Optimal design of an Autonomous Emergency Braking (AEB) system for a passenger vehicle

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Abstract. This paper models the performance of a passenger vehicle equipped with Autonomous Emergency Braking (AEB) using a feedback control system in MATLAB Simulink. Two types of AEB control systems are simulated and compared; proportional-integral (PI) control and fuzzy logic control (FLC). Performance of both control systems simulated are compared using AEB City collision scenario defined in Euro New Car Assessment Protocol (NCAP). Results show that the proposed PI control system is able to meet Euro NCAP AEB City set requirements.

1. Introduction

In Europe and Malaysia, passenger vehicles equipped with AEB could contribute to the vehicle’s European New Car Assessment Protocol (NCAP) and ASEAN NCAP score ratings. Based on this market scenario, it is important that vehicle manufacturers adopt an optimal AEB system to meet safety rating requirements outlined by vehicle safety authorities like Euro and ASEAN NCAP. The AEB system uses radar, (stereo) camera and/or lidar-based technology to identify potential frontal collision. Some AEB systems include Front Collision Warning (FCW) feature to warn the driver of a potential collision. Other AEB systems apply full braking force or cascaded level in addition to FCW or exclusively. This paper focuses on AEB with cascaded braking levels only.

During AEB activation, the dynamic driving tasks associated with braking is automated by the AEB controller. Some AEB control for example in Audi A7, Mercedes CLS, and Infiniti M adopt cascade braking based on fixed levels of deceleration which is activated at certain time-to-collision (TTC) range [1]. This type of control strategy can be implemented using a look up table and the deceleration levels cannot be changed dynamically based on changes in parameters e.g. rate of TTC change.

An improvement to the fixed deceleration level AEB control strategy described above is to provide a dynamic deceleration AEB control. The works of [2] describes the use of Risk Assessment strategy for AEB implementation calculated by the Potential Field (PF) strategy which formulates the risk of a collision with a frontal obstacle relative to the state of the subject vehicle; current position and velocity. PF provides an attractive force, which represents safe areas for the vehicle to navigate, and a repulsive force around the obstacle. The vehicle will decelerate in the presence of repulsive force. The works of [3] implements automatic braking system using proportional-derivative (PD) fuzzy logic.
controller (FLC) where the inputs to the FLC are subject vehicle position and velocity and the output is brake. Works of [4] describes the use of Petri net modeling of events for pedestrian/cyclist transitions in a potential collision area to design the AEB controller response.

This paper analyzes two types of AEB control; PI and FLC. The PI controller provides a reference vehicle velocity based on inputs of TTC from the objection detection sensor. The FLC also provides a reference vehicle velocity but based on gap distance and relative velocity between subject and lead vehicle. The reference vehicle velocity serves as input to the PI brake actuator controller for braking actuation.

Both PI and FLC controllers are compared by simulating an AEB City assessment collision scenario at 100% subject and lead vehicle lateral overlap. This assessment is carried out for subject vehicle velocities from 25kph to 50kph at 5kph increment whilst the lead vehicle remains stationary. The AEB system is deemed to meet requirement if the impact velocity falls below the ‘red’ grid impact velocity range outlined in [5].

2. Modelling

2.1. Vehicle longitudinal dynamics model

The drag force against vehicle velocity data for a Sport Utility Vehicle (SUV) segment passenger vehicle i.e. subject vehicle is measured using coast down method [6]. The drag force acting on the vehicle is modelled using the equation obtained from 2nd order polynomial curve fitting method from the coast down data as shown in (1).

\[ F_d = 0.0558v^2 - 0.5061v + 218.16 \]  

The tractive force acting on the vehicle is equal to the drag force when the vehicle is coasting at constant velocity. When AEB is activated, the tractive force is set to zero to ensure efficient deceleration. The tractive force acting on the vehicle is shown in (2).

\[ F_{tract} = \begin{cases} F_d & \text{if } F_{brake} = 0 \\ 0 & \text{if } F_{brake} > 0 \end{cases} \]  

The brake force acting on the vehicle is controlled by the brake actuator controller which provides brake pressure input to the vehicle Electronic Stability Control (ESC) module which actuates the brake. The brake force equation is shown in equation (3) and its corresponding values is shown in ‘table 1’.

\[ F_{brake} = \frac{\mu P \pi RD^2 N}{4R_{tyre}} \]  

| Parameter                      | Value                  |
|--------------------------------|------------------------|
| Disc pad coefficient of friction (μ) | 0.40 (front), 0.37 (rear) |
| Applied brake pressure (Pa) (P)   | -                      |
| Brake pad radius (m) (R)          | 0.132 (front), 0.134 (rear) |
| Brake actuator bore diameter (m) (D)| 0.064 (front), 0.038 (rear) |
| Number of disc pads (N)           | 2                      |
| Tyre radius (m) (R_{tyre})        | 0.3636                 |
The brake pressure transfer is subjected to hydraulic lag as shown in the transfer function in equation 4.

\[ TF_{\text{hydraulic\_lag}} = \frac{1}{0.1s + 1} \]  

(4)

The actual subject vehicle velocity is computed from drag, tractive and brake forces acting on the subject vehicle with mass, \( m = 1,775 kg \) as shown in (5).

\[ v_{\text{act}} = \int \frac{F_{\text{traction}} - F_{d} - F_{\text{brake}}}{m} \]  

(5)

2.2. Brake Actuation Control Model

The brake actuator controller utilizes PI control with proportional gain, \( k_p = 100 \) and integral gain, \( k_i = 1 \) which compares reference and actual vehicle velocities and produces target brake pressure values as shown in (6).

\[ P = k_p (v_{\text{ref}} - v_{\text{actual}}) + k_i \int (v_{\text{ref}} - v_{\text{actual}}) \]  

(6)

2.3. Front Object Detection Module Model

The front objection detection module is utilized to compute the TTC (7) between the subject and lead vehicles.

\[ TTC = \frac{\int (v_{\text{lead}} - v_{\text{subject}})}{v_{\text{subject}}} \]  

(7)

2.4. AEB PI Control Model

The AEB PI controller is used to produce reference subject vehicle velocity from reference deceleration (8) and to compute the TTC AEB activation threshold crossing (9). Based on the TTC value with respect to the TTC partial braking and full braking thresholds, the maximum value of partial braking deceleration and full braking deceleration are computed (10). The PI gain values, maximum deceleration and TTC settings are summarized in ‘table 2’.

\[ v_{\text{ref}} = \int a_{\text{ref}} \]  

(8)

\[ \varepsilon = TTC - TTC_{pb} \]  

(9)

\[
\begin{align*}
    a_{\text{ref}} &= 0 \quad \text{if} \quad TTC \geq TTC_{pb} \\
    a_{\text{ref}} &= k_p \varepsilon + k_i \int \varepsilon \quad \text{max} \Rightarrow a_{\text{pb}} \\
    a_{\text{ref}} &= k_p \varepsilon + k_i \int \varepsilon \quad \text{max} \Rightarrow a_{fb} \\
    a_{\text{ref}} &= k_p \varepsilon + k_i \int \varepsilon \quad \text{max} \Rightarrow a_{fb}
\end{align*}
\]  

(10)
Table 2. AEB PI control parameters and values

| Parameter                              | Value |
|----------------------------------------|-------|
| Proportional gain                      | \( k_p \) 1 |
| Integral gain                          | \( k_i \) 30 |
| TTC partial braking (s) threshold       | \( TTC_{pb} \) 1.3 |
| TTC full braking (s) threshold          | \( TTC_{fb} \) 0.5 |
| Partial braking max. deceleration \((m/s^2)\) | \( a_{pb} \) 3.8 |
| Full braking max. deceleration \((m/s^2)\) | \( a_{fb} \) 8 |

2.5. AEB Fuzzy Logic Model

A fuzzy logic controller is modelled to produce subject vehicle reference deceleration based on relative velocity and gap between subject and lead vehicles. Two membership functions (MF) are produced for the relative velocity fuzzy interference system (FIS); high relative velocity and low relative velocity. Three MFs are produced for gap FIS; very near, near and far. Two MFs are produced for reference deceleration FIS; partial brake and full brake. Six fuzzy rules are formulated as summarized in ‘table 3’. The surface viewer for the fuzzy logic controller is shown in ‘Figure 1’.

Table 3. AEB fuzzy logic fuzzy rules

| Rule | Description |
|------|-------------|
| 1    | If relative velocity is high and gap is very near then deceleration is full braking |
| 2    | If relative velocity is low and gap is very near then deceleration is partial braking |
| 3    | If relative velocity is high and gap is near then deceleration is full braking |
| 4    | If relative velocity is low and gap is near then deceleration is partial braking |
| 5    | If relative velocity is high and gap is far then deceleration is no braking |
| 6    | If relative velocity is low and gap is far then deceleration is no braking |

Figure 1. Fuzzy logic control surface viewer
2.6. Overall AEB Model

The overall block diagram of the AEB model is depicted in ‘Figure 2’.

![Figure 2. AEB model](image)

3. Results and discussions

The performance of AEB PI controller and AEB FLC are compared following the AEB City collision scenario where the subject vehicle moves forward from 25kph to 50kph at 5kph increment approaching a stationary target vehicle with 100% vehicle lateral overlap and 50m apart at the start of assessment.

The AEB system is deemed to meet requirement if the impact velocity falls below the ‘red’ grid impact velocity range outlined in [5]. Results of the simulation shows that AEB PI controller meets this requirement and has lower average impact velocities as summarized in ‘table 4’.

| Subject vehicle velocity (kph) | Target impact velocity (kph) | AEB PI impact (kph) | Pass / Fail | AEB FLC impact (kph) | Pass / Fail |
|-------------------------------|------------------------------|--------------------|-------------|----------------------|------------|
| 25                            | <15                          | 2.9                | Pass        | 0                    | Pass       |
| 30                            | <25                          | 12.7               | Pass        | 0                    | Pass       |
| 35                            | <25                          | 19.0               | Pass        | 21.7                 | Pass       |
| 40                            | <35                          | 24.8               | Pass        | 28.6                 | Pass       |
| 45                            | <35                          | 30.3               | Pass        | 33.9                 | Pass       |
| 50                            | <40                          | 35.6               | Pass        | 44.5                 | Fail       |
| Average impact velocity (kph) |                              | 20.8               |             | 21.4                 |            |

The braking performance of both controllers were also compared using brake stop time values. From the simulation, AEB PI control shows faster braking stopping time performance; 5.7% faster than compared to AEB FLC at the most stringent subject vehicle test velocity; 50kph as shown in ‘figure 4’.
Figure 3. AEB PI controller vs AEB FLC braking performance at subject vehicle 50kph approaching a stationary lead vehicle

4. Conclusion
This paper proposes PI control as the optimal solution for a passenger vehicle AEB system. Simulation comparison was made with an AEB FLC and the result shows that the AE PI controller was superior than compared to AEB FLC when evaluated using the AEB City collision scenario.

For future works, more complex scenarios will be used for the validation of the system. A hybrid of PI and FLC will also be considered due to the fact that at lower subject vehicle velocity, AEB FLC has a lower impact collision than AEB PI controller.

References
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