DEVELOPMENT OF AN AUTONOMOUS BRAKING SYSTEM USING THE PREDICTED STOPPING DISTANCE

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ABSTRACT—An autonomous braking system is designed using the prediction of the stopping distance. The stopping distance needs to be determined by considering several factors such as the desired deceleration and the speed of the hydraulic brake actuator. In particular, the actuator speed is very critical because it affects the shape of the deceleration response and it determines the accuracy of the predicted stopping distance. The autonomous braking control algorithm is designed based on the predicted stopping distance. The proposed autonomous braking system has been validated in autonomous vehicle tests and demonstrates that the subject vehicle can avoid the collision effectively.

KEY WORDS: Autonomous braking system, Stopping distance, Response speed, Brake actuator

1. INTRODUCTION

The several manufacturers have developed autonomous braking technologies which can help the driver to avoid accidents or, at least, to reduce its severity when the collision is unavoidable. The technologies include Adaptive Cruise Control (ACC) systems combined with Electronic Stability Control (ESC) and Autonomous Emergency Braking (AEB) systems. The ACC systems have been already commercialized by Car manufacturers for driver’s convenience and safety. These systems allow vehicle’s cruise control with adapting the speed to the traffic environment. If a slower moving vehicle is detected in front, the ACC system will slow down the vehicle by autonomous braking and control the clearance or time gap between the ACC vehicle and the forward vehicle, whereas if the forward vehicle is no longer in the ACC vehicle’s path, the ACC system will accelerate the vehicle back to its set cruise control speed (Szuszman, 2005).

Regarding the AEB systems, the Euro NCAP (2013) believes that they can offer a great safety potential. Starting in 2014, their assessment will be included in the safety rating scheme, and test protocols are being developed to compare the performance of different AEB systems. The AEB systems are divided into three main categories by the Euro NCAP such as City, Inter-Urban and Pedestrian AEB. The City AEB is a low speed collision avoidance system using short range sensors to mitigate and in certain situations avoid rear-end collisions at junction and roundabouts (Distner et al., 2009). If the relative speed difference between the two vehicles is less than 15 km/h, the City AEB system can help to entirely avoid the collision by autonomous braking. The Inter-Urban AEB System is a high speed collision mitigation system using long range radars, typically up to 200 m. If the driver does not respond to the imminent collision, the system will apply heavy deceleration by autonomous braking to mitigate the severity of impact. Some systems also provide the restraint systems to the driver by pre-tensioning the seatbelts (Mellinghoff et al., 2009). The Pedestrian AEB System is designed to detect pedestrians and other obstacles using forward-looking camera and applies full autonomous braking if they are in danger of being struck (Coelingh et al., 2010).

In order to entirely avoid the collision regardless of speed by autonomous braking, accurate collision detection is necessary for the braking control. For example, Time to collision (TTC) index has been utilized in many control systems (Forkenbrock and O’Harra, 2009) and it is typically used as the inverse form, TTC⁻¹. Lee et al proposed a collision decision algorithm which includes path prediction utilizing motion data such as yaw rate and acceleration (Lee et al., 2012). Raphael et al introduced a camera-based collision alert system to detect an object and calculated the TTC based on the vision method called image scale change (Raphael et al., 2011). Chen et al proposed to estimate the stopping distance for heavy trucks assuming that the acceleration is constant without considering braking dynamics (Chen et al., 2008).

In this study, an algorithm for the autonomous braking system is designed using the prediction of the stopping distance. The prediction of the stopping distance is very important to decide when the braking should be applied not
to collide with the obstacles. For instance, if the autonomous brake system starts to operate when the required stopping distance is longer than the actual distance between the vehicle and an obstacle, it may be too late to avoid the collision by the autonomous braking.

The key idea of the proposed algorithm is to use the desired deceleration and the response speed of the brake actuator to calculate the predicted stopping distance. The desired deceleration can be set by a driver for the comfort and driving fun. The larger the desired deceleration is, the more aggressive the autonomous braking system operates. For the prediction accuracy of the stopping distance, the characteristics of the brake actuator should be considered such as response speed and time delay. The time delay of the hydraulic actuator is not considered in this study because the brake pressure is assumed pre-filled for the autonomous braking. The response speed of the brake actuator can have different values depending on ESC models and it is determined experimentally. The speed control algorithms are designed for the autonomous braking utilizing the similar concept of the ACC systems. The performance of the proposed system is evaluated experimentally using the autonomous vehicle. The active braking mechanism is constructed using an external motor-driven cable unit and the GPS sensor is used to measure the distance between the vehicle and the obstacle.

2. AUTONOMOUS BRAKING CONTROLLER

Figure 1 shows the flow chart of the proposed autonomous brake algorithm which consists of four modes: standby mode, cruise mode, brake mode and stop mode. The standby mode represents the general driving mode without obstacles. The subject vehicle is driven by a speed control system such as cruise control or by a driver on the standby mode. The design of the speed control system is explained in section 2.3. When an obstacle is detected in front, the system switches to the cruise mode where the subject vehicle is still controlled by the speed controller. The obstacle is a certain object existing ahead of the subject vehicle such as a front vehicle on highway environment. On cruise mode, the autonomous braking system does not operate because the predicted stopping distance, \( d_{\text{brake}} \), is shorter than the actual spacing, \( d_{\text{err}} \), which means that the actual spacing is enough to stop the subject vehicle for avoiding the collision.

The brake mode starts to operate as soon as the predicted stopping distance is close to the actual spacing distance. In this mode, the autonomous braking system is operated to slow down the vehicle using the brake actuator such as ESC or brake pedal mechanisms. Finally, in the stop mode, the vehicle is completely stopped for avoiding front collision. Figure 2 shows an operation example of the autonomous braking system in accordance with each mode. The prediction of the stopping distance, which is used on the cruise and brake modes, is very important for designing the autonomous braking algorithm. The brake system can decide whether to operate the brake actuators or not by comparing the predicted stopping distance with the spacing distance.

\[ d_{\text{brake}} = \frac{V^2}{2a_r} + \frac{V}{2J_{\text{act}}} a_r - \frac{1}{24J_{\text{act}}} a_r^3 \]

\[ d_{\text{err}} = d_{\text{brake}} \]

Figure 2. Strategy of the proposed algorithm.

![Figure 1. Flow chart of the algorithm.](image1)

![Figure 2. Strategy of the proposed algorithm.](image2)