Development and Evaluations of Advanced Emergency Braking System Algorithm for the Commercial Vehicle

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ABSTRACT

This paper presents a development and evaluations of the Advanced Emergency Braking System (AEBS) Algorithm for the commercial vehicle. The AEBS is the system to slow the vehicle and mitigate the severity of an impact when a rear end collision probability is increased. To mitigate a rear end collision of the commercial heavy truck, the AEBS comprises of a millimeter wave radar sensor, CCD camera and vehicle parameters of which are processed to judge the likelihood of a collision occurring. If the likelihood of a rear end collision with an obstacle is judged as probable, warning signals are provided to alert the driver by the AEBS algorithm. If driver fail to react to the warnings when the collision likelihood is judged as being high, the AEBS algorithm applies autonomous braking in order to reduce the impact speed.

To demonstrate the control performance of the proposed AEBS algorithm's, longitudinal vehicle model of the commercial target vehicle was developed by using the real vehicle's test data and vehicle dynamics. Also, closed-loop simulation of the AEBS was conducted.

In order to indicate the safety level of the driving situation, new safety indexes are suggested. From the simulation result and analysis using this safety indexes, it is shown that proposed AEBS algorithm can enhance the commercial heavy truck's longitudinal safety in the dangerous driving situation which can be occurred rear-end collision.

INTRODUCTION

Road safety is a major concern in most countries and the attention is turning towards active safety system that is not only developed to reduce the consequences of accidents but also to reduce the number of driver errors and thereby the number of accidents. In case of Korea, there is the unenviable record being one of the highest traffic accidents and fatality rates. In 2009, there were 5,838 fatalities on the road.[1] Therefore, a new and systematic approach to safety system is necessary to reduce traffic casualties. In this point of view, an Adaptive Cruise Control (ACC) system for the passenger vehicle had entered the market to mitigate the consequences of an accident and to reduce the number of fatalities among car occupants.

Especially, with truck-related accidents are made up a relatively large part of all road fatalities. In 1998 heavy goods vehicles were involved in 17% of all road accident fatalities despite making up just 7% of the traffic on the roads of Great Britain[2]. Also, according to Swedish and European authorities, approximately 13000 lives are lost in Europe yearly in traffic accidents involving Heavy Goods Vehicles. 40% of these fatalities are unprotected road users, 6% are truck drivers, and 54% are drivers and passengers of cars.[3] Hence, an Autonomous Emergency Braking System (AEBS) for trucks is able to not only decrease the truck-related accidents, but also lead the reduction of road fatalities. [4]

To assure real road safety improvements by the AEBS, the relationship between changes with and without of the AEBS in the same driving situation must be established. In order to obtain the estimation of the overall safety impact of the AEBS, a safety index which is able to measure an objective safety of the system is needed.

The goal of this research is the development of the AEBS Algorithm for the Commercial Vehicle and relevant assessment methods of the AEBS by the objective safety index in the dangerous driving situation which can be occurred rear-end collision.

The AEBS control algorithm consists of two parts: obstacle detection part and main controller part. In the obstacle detection part, front obstacle information was measured and collected for the main controller's decision. The main controller for the AEBS is composed of the two control stage: upper and lower level controller. By using the collected obstacle information, the upper level controller of the main controller decides the control mode. Next, the lower level controller determines warning level and braking level to maintain the longitudinal safety. When the control algorithm calculates the desired deceleration, braking part generate the brake pressure to maintain the controller’s decision.

To formulate the safety level of the driving situation, it is suggested that Longitudinal Safety Index (I_{Longi}) which is derived by using a warning index and an inverse Time To Collision (TTC^{-1}). Also, by using this safety index, Total Warning Time (*TWT*) and Total Longitudinal-safety Value (*TLV*) are defined.

Finally, closed-loop simulation was conducted to demonstrate the proposed algorithm by using longitudinal vehicle model which is developed by using the real vehicle’s test data and vehicle dynamics. From the simulation result, the control performances of the proposed AEBS algorithm was concluded in the rear-end collision probable situation.

SAFETY INDEXES FOR DEVELOPMENT OF THE AEBS ALGORITHM

Several authors have derived safety indexes for evaluation of vehicle’s safety systems. Especially, the *TTC* and the warning index are well-known parameters in Adaptive Cruise Control (ACC) system and Collision Warning/Collision Avoidance (CW/CA) systems.

The *TTC* is defined as the time left to a collision. Form the definition of the *TTC*, TTC^{-1} can be defined as:

$$TTC^{-1} = \frac{v_{long}}{P_{long}} \tag{1}$$

where, v_{long} is the relative velocity between the subject vehicle and the preceding vehicle and p_{long} is the longitudinal vehicle spacing for the subject’s driving direction.

The warning index represents the danger of physical collision in the current driving situation and this is defined as follows:

$$x = \frac{p_{long} - d_{br}}{d_w - d_{br}} \tag{2}$$

where, d_{br} and d_w are the braking-critical and warning-critical distances. If p_{long} exceeds d_{br} and d_w, then the warning index is a positive value that is greater than unity, and indicates that the current driving situation is in a safe region. If p_{long} is below d_{br}, then the warning index is a negative value and indicates that the current driving situation can be dangerous. The warning-critical and braking-critical distances are defined as follows:

$$\begin{aligned} d_{br} &= v_{long}T_{s,delay} + f(\mu)\left(\frac{{v_s}^2 - (v_s - v_{long})^2}{2a_{\max}}\right) \\ d_w &= v_{long}T_{s,delay} + f(\mu)\left(\frac{{v_s}^2 - (v_s - v_{long})^2}{2a_{\max}}\right) + v_s T_{h,delay} \end{aligned} \tag{3}$$

where, $T_{sys,delay}$ is the system delay, which is given by the brake-system hardware, a_{max} is the maximum deceleration of the vehicle under normal road conditions, v_s is the velocity of the subject vehicle, $T_{h,delay}$ is the delay in human response between recognition and manipulation, *f(-)* is the friction scaling function, and μ is the estimated value of the tire-road friction coefficient. [5]

Longitudinal Index

In case of the TTC^{-1}, it is suitable for assessments of safety measure with the vehicle in front of the speed difference between the vehicle and its leader is maintained. On the other hand, the warning index is physically driven index based on the driving situation and considered as maximum deceleration of the vehicle.

To make up for the each parameter’s insufficiency, the longitudinal index to monitor the vehicle-to - vehicle collision can be determined by using the warning index and the TTC^{-1}.

In the case of the warning index beyond a threshold value and the TTC^{-1} 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 using the warning index and the TTC^{-1} can be determined as follows:

$$I_{longitudinal} = \max\left(\frac{|x_{\max} - x|}{|x_{\max} - x|}, \frac{|TTC^{-1}|}{|TTC_{th}{}^{-1}|}\right) \tag{4}$$

where, x_{max} is the maximum warning index, TTC_{th}^{-1} is the threshold of the TTC^{-1}.

Figure 1 shows the warning index- TTC^{-1} plane and describes the determination of the longitudinal index more detail. [5]

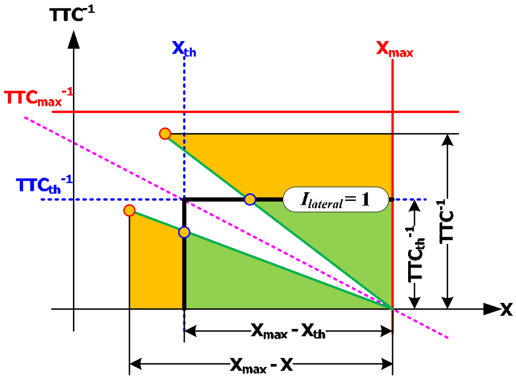


Figure 1. The Longitudinal Safety Index in the warning index- TTC^{-1} plane

From the definition, the longitudinal safety index is able to indicate the dangerous ratio about the longitudinal safety threshold of the warning index and TTC^{-1}. In other words, in the case of the longitudinal safety index is exceed '1', it indicates that the current driving situation's dangerous level is directly proportional to the longitudinal safety index value.

Safety Indexes: Total Warning Time & Total Longitudinal-safety Value

The safety values derived in the longitudinal safety index indicate vehicle's instantaneous safety level. Therefore, if the longitudinal safety index with respect to the preceding vehicle in every simulation time step can be recorded, it is possible to check the system's overall control performance during the driving the driving from analysis of the longitudinal safety index trajectories.

To evaluate the overall safety of the system, *Jan Lundgren at al.* suggests the Time Exposed TTC and Time Integrated TTC values. [6]

Similarly this study, safety indexes can be derived from the trajectories by defining the longitudinal safety threshold, I_{Longi_th}. One measure of the total time spent in dangerous situations is Total Warning Time, which is defined as

$$TWT = \sum_{t=0}^{T} \delta(t) \cdot \tau$$
$$where \quad \delta_i(t) = \begin{cases} 1 & 0 \le I_{Longi_i}(t) \le I_{Longi}^{*} \\ 0 & otherwise \end{cases} \qquad (5)$$

$I_{Longi}(t)$ is the longitudinal safety index of vehicle in time step t . The simulation time step is denoted τ ,

The severity of the danger can be measured by Total Longitudinal-safety value of the total exceed values of the threshold which is defined as

$$TLV = \int_0^T \left(I_{Longi,i}(t) \right) \cdot \delta(t)\, dt \qquad (6)$$

The TWT and TLV are illustrated in Figure 2. The TTC trajectory

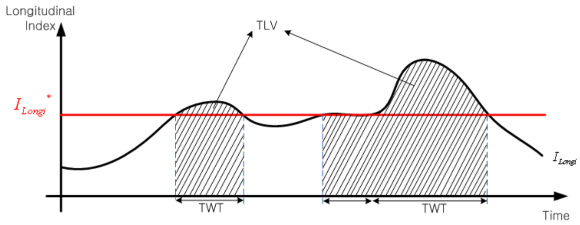


Figure 2. Longitudinal Safety Index trajectory and definition of TWT and TLV

AEBS CONTROL ALGORITHM FOT COMECIAL VEHICLES

To avoid or mitigate a rear end collision of the commercial heavy truck, the AEBS algorithm was developed. The AEBS control algorithm consists of two parts: obstacle detection part and main controller part.

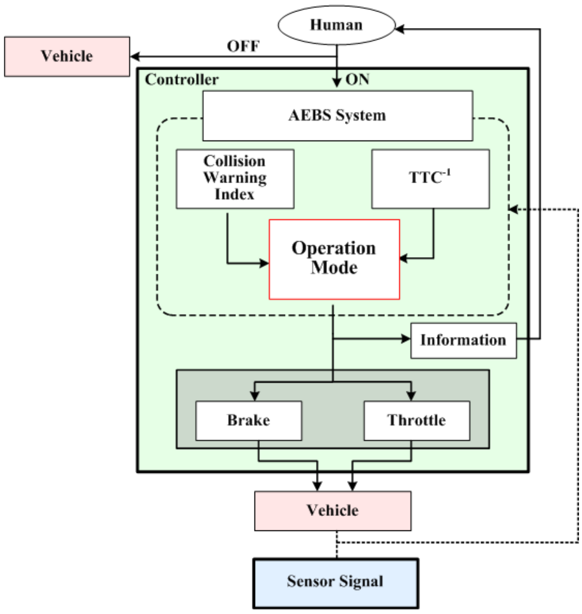


Figure 3. Flow chart of the AEBS algorithm

Obstacle Detection

In the obstacle detection part, front obstacle information was measured and collected for the main controller's decision. Vision sensor is known for its capability of measuring of a target's outline accurately. Also, vision system can provide a classification of objects. However, range and speed measurements are less accurate. On the other hand, radar sensor has a high accuracy in measuring of the range and speed. Therefore, these two types of the sensor are used to detect the front obstacle information.

Considered each sensor's detecting range and accuracy, the main target information is decided in the data fusion part. The data fusion part receives primary target information which is processed to judge in-lane target from the individual sensors and merges them to decide main target information.

Main Controller

The main controller of the AEBS algorithm is composed of the two control stage: upper and lower level controller.

Upper-level Controller: Control Mode Decision

By using the collected obstacle information, the upper level controller of the main controller decides the control mode.

To decide the control mode of the AEBS algorithm, warning index and TTC^{-1} parameters are considered. From the definition of theses parameters, if the vehicle's longitudinal safety comes to dangerous situation, TTC^{-1} will be increasing but warning index will be decreasing. Therefore, vehicle's longitudinal safety level can be defined in the warning index – TTC^{-1} phase.

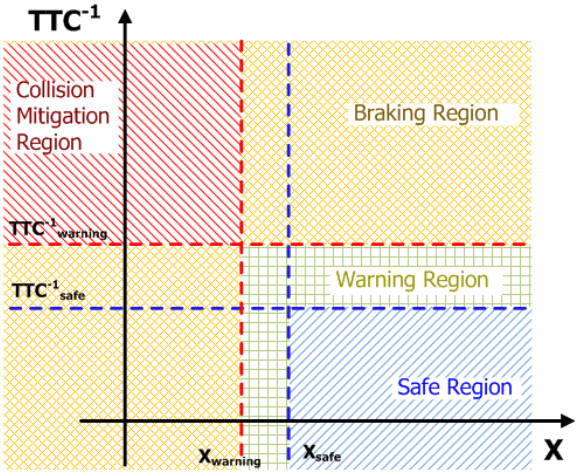


Figure 4. Safety Mode in the warning index – TTC-1 phase plane

To divide the control model, threshold value for each parameter is set two levels: 'Safety threshold' and 'Warning threshold'. The 'Safety threshold' means the value of which driver start feeling fear for driving situation. When the parameter near the 'Warning threshold' value, it means that driver should be start braking to avoid the rear-end collision.

By using these two level threshold values of each parameter, control mode can be defined as 4 Phase: 'Safe Region', 'Warning Region', 'Braking Region' and 'Collision Mitigation Region'.

In case of the 'Braking Region' and 'Collision Mitigation Region', it is important that the assurance assessing approach whether a collision with an observed object is avoidable or not.

To check the physical collision capability, the last moment of the physical collision is defined as the situation when relative velocity and clearance between subject vehicle and target vehicle are zero. Also, assume the 'required relative acceleration' for the last moment of the physical collision during 'physically required time'. From these definitions and assumption, physically required time can be calculated as equation (7).

$$\begin{cases} p_{long} + v_{long} \cdot \left(T_{req}\right) + \frac{1}{2} \cdot a_{r,req} \cdot \left(T_{req}\right)^2 = 0 \\ T_{req} = -\frac{v_{long}}{a_{r,req}} \end{cases} \tag{7}$$

where, T_{req} is physically required time and $a_{r,req}$ is required relative acceleration.

From this method, 'Collision Mitigation Region' is decided based not only on parametric division, but also on physical collision capability.

Lower-level Controller: Control Input Decision

When the upper-level controller decides the control mode, the lower level controller determines warning level and braking level to maintain the longitudinal safety.

i) Warning phase

If the upper-level controller decides that vehicle isn't in the 'Safe Region', lower-level controller gives the warning signal to the driver. The warning level is classified two levels. When the driving state is in a 'Warning Region', the first level warning starts running. If the driving state is in the 'Braking Region' or 'Collision Mitigation Region', the second level warning is operated. According to the warning level, the warning is composed of two kinds of alarm: 'alarm sound only' and 'alarm sound with tightening a seat-belt'.

ii) Braking phase

If the vehicle is in the 'Braking Region' or 'Collision Mitigation Region', in spite of the driver doesn't give a braking maneuver, autonomous braking is necessary until the vehicle's control mode return to 'Safe Region'. Also, when the driver gives a brake actuation, the driver's braking intention should influence to the AEBS braking level. Therefore, the braking level of the AEBS algorithms are based on control mode and braking maneuver.

In case of the 'Braking Region', lower-level controller gives first level brake operation. When the lower-level controller decides the 'Collision Mitigation Region', the second level brake starts operating. Only if both 'Collision Mitigation Mode' is decided and driver's braking maneuver is operation, the full braking action is triggered.

EVALUATIONS OF THE AEBS ALGORITHM

To demonstrate the AEBS algorithm, closed-loop simulation with human driver model was comprised ‘with AEBS driving case’ and ‘without AEBS driving case’ by using the proposed safety indexes. Also, for evaluation of the AEBS algorithm, simulation model is composed of longitudinal vehicle model and sensor model. The longitudinal vehicle model of the commercial target vehicle was developed by using the real vehicle’s test data and vehicle dynamics. The sensor model gives the front obstacle information which is consists of clearance, relative velocity and target on/off signal.

Two simulation scenarios were selected: emergency deceleration case and vehicle cut-in case.

Case □: Emergency Deceleration

To evaluate the proposed AEBS algorithm, simulation scenario is composed of emergency deceleration case as follow:

- Preceding Vehicle Speed: 80km/h
- Subject Vehicle Speed: 80km/h
- Initial Clearance: 20m
- Preceding Vehicle’s Final Speed : 30km/h
- Preceding Vehicle’s Deceleration: -4.5m/s^2
- Driver’s Reaction Delay Time: 0.8sec

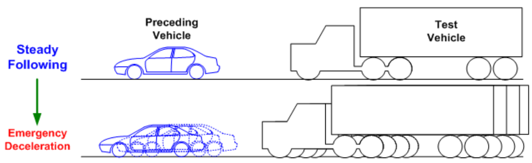
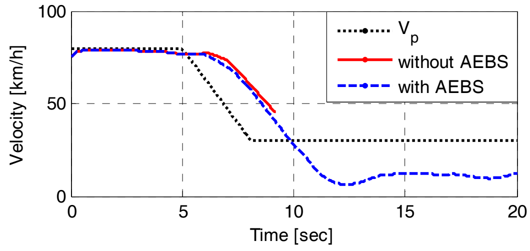


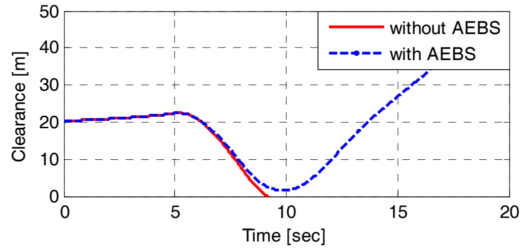
Figure 5. Simulation scenario for evaluation of the AEBS algorithm: Emergency Deceleration Case

As shown in Figure 6-d, when the preceding vehicle starts to decelerate, the AEBS algorithm gives a warning signal immediately. Also, as shown in Figure 6-a and 6-b, the AEBS algorithm operates autonomous braking to avoid the rear-end collision. However, without AEBS algorithm case, driver's braking input which is working after reaction delay cannot prevent the vehicle’s collision.

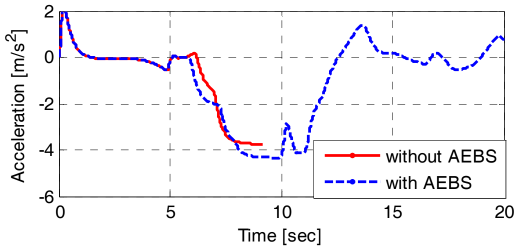
In order to validate the AEBS algorithm, safety indexes are comprised between ‘with AEBS’ and ‘without AEBS’. Safety indexes (‘Warning index’, ‘TTC^{-1}’ and ‘I_{Longi}’) are shown in Figure 7. After preceding vehicle starts deceleration, all safety indexes over the safety threshold. In case of the ‘without AEBS’, safety indexes are getting dangerous until collision occurred. However, ‘with AEBS case’ returns to the safety region by using the AEBS operation.



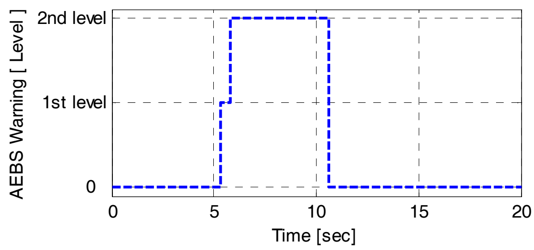
a. Velocity [kph]



b. Clearance [m]

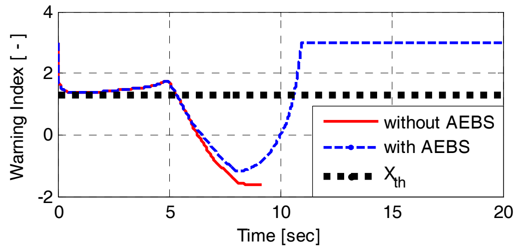


c. Acceleration [m/s2]

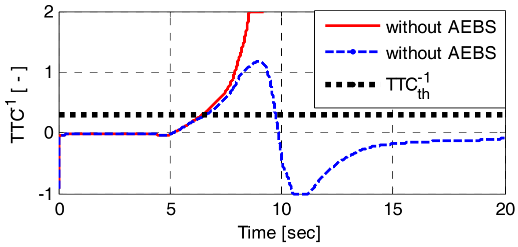


d. Warning Signal

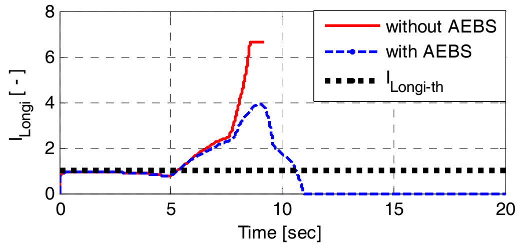
Figure 6. Simulation Results: Emergency Deceleration Case



a. Warning Index



b. Inverse TTC



c. Longitudinal Index

Figure 7. Safety Indexes: Emergency Deceleration Case

Also, 'TWT' and 'TLV' can be calculated by using I_{Longi} trajectories as shown in Figure 7-c. From these result, Table 1 contains the resulting of comparison of safety indexes between 'with' and 'without' AEBS. As shown in Table 1, all safety indexes indicate with AEBS case is safer than without case.

Table 1 Values of safety indexes: Emergency Deceleration Case

	without AEBS	With AEBS
Min. X	*-1.62*	*-1.20*
Max.TTC^{-1}	*2.0*	*1.76*
Max. I_{Longi}	*6.67*	*3.92*
TWT	*3.83*	*5.28*
TLV	*12.14*	*12.09*

Case Ⅱ: Low-speed Vehicle Cut-in Case

The second simulation scenario is low-speed vehicle's cut in situation. The detail options of the scenario are as follow:

- Preceding Vehicle Speed: 80km/h
- Subject Vehicle Speed: 80km/h
- Initial Clearance: 20m
- Cut-In Vehicle Speed : 65km/h
- Cut-In Distance: 15m
- Driver's Reaction Delay Time: 0.8sec

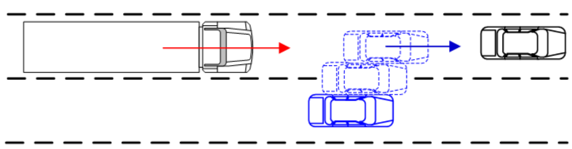
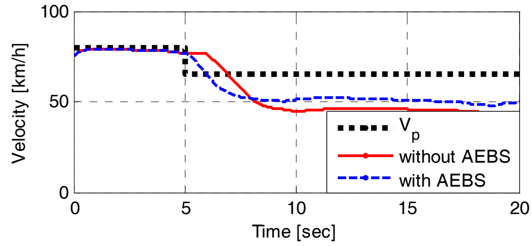
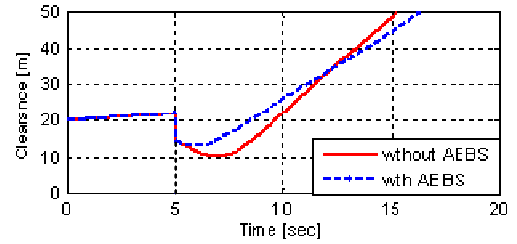


Figure 8. Simulation scenario for evaluation of the AEBS algorithm: Low-speed Vehicle Cut-in Case

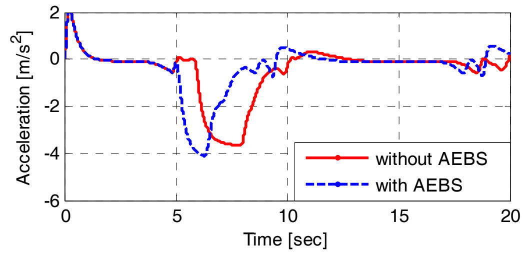
As shown in Figure 9, the braking operation of the 'with AEBS' case was faster than 'without AEBS' case. Also, when the lower speed vehicle starts to cut-in, the AEBS algorithm gives a warning signal immediately as shown in Figure 9-d.



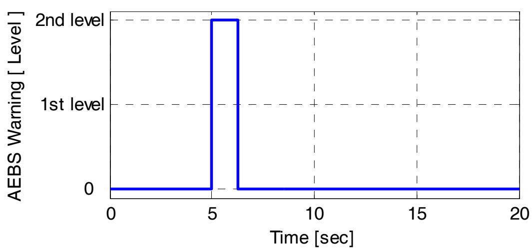
a. Velocity [kph]



b. Clearance [m]



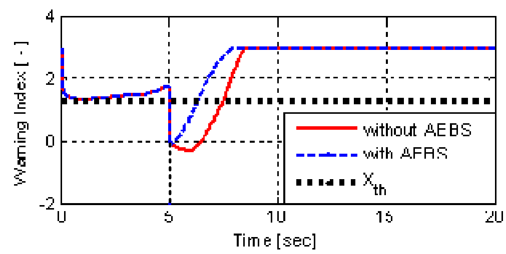
c. Acceleration [m/s2]



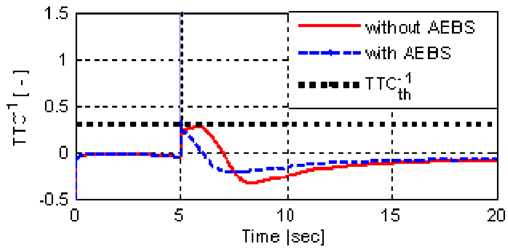
d. Warning Signal

Figure 9. Simulation Results: Low-speed Vehicle Cut-in Case

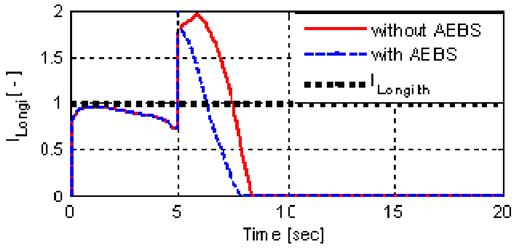
Safety indexes in the low-speed vehicle cut-in scenario are shown in Figure 7. In case of the warning index and longitudinal safety index exceed the safety threshold during the low speed cut-in is operation and return to the safe region. However, in case of the TTC^{-1} value, the whole of driving trajectories are maintained the safe region.



a. Warning Index



b. Inverse TTC



c. Longitudinal Index

Figure 10. Safety Indexes: Low-speed Vehicle Cut-in Case

Safety indexes can be compared between 'with' and 'without' AEBS in detail, as shown in Table 2. As shown in Figure 10-b and Table 2, TTC^{-1} values are not suitable for comparison in this simulation scenario. Also, maximum values of the warning index and I_{Longi} are little different. On the contrary to this, TWT and TLV can be distinguished from with AEBS and without AEBS.

Comparison results of the TWT and TLV indicate that the proposed AEBS algorithm can be improved the commercial vehicle's longitudinal safety compared to the without control case.

Table 2 Values of safety indexes: Low-speed Vehicle Cut-in Case

	without AEBS	With AEBS
Max. X	*-0.34*	*0.07*
Min.TTC^{-1}	*0.3*	*0.22*
Max. I_{Longi}	*1.96*	*1.81*
TWT	*2.50*	*1.29*
TLV	*4.24*	*1.95*

CONCLUSIONS

In this paper, the AEBS algorithm for the commercial vehicle was proposed. The proposed AEBS Algorithm consists of obstacle detection part and main controller part. In the obstacle detection part, front obstacle information was measured and collected by using the vision sensor and radar sensor. Considered each sensor's detecting range and accuracy, the main target information is decided. The main controller of the AEBS algorithm is composed of the two control stage: upper and lower level controller. By using the collected obstacle information, the upper level controller of the main controller decides the control mode based not only on parametric division, but also on physical collision capability. The lower level controller determines warning level and braking level to maintain the longitudinal safety.

To formulate the safety level of the driving situation, safety indexes (Total Warning Time: *TWT* and Total Longitudinal-safety Value: *TLV*) are suggested which are defined by using the longitudinal safety index and its threshold value.

Finally, closed-loop simulation was conducted to demonstrate the proposed algorithm by using longitudinal vehicle model and sensor model.

From the simulation result and analysis using this safety indexes, it is shown that proposed AEBS algorithm can enhance the commercial heavy truck's longitudinal safety in the dangerous driving situation which can be occurred rear-end collision.

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