The potential of autonomous emergency braking systems to mitigate passenger vehicle crashes

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Abstract

This paper details part of a research program conducted to examine the potential effect of autonomous emergency braking (AEB) systems on common crash types that involve a frontal collision. To accomplish this, simulations were conducted of 103 real world crashes. AEB system models with differing specifications were applied to these simulations to determine the change in impact speed that various AEB interventions could produce. It was found that AEB systems have the potential to reduce the impact speed, and hence the severity, in pedestrian crashes, right turn crashes, head on crashes, rear end crashes and hit fixed object crashes. The greatest potential reductions were for pedestrian crashes, head on crashes and rear end crashes. The variations in system specification demonstrate the advantages of a longer time-to-collision and higher autonomous deceleration. A system that has less potential to generate false alarms than the other systems was considered and demonstrated potential for reducing the impact speed in pedestrian, head on, rear end and hit fixed object crashes.

Keywords: autonomous emergency braking; traffic accident; speed; accident reduction

1. Introduction

The last decade has seen the advent of various intelligent driver aids that are commonly referred to as advanced driver assistance systems (ADAS). Some examples of ADAS are lane departure warning, intelligent speed adaptation, automatic parking, electronic stability control and adaptive cruise control (ACC). Autonomous emergency braking (AEB) is an emerging ADAS that autonomously brakes the vehicle when an impending collision is detected. More broadly, such systems are referred to as forward collision avoidance technologies.

An AEB system is made up of three key components; sensors to detect and classify objects in front of the vehicle, a control system to interpret the data from the sensors and decide when to intervene, and a braking system that allows the vehicle to be braked autonomously.

The sensor types that can be used include RADAR, LiDAR, ultrasonic, infrared sensors, and video cameras. Each type of sensor has strengths and weaknesses with regard to the information supplied to the control system. Multiple sensors can be used in combination to collect more complete information on which to base decisions. For example, a camera may be used to aid the classification of objects, the relative location of which is detected by a RADAR sensor.

The algorithm used by the control system is designed to take effective action, taking account of constraints that will include the minimisation of false-positive detection and interventions. There may be a trade-off to be made between taking the earliest possible action, and high levels of false-activation, and hence many systems may only initiate emergency braking one second before the collision, limiting velocity change to 35 or 40 km/h prior to the collision. Some systems may ameliorate this kind of limitation by providing early feedback to the driver of the potential for a collision and allowing the driver to initiate appropriate actions to avoid a collision if needed.

Theoretically, forward collision avoidance technologies are likely to be highly effective as they are designed to reduce impact speed, and hence crash energy. Injury risk is non-linearly related to crash speed. Therefore speed reductions produced by AEB may result in a large reduction in injury risk. In many cases, particularly in an urban environment where travel speeds are lower, crashes will be avoided altogether.

Most previous research on the benefits of AEB systems has looked exclusively at effects on rear ends crashes and crash avoidance was often used as the measure of effectiveness. The estimates of the effectiveness of an AEB system at avoiding a crash varied from 10 to 72 per cent (Coelingh et al. 2007; Georgi et al., 2009; Kusano and Gabler, 2010; Najm et al., 2006; Schiittenhelm, 2009). Estimates of the reduction in fatal rear end crashes are between 36 and 44 per cent (Sugimoto and Sauer, 2005; Grover et al., 2008).

We identified only three studies that considered crash types other than rear end crashes. Two considered all crash types and found crash reductions of 22 and 43 per cent respectively (Highway Loss Data Institute, 2011; Hummel et al., 2011). The third study considered pedestrians and estimated that fatal collisions might be reduced by 40 per cent and serious injury collisions by 27 per cent (Rosén et al., 2010). These figures are similar to the reductions found in the studies that only considered rear end crashes.

The aim of this paper is to use simulation to examine the potential effect of AEB systems on collision speeds in a range of common crash types that involve a frontal collision.

The study that is described in this paper is a component in a broader research project that we undertook for the Queensland Department of Transport and Main Roads. That project included the conversion of speed reductions to injury risk reductions and the weighting of results to match crash incidence as described by police-reported crash data.

2. Method

The specific operation of the sensors used in AEB systems, and the processes involved in the detection, classification, and tracking of objects is complex and beyond the scope of this paper. However, if it is accepted that an object can be identified and tracked successfully, the mechanism of the effect of an AEB system is largely predictable: braking is optimised and effective reaction time (which is normally a human factor) is reduced. Both these effects reduce stopping distances and the speed of the vehicle at any given point along its stopping path.

Because the mechanism is predictable, the effects of AEB systems are amenable to simulation. If the paths of vehicles (or other road users) in a collision are known, the collision can be described numerically in terms of the speed, direction, and the timing and strength of braking. Once the crash is described, AEB effects can be superimposed on the collision history, and the effect of the AEB system on the impact speed can be simulated.

2.1 Crash data

To simulate the effect of an AEB system on a crash, detailed information about the crash is required including; the trajectories of vehicles, the speed of the vehicles, braking location, and impact locations. At-scene crash investigation can provide this level of information. The Centre for Automotive Safety Research (CASR) has been conducting such investigations for over four decades. The data used in this report was limited to investigations taking place between 1995 and 2011. During this time 1,145 crashes were investigated and, of these, 364 had been reconstructed so that travel and impact speeds were known.

Definitions for Coding Accidents (or DCA codes) describe the movements of vehicles prior to collision and are therefore useful in identifying those crashes whose incidence will be sensitive to AEB systems (see Andreassen, 1994). DCA codes were used to determine crash types within the in-depth database that had potential to be mitigated by an AEB system and that were also common in mass crash data (see Figure 1).

When deciding what DCA codes to include, it became apparent that in some cases multiple codes covered crashes that, for the purpose of examining the effect of AEB on different crash types, were essentially the same. These DCA codes were grouped together. The crash types included and their corresponding DCA code diagrams can be seen in Figure 1.

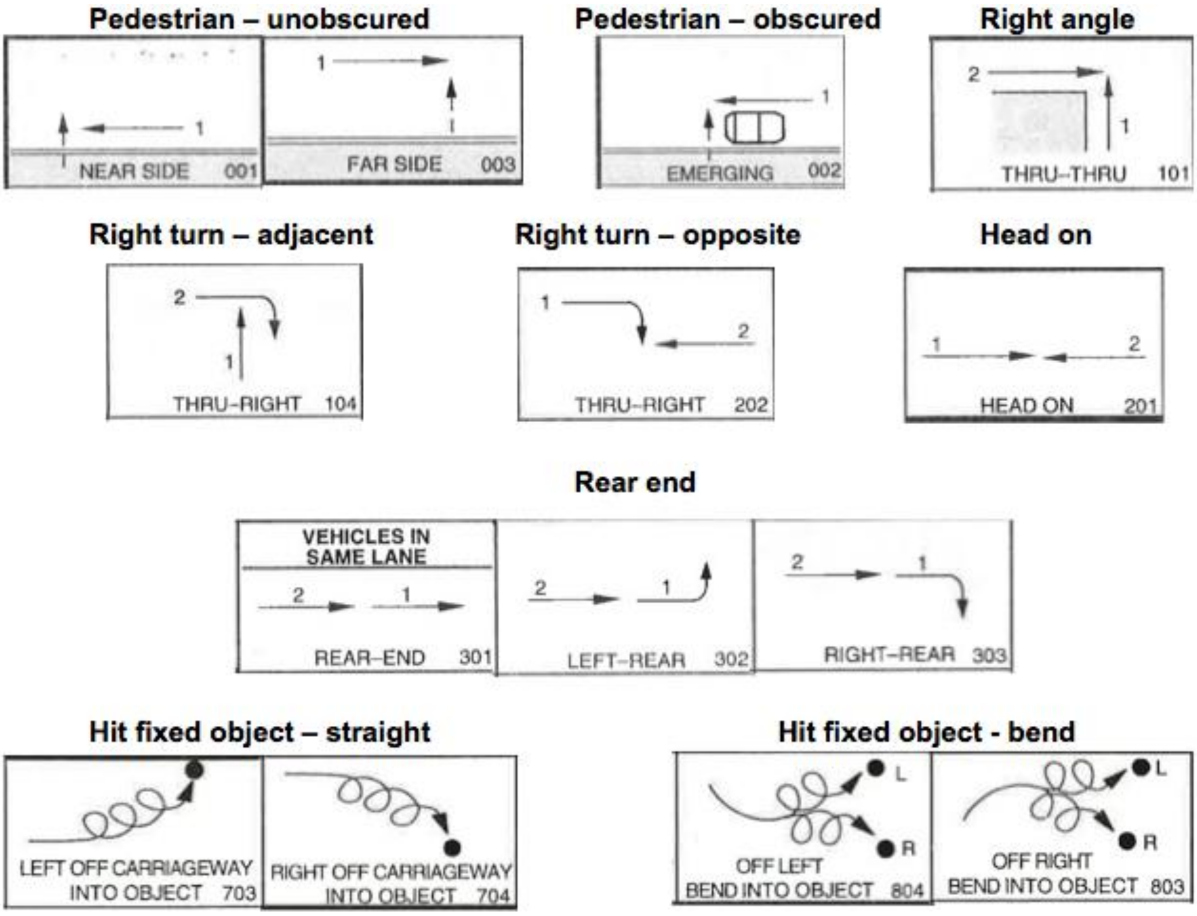

Figure 1: DCA code diagrams with potential to be mitigated by AEB/FCAT by crash type grouping (adapted from Andreassen, 1994)

The crashes that fell within relevant groups of DCA codes were disaggregated into speed zone groups: 50 and 60 km/h zones; 70, 80 and 90 km/h zones; and 100 and 110 km/h zones.

From the 364 crashes an attempt was made to randomly select five injury crashes from each combination of relevant DCA code and speed zone group (giving up to 15 in each crash type grouping). However, there were not always five crashes available for simulation within each speed zone group.

It should be noted that AEB systems cannot be expected to work when the vehicle has lost control. Furthermore, it is to be expected that many such crashes will be eliminated or modified by the stability control systems that will be ubiquitous in vehicles with AEB. For this reason the hit fixed object crashes that were chosen for simulation were only crashes where the vehicle dynamics did not satisfy criteria that would have activated stability control. For this reason they only represent a subset of hit fixed object crashes, as the DCA code descriptions make no distinction between vehicles that had loss control and ones that had not, despite the diagram implying a loss of control.

A total of 103 crashes were chosen for simulation. The number of cases in each crash type by speed zone group is given in Table 1.

Table 1: Number of simulated cases by crash type and speed zone group

Crash Type	Speed zones			Total
	50 and 60 km/h	70, 80 and 90 km/h	100 and 110 km/h	
Pedestrian - unobscured	9	2	0	11
Pedestrian – obscured	3	0	0	3
Right Angle	5	4	5	14
Right turn – adjacent	5	3	5	13
Right turn – opposite	5	4	0	9
Head on	5	4	5	14
Rear end	8	1	2	11
Hit fixed object – straight	6	2	10	18
Hit fixed object - bend	2	2	6	10
Total	48	22	33	103

2.2 Crash simulation

The trajectory, speeds, braking and impact configuration of the vehicles in the selected in-depth cases were modelled in PreScan[1], a simulation environment for designing and evaluating primary safety technologies. While PreScan is capable of performing very detailed simulations of advanced driver assistance systems, including the characteristics of specific sensors, these capabilities were not used in this study. Instead, PreScan was used to generate a time based trajectory of the struck vehicle, pedestrian, or object (the crash partner) in the coordinates of the AEB equipped vehicle. This trajectory was then used as a basis for determining the response of various AEB systems to the crash partner entering the scan zone. This response, and consequent changes in impact speed, were subsequently modelled using program routines implemented in MATLAB[2].

An example of how an in-depth crash investigation case was modelled in PreScan is shown in Figure 2. The site diagram from the crash is shown on the left and the scenario modelled in PreScan is shown on the right. The coloured lines in the PreScan diagram represent the trajectories of the vehicles with the spacing of the coloured symbols representing the speed of the vehicle.

[1] TASS-SAFE, Netherlands
[2] MathWorks, MA, USA

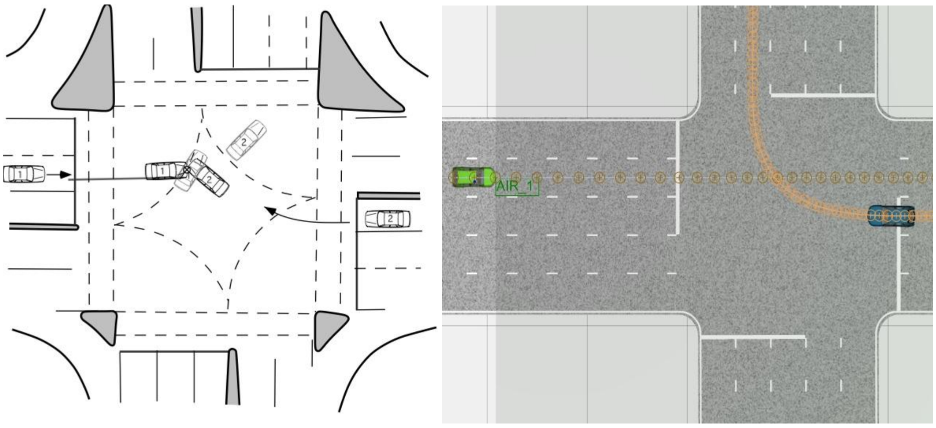

Figure 2: Site diagram of in-depth crash investigation case (left) and corresponding PreScan scenario (right)

2.3 AEB system modelling

For each crash, the trajectory data was analysed to determine how the closing speed at the collision point might have been affected by an AEB system. To do this, a model of an AEB system was developed for which performance parameters could be specified. The parameters that were used to define the performance of the system were shape, range, angle, computation time, time-to-collision (TTC) action time, system deceleration level and driver supported deceleration level.

- The *shape* refers to the shape of the area in which objects can be detected.
- The *range* and *angle* define the area forward of the vehicle in which an object can be detected. In the case of a rectangular detection area *width* is used in place of *angle*.
- The *computation time* (in seconds) was used to represent the time required by the system to observe an object and predict its future motion.
- *TTC action* dictated the time before the predicted collision that the AEB system applied the brakes.
- The *system deceleration* defined the level of deceleration applied autonomously.
- Most systems will also assist with the braking actions of the driver; if the driver brakes after a potential collision has been detected then their deceleration is increased to the maximum possible. In the reconstruction of the crashes, driver activated emergency braking of 0.7g was assumed. The *driver supported deceleration* level in the AEB model was 0.8g. (Note that some AEB manufacturers claim to provide up to 1.0g braking).

In the model, when a vehicle enters the detection area of the AEB equipped vehicle the model waits for the computation time to expire then calculates predicted positions of the crash partner into the future, in both the longitudinal and lateral direction, based on the object's current position, velocity, and acceleration in the host vehicle's reference frame. If a collision is predicted to occur within the TTC action time the system brakes the vehicle at either the system deceleration or the driver supported deceleration, depending on the drivers response at that point in time in the real crash.

The parameters used to describe the different systems are shown in Table 2 and a visual representation of the detection areas are shown in Figure 3. The first set of parameters describes a baseline system with a long field of view, a two-second TTC action time and strong emergency braking. This is likely to be most effective but it also may produce a relatively large number of false alarms. The second and third systems describe variations on this: one with a shorter TTC and the other with a lower level of braking. The fourth system describes a shorter range, short TTC system with a field of view that has been restricted to only look at the lane ahead in order to minimise false alarms. It should be noted that this restricted view system uses a simplified collision prediction method that is only based on the longitudinal position and velocity of the crash partner. This simplified prediction method was the basis for selecting a lower computation time than other systems.

Table 2: Attribute values for AEB systems modelled

Attribute	Baseline	Short TTC	Low system deceleration	Restricted view
Shape	Cone	Cone	Cone	Rectangle
Range (m)	100	100	100	40
Angle (deg) or width (m)	15	15	15	4
Computation time (s)	0.2	0.2	0.2	0.1
TTC action (s)	2.0	1.0	2.0	1.0
System deceleration (g)	0.8	0.8	0.4	0.8
Driver supported deceleration (g)	0.8	0.8	0.8	0.8

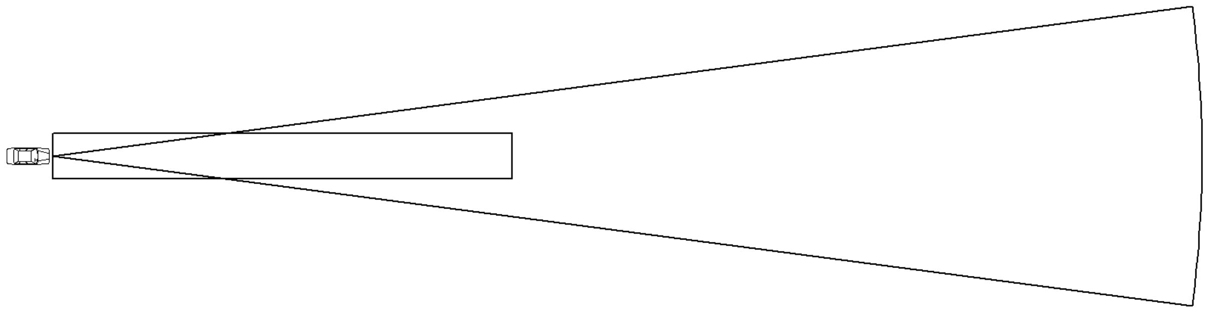

Figure 3: Fields of view of the AEB systems modelled

The AEB system model was only applied to one vehicle in the crash. This was the vehicle that had the most ‘frontal’ collision in the crash. If both vehicles in the crash had a frontal collision (i.e. head on crashes) the vehicle that was travelling straight ahead and had not crossed the centre-line of the road was chosen as the vehicle with the AEB system. The results are therefore conservative, with respect to a scenario in which both vehicles are equipped with an AEB system and in which both vehicles can respond.

It should be noted that no vehicle dynamics were taken into account once braking began. That is, the model simply calculated the new travelling speed at the original collision point. Because of this, crashes where a change in trajectory might have prevented a collision from occurring were not identified as such. Intersection crashes where a vehicle is travelling across the path of another vehicle are most likely to be affected by this limitation.

2.4 Modified crash speed estimation

The metric that was used to examine the effect of the AEB system is the longitudinal closing speed at impact from the reference frame of the vehicle that is equipped with an AEB system. This was done to properly illustrate the severity of the impact across all configurations. This is referred to as ‘impact speed’ for simplicity.

The modified relative impact speed at the collision point was calculated as shown in equation (1), where S_f is the impact speed, S_i is the initial relative speed, A is the deceleration value in units of g, and D is the distance over which the deceleration occurs.

$$S_f = \sqrt{S_i^2 - 19.62AD} \qquad (1)$$

3. Results

3.1 Position of vehicles at critical times-to-collision

As a preliminary step, the locations of the crash partners at two seconds TTC and one second TTC were plotted for each crash. These are shown in Figure 4. Over-plotted on this data are areas corresponding to certain fields of view. The shaded area corresponds to a width of four metres. These figures provide a visual representation of the range and field of view required to detect an impeding crash two seconds or one second before it occurs, less any computation time. It might be noted how the position of the crash partner at the given TTC varies by crash type. For example, the crash partners in rear end crashes are positioned within the dark grey area that represents a total width of four metres, while the right angle crashes are generally positioned at large lateral offsets, outside even a 40 degree field of view in most cases.

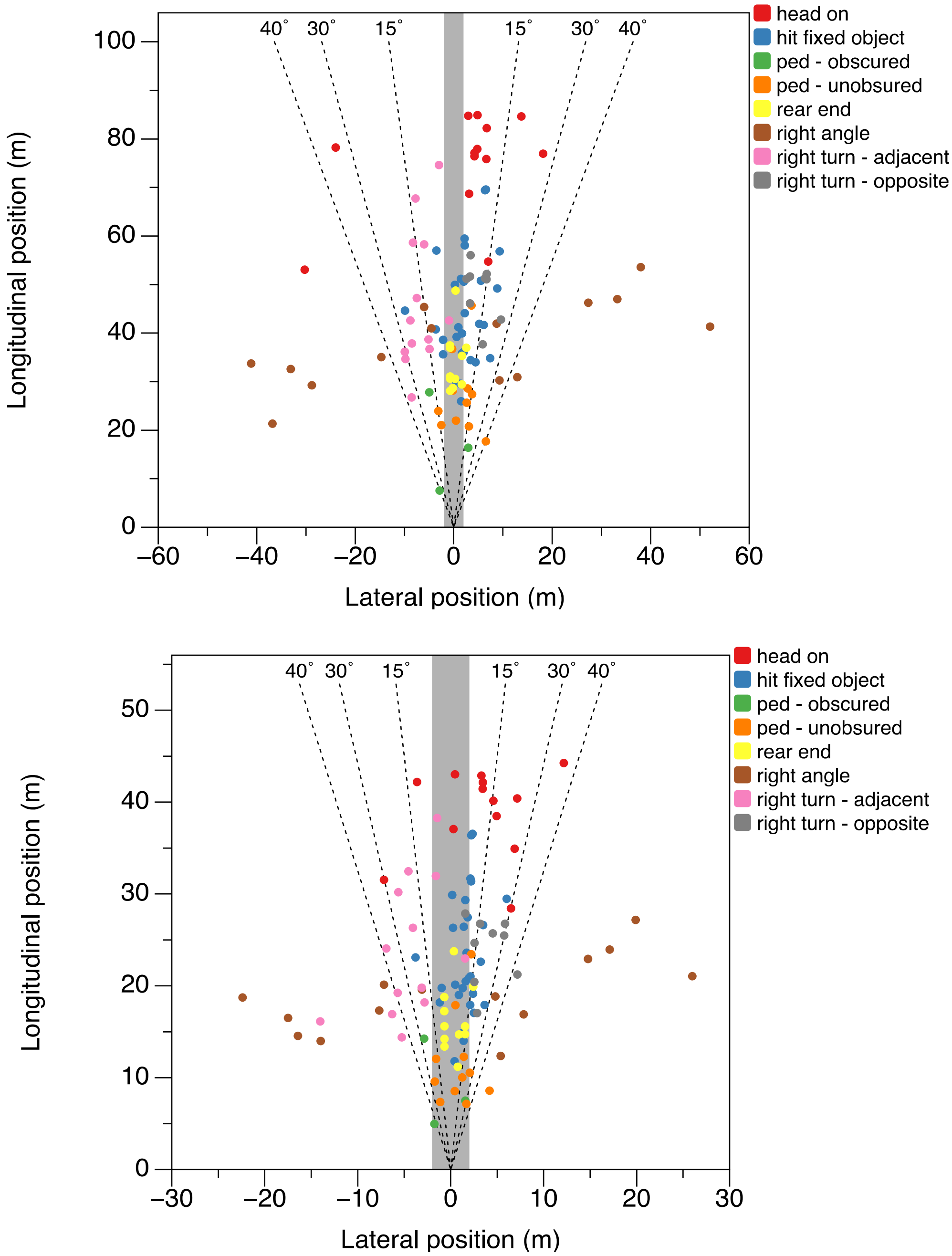

Figure 4: Location of crash partner at two (top) and one seconds (bottom) TTC by crash type

Figure 4 also hints at the limitations that AEB systems will have in preventing some crash types. For example, it would be ideal if an AEB system could warn of an impending head on collision at two seconds TTC. But Figure 4 suggests that this is unlikely to be possible, given the crash partner was typically in its correct lane at two seconds TTC. Even at one-second TTC, the majority of the head-on crash partners are not yet in the forward path of the host vehicle. One of the challenges for the designers of AEB systems is likely to be successfully identifying crash threats from benign traffic in these kinds of circumstances. Trajectory tracking may assist in this, but it remains to be demonstrated whether threats can be identified with high sensitivity and specificity.

3.2 Effect of AEB systems on crash speeds

The effect of the various AEB systems are summarised in Figure 5, which shows the average speed for each crash type according to AEB parameters.

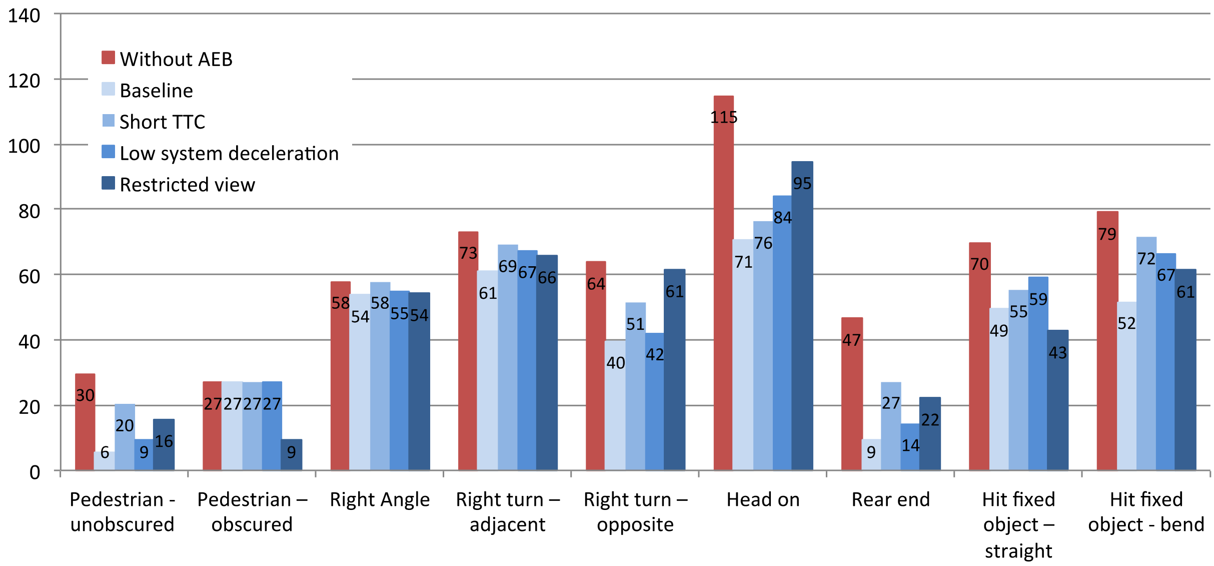

Figure 5: Average impact speeds by crash type and AEB system

Not all crash types were affected equally. AEB systems had little effect in right angle crashes, whereas relative and absolute speed reductions were large in other crash types. Obscured pedestrian crashes were not affected except in the case of the restricted view system. This is due to a combination of a wider field of view at close range produced by the rectangular shape (see Figures 3 and 4) and a shorter computation time. The relative effects of a shorter TTC and lower system deceleration vary between crash types.

3.3 Crashes reduced to a negligible impact speed

The numbers of crashes either avoided or reduced to an impact speed of 10 km/h or less (including crashes that were avoided) are shown in Table 3. The baseline system avoided 19 of 103 crashes while a shortened TTC reduced this number to five. A reduced braking level also reduced the number of crashes avoided, but to a lesser extent. Increasing the view angle at short range was also effective in increasing the number of crashes avoided (relative to the longer range system with a one second TTC), with the majority of the additional crashes avoided being pedestrian crashes.

The potential of AEB systems to avoid crashes altogether appears to be greatest for pedestrian crashes and rear end crashes, though this depends on the parameters of the system.

The AEB systems were unable to avoid any of the right turn (both adjacent and opposite) and head on crashes. This is unsurprising for head on crashes as, even if the vehicle fitted with an AEB system came to a stop, the other vehicle's speed is unaffected. Though none of the right turn – opposite crashes were avoided, four had an impact speed that was reduced to 10 km/h or less. However, reductions in impact speeds in head on crashes were significant and this would translate into much reduced risks of serious and fatal injury. Given that no vehicle dynamics were taken into account once braking began it is possible that in reality more crashes could have been avoided.

Table 3: Crashes avoided or reduced to 10 km/h or less by crash type

Crash Type	Sample size	Crashes avoided with AEB				Crashes at 10 km/h or less with AEB			
		Baseline	Short TTC	Low sys. dec.	Restricted view	Baseline	Short TTC	Low sys. dec.	Restricted view
Pedestrian - unobscured	11	6	1	5	3	8	1	7	4
Pedestrian – obscured	3	0	0	0	2	0	0	0	2
Right Angle	14	1	0	0	0	1	0	0	1
Right turn – adjacent	13	0	0	0	0	1	0	0	0
Right turn – opposite	14	0	0	0	0	0	0	0	0
Head on	9	0	0	0	0	3	1	2	0
Rear end	11	7	2	5	3	8	2	6	4
Hit fixed object – straight	18	4	1	1	1	5	2	2	3
Hit fixed object - bend	10	1	0	0	0	2	0	0	0
Total	103	19	4	11	9	28	6	17	14

4. Discussion

Much of the previous research on the effectiveness of AEB has centred on its effect on rear end crashes and pedestrian crashes. The results presented in this paper confirm that AEB has the potential to be effective at avoiding or reducing impact speed in rear end crashes while also demonstrating that AEB could be an effective vehicle technology for reducing the impact speed of vehicles in a broad range of crash types.

The AEB system model used in this analysis is a simplification of complex technology that is still evolving. One of the greatest challenges facing manufacturers of AEB systems is to correctly identify collision threats and avoid false alarms in complex environments. The AEB system model used in this analysis assumed that if a vehicle was inside the detection zone it could be identified and tracked (after the computation time had passed). In reality this is a complex task and we may not have completely represented some current systems; for example, an AEB system may not activate braking until the crash partner is more-or-less directly in front of the vehicle, even if the crash partner is within the detection area, in order to minimise false alarms. The restricted view system presented in this paper attempts to represent this kind of system. A further simplification we have made is to assume that all the variables included in the model are static. In actual systems they may be dynamic (e.g. TTC may be increased at higher speeds, or reduced in some environments to prevent false alarms). It should also be noted that there are differences in the design and mode of operation of current AEB systems that imply different levels of effectiveness. For these reasons, the results should be interpreted as showing the potential range of the effects of some AEB systems.

Unsurprisingly, reductions in the TTC at which an AEB system acts and in the system deceleration reduced the effectiveness of the baseline AEB system. Both variations represent potential countermeasures to the false-alarm problem (as does restricting the view of a system) highlighting the benefit in investing in methods to increase the reliability of AEB system without increasing the rate of false alarms.

The restricted view system was not as effective as the baseline system in all but pedestrian – obscured crashes and hit fixed object crashes occurring on a straight stretch of road. However, it did still show impact speed reductions of more than 10 km/h in all pedestrian, head on, rear end and hit fixed object crashes. The largest differences between the baseline and the restricted view systems were in right turn – opposite and head on crashes, with differences of 21 and 24 km/h in impact speeds respectively. These results show that such a system, which would be expected to produce less false alarms than the other systems, can still be effective in reducing impact speeds in a variety of crash types.

The reductions in average impact speed found in the pedestrian crashes and head on crashes are encouraging as these are two crash types that can be particularly severe. While no head on crashes would be avoided the average impact speed was reduced from 114 km/h to as low as 71 km/h. This represents a considerable reduction in impact severity and may result in a much-reduced risk of injury, especially fatal injuries. However, it should be borne in mind that the results pertain to a system that tracks and predicts and responds to an imminent crash even if the crash partner is not directly in front of the vehicle. If the AEB system was amended to react only to objects within the vehicle's lane, Figure 4 shows that the vehicle would not have commenced braking in any of the head on crashes at two seconds TTC, and only in two of the nine at one second TTC. The success of AEB in mitigating head on crashes may therefore be largely dependent upon the ability of the system to correctly discern a threating vehicle before it impinges on the AEB equipped vehicle's lane of travel.

There are other potential limitations to the performance of AEB systems that were not considered in this analysis. These include the ability to function in low light and the ability to function in inclement weather.

Predicted speed reductions estimated from in-depth crashes are subject to error from various sources, including estimates of speed in the actual crash, but also from the number of crashes in the sample. While we simulated over 100 crashes, the number in each crash type was less than 20 in every case, and the results are correspondingly subject to random error.

The simulation methodology did not account for crashes that may have been avoided due to one vehicle slowing sufficiently to allow the other vehicle to safely pass. This is most likely to affect right angle crashes. Conversely, the possibility that rear end crashes may occur when a second vehicle following an AEB equipped vehicle is not able to brake as quickly or as hard as the AEB equipped vehicle, is sometimes raised. In fact, Schittenhelm (2009) found the opposite to be true. He suggested that AEB systems result in earlier, less severe braking, and helped to avoid last moment panic braking that can precede a vehicle being struck in the rear.

5. Conclusions

AEB has the potential to reduce the impact speed, and hence the severity, in pedestrian crashes, right turn crashes, head on crashes, rear end crashes and hit fixed object crashes. It appears that they may have little or no effect on right angle crashes, but secondary effects that improve drivers' abilities to avoid collisions may be important in this case. Potential benefits appear to be greatest in pedestrian crashes, rear-end crashes and head on crashes.

The variations in system specification demonstrate the advantages of a longer time-to-collision and higher autonomous deceleration.

A system that has less potential to generate false alarms than the other systems was considered and demonstrated potential for reducing the impact speed in pedestrian, head on, rear end and hit fixed object crashes.

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