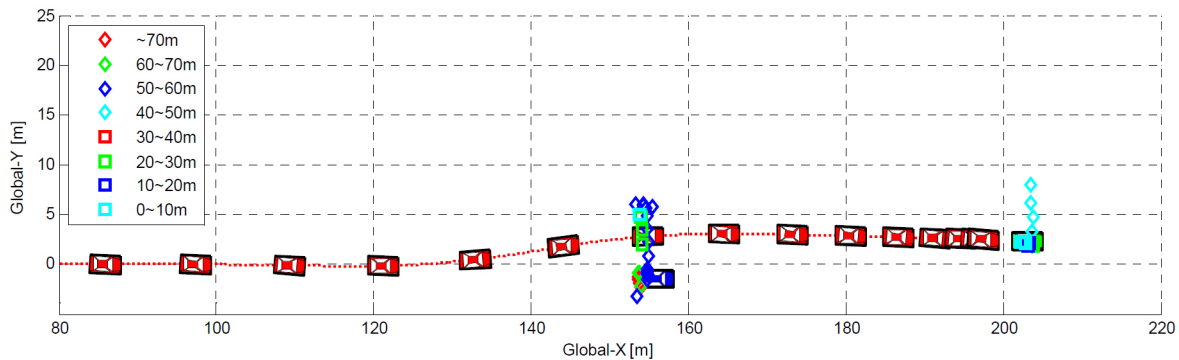
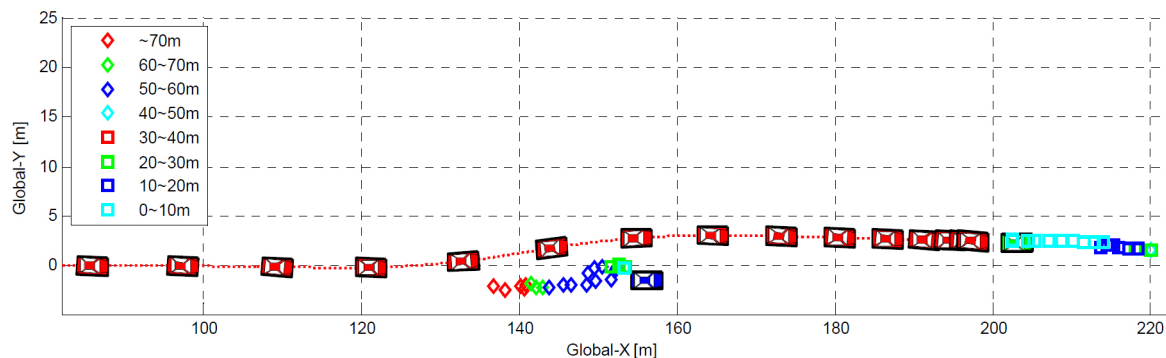


Figure 2. Sensor test scenario



(a) Global position of detected target vehicle from radar data



(b) Global position of detected target vehicle from vision data

Figure 3. Sensor test results

front vehicle when the front vehicle is stopped. The width of front vehicle and center position of back side information are used to calculate the danger area. It should be determined considering accuracy of sensor information and relative speed [19]. In index module, driver's intention, collision risk and vehicle stability are monitored. The lane change intention index is designed in last research about lane keeping assistance system (LKAS) [11]. The collision risk is observed using well-known index, inverse time-to-collision (TTC) and newly designed index, minimum lateral acceleration for collision avoidance [12]. State manager determines control mode of EDS using the indices. It determines a state of EDS and returns control mode of actuators. The actuator is controlled to support driver's collision avoidance using evasion trajectory designed using trapezoidal acceleration profile (TAP).

3. DANGER AREA ESTIMATION

In order to obtain danger area which is should be avoided by subject vehicle radar and vision information is combined. The information of the object such as a width of the object

and the relative motions of the object such as relative position, relative velocity of the object to the subject vehicle, and relative angle to the object from the subject vehicle are recognized by the radar and vision sensors. The sensor fusion algorithm is not designed and used in this research. However for restricted situation, the effect of sensor fusion can be tested. To investigate performance of radar and vision sensors, simple detection test has been accomplished. Fig. 2 shows the test scenario. The subject vehicle drives straight about 80 km/h and make a lane change maneuver about 20 m in front of first stopped vehicle. Then the subject vehicle stops in front of second stopped vehicle. The radar and vision sensors are used to detect the stopped vehicles. The characteristics of sensor detection in emergency collision avoidance using steering and emergency collision avoidance using braking are compared.

The results are shown in Fig. 3. The global position of detected vehicle is derived from GPS signal of subject vehicle and radar and vision signals. The radar signal is more accurate than vision signal for the longitudinal position. However vision signal is more accurate than radar signal for

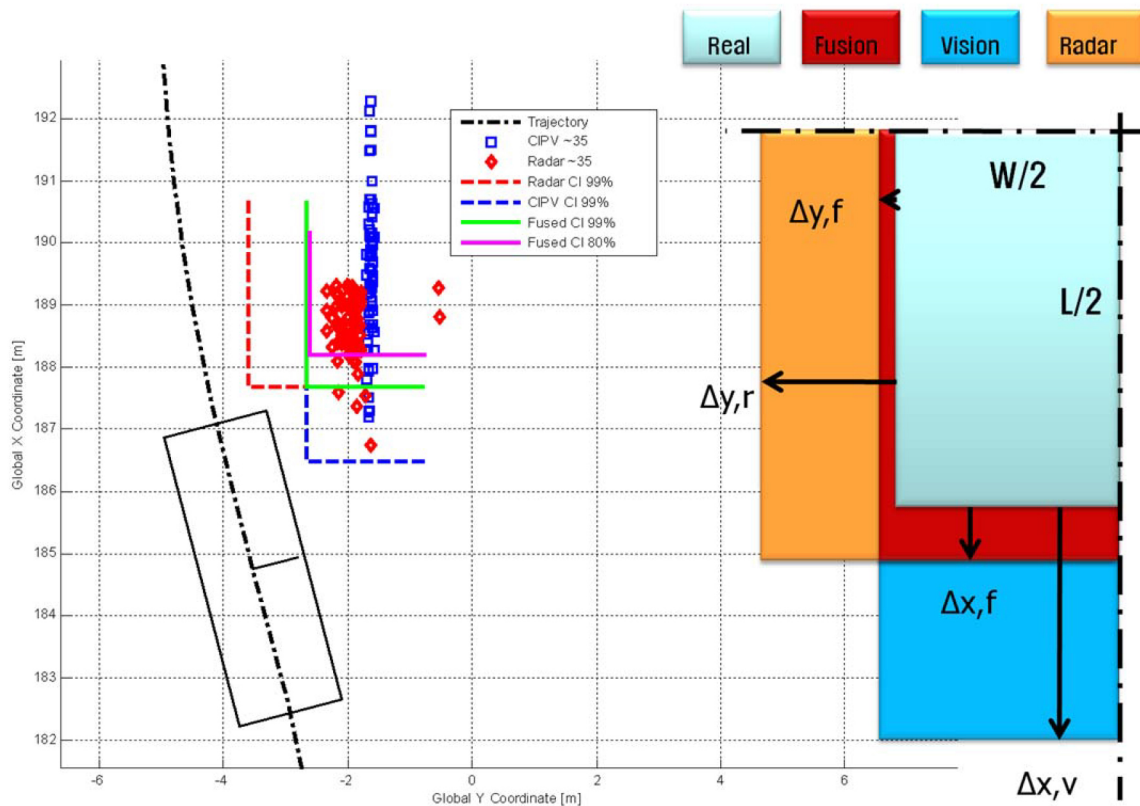


Figure 4. Danger area estimation

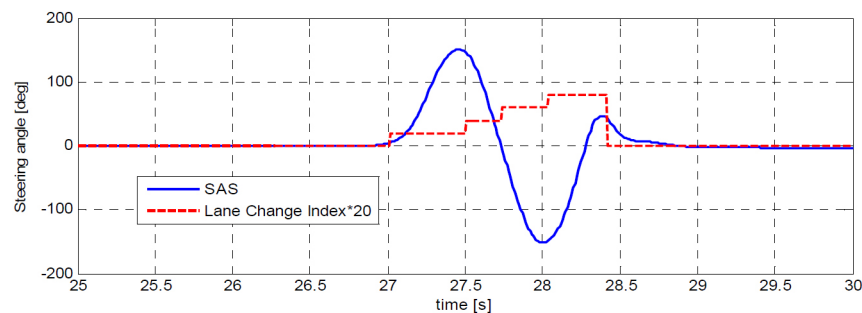


Figure 5. Test result of lane change index

the lateral position. With the each signals, the resultant danger areas which is 99% confidential interval are estimated and shown in Fig. 4. In left graph in Fig.4, the 80% and 99% confidential danger area using radar data only, camera data only and using two sensor data together. Of course further tests in various environments should be followed to design sensor fusion algorithm, however the feasibility of sensor fusion can be investigated.

4. INDEX MODULE

For EDS activation, following conditions should be satisfied. First, the risk of front vehicle should be confirmed. Second, driver's intention of collision avoidance using steering input should be confirmed. Time-to-collision and minimum lateral acceleration is used to confirm collision risk. The driver's intention index is designed to confirm

intention of collision avoidance using steering input. The stability of vehicle should be monitored while EDS is in activation. If vehicle is not stable, the differential braking should be controlled as a conventional stability control. The vehicle stability is monitored using stability index [15].

In intentional lane change, the driver tends to maintain large steering angle and steering rate consistently. From this analysis, forgetting filter is designed to detect lane change intention [11]. The designed lane change index has been modified for EDS. It classifies stages of lane change as 4 stages: steer-in, counter-steer start, counter-steer to opposite direction, returning to normal. Each stage is shown in Fig. 5. The direction of steering angle and steering rate is used for this classification.

The collision risk is observed using well-known index, inverse time-to-collision (TTC) and newly designed index,

minimum lateral acceleration for collision avoidance. The inverse time-to-collision can express driver's feeling about longitudinal danger [13]. It has simple structure and easy to be handled. However the inverse time-to-collision cannot express the difficulty from width of front vehicle which subject vehicle should travels to avoid collision. Therefore the minimum lateral acceleration for collision avoidance is used to confirm the difficulty from width of front vehicle. It can be defined as (1) and Fig. 6.

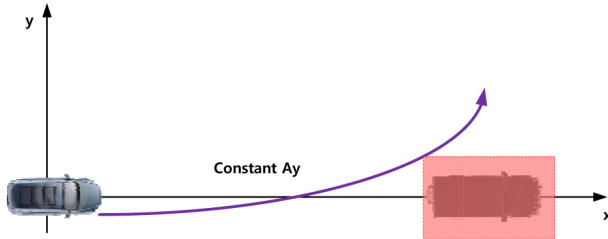


Figure 6. Minimum lateral acceleration for collision avoidance

For that, the right front vertex point of vehicle should meet the left vertex point of danger area. Assume the vehicle drives with constant lateral acceleration, the radius of trajectory should satisfy equation (1):

$$R^2 = \left(x_0 - \frac{1}{2}L_{veh}\right)^2 + \left(y_0 + \frac{1}{2}B_{veh}\right)^2 = (x_0 - x_d)^2 + (y_0 - y_d)^2 \quad (1)$$

The (x_0, y_0) is center of circular trajectory of vehicle. The initial direction of vehicle trajectory should be perpendicular that the x_0 should be half of vehicle length. Solve the equation (1), the radius can be obtained without (x_0, y_0) . Then the minimum lateral acceleration can be calculated as follow:

$$a_{y,min} = \frac{2V^2 \left(\frac{1}{2}B_{veh} + y_d \right)}{x_d^2 + y_d^2 + \frac{1}{4}L_{veh}^2 + \frac{1}{4}B_{veh}^2 - 4L_{veh}x_d + 4B_{veh}y_d} \quad (2)$$

In this equation, L_{veh} is vehicle length, B_{veh} is vehicle width, (x_d, y_d) is vertex point of danger area.

4. STATE MANAGER

From the indices, control mode is decided in state manager. It determines a state of EDS and returns control mode of actuators as Fig. 7. As subject vehicle get close to front vehicle, the time-to-collision increases. If the time-to-collision index exceeds threshold, warning mode is started.

After the warning mode is started, if vehicle consistently approach the front vehicle, the inverse time-to-collision and minimum lateral acceleration increases and exceeds threshold, the EDS is in ready. After that if driver tries to avoid collision using steering input, lane change index is observed and the EDS system is activated. The mode of EDS is separated by stages of lane change index. The steering angle increases in first phase to avoid collision, and driver makes counter-steer to stabilize vehicle. The EDS mode is designed to support driver's each phase. The EDS supports collision avoidance of driver in first phase, and supports to recover vehicle stability and reduce lateral travel distance.

To satisfy driver's purpose in collision avoidance, the actuators should be controlled according to state of EDS. The collision avoidance trajectory is designed according to the EDS state, the details about collision avoidance trajectory is in chapter 5. The desired lateral acceleration and jerk are standard for the MDPS torque overlay control. The differential braking control is designed to maximize minimum distance between vehicles in first stage of EDS, and support to stabilize vehicle from counter-steer as conventional ESC.

5. COLLISION AVOIDANCE TRAJECTORY GENERATION

To control the MDPS overlay torque and differential brake pressures, a collision avoidance trajectory should be designed. In previous researches, collision avoidance trajectory is designed using sigmoid function [6], trapezoidal acceleration profile (TAP) [5], sinusoidal function [4]. In this research, the modified TAP is adjusted. The sigmoid function and sinusoidal function are not easy to generate and be modified during collision avoidance. In order to adjust present lateral acceleration and lateral velocity during avoidance, the TAP is useful and easy to be modified than others.

The collision avoidance trajectory is designed to satisfy following 3 conditions:

- The lateral travel distance which can be obtained from double integration of designed acceleration profile should have safe distance with the danger area. This condition can be approximated as condition of lateral travel distance at time-to-collision as (3):

$$y(TTC) > \hat{y}_{danger} + L_{safe} \quad (3)$$

where $\hat{y}_{danger}$ is lateral boundary of danger area and L_{safe} is safety length between vehicle center to danger area which should be bigger than half of vehicle width.

- After avoiding a collision, the vehicle should place in the driving lane. The lateral travel distance of vehicle at the end