POTENTIAL BENEFITS OF AUTONOMOUS EMERGENCY BRAKING BASED ON IN-DEPTH CRASH RECONSTRUCTION AND SIMULATION

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ABSTRACT

The objective of this study was to estimate the potential effectiveness of AEB systems using simulation of crashes drawn from Australian in-depth crash data.

104 crashes that occurred within 100 km of Adelaide, South Australia, were used to assess the potential effect of AEB systems. The crashes had been investigated at the scene, re-constructed to determine collision speeds, and in this study they were analyzed using simulation to estimate how collision speeds and injury risks would have been modified by each of several AEB systems considered.

Crash types considered were rear-end, pedestrian, head-on, right angle, right turn and a proportion of hit-fixed-object crashes. Other crash types were thought to be less responsive to the effects of AEB and were not considered.

The variation in AEB systems were described using several parameters: the range of the forward-looking zone, the angle or width of the forward-looking zone, the processing time for the system to respond to the road user or object in its path (latency), the time-to-collision (TTC) at which the system would intervene, and the strength of the intervention (the level of braking). The AEB simulation used information from the trajectory of vehicles in the 104 crash reconstructions to estimate what difference each system would have made to the collision speed in each case and for each AEB system considered. Injury risk curves were used to estimate changes in fatal and injury crash risk in each case.

The reductions in risk were weighted according to the rate of crash involvement of vehicles, based on the patterns of crashes in New South Wales for years 1999-2009.

The overall reductions in risk produced by the various AEB systems were substantial. Systems were predicted to reduce fatal crashes by 20-25% and injury crashes by 25-35%. Note that these estimates rely on assumptions about universal operability and reliability of systems.

INTRODUCTION

Autonomous Emergency Braking (AEB) is one of a number of new safety technologies that has emerged in recent years. Such systems have the potential to deliver substantial road safety gains through assisting drivers to detect and respond to hazards through the optimization of braking. Normal emergency braking entails the driver to become cognizant of, and to react to the hazard by applying the brake of braking (and/or steering). AEB promises to be highly effective, as it should effectively reduce average cognition/reaction periods, and hence commence braking the vehicle sooner than a driver would find it possible to do, with optimum brake pressure.

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 performance of a particular AEB system will rely on the performance of these three elements.

At this stage, there are several versions of AEB systems and the performance of each system is likely to vary; it would be expected that their performance will improve as the technology evolves. It is important therefore that the influence of each aspect of AEB performance on overall effectiveness can be established, and one method of doing so is through the simulation of many kinds of accident scenarios.

If forward collision avoidance technologies are effective, it be will be because some crashes will be avoided and others will occur at reduced impact speeds. The mechanism of the effect is largely predictable: as mentioned above, braking is optimized and effective reaction times are 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. Consider a crash that has been investigated at the scene. If the paths of vehicles (or other road users) in a collision are known, the collision can be described mathematically in terms of vehicle speeds, trajectories and the timing and strength of braking (the latter based on scene evidence and/or assumptions about human response to emergency situations). Once the crash is thus described, AEB effects can be superimposed on the collision, and the effect of the AEB system on the collision speed can be simulated. Several investigators have used such an approach before to demonstrate benefits (e.g. Rosen et al., 2010; Sugimoto and Sauer, 2005; Georgi et al., 2005). Other methodologies have also suggested substantial benefits of AEB (Coelingh et al., 2007; Grover et al., 2008; HDLI 2011; Hummel et al., 2011; Kusano and Gabler, 2010; Lindman et al., 2012; Najm et al, 2006).

The objectives of this study were to estimate potential benefits of AEB in all injury and fatal crashes, by considering how it would have affected representative sample of crashes that had been investigated in-depth and at-the-scene.

A more comprehensive report on this study is available (Anderson et al., 2012).

METHODOLOGY

The process by which estimates of the benefits of AEB systems were made in this study is described in Figure 1. The process was as follows:

- Mass crash data was used to select the most common injury and fatal crashes that are relevant to AEB systems
- Crashes that had been investigated in-depth were selected to represent the relevant crash types found in the mass data
- The selected in-depth crashes were reconstructed and simulated to determine trajectories and closing speeds
- The specification (general performance) of AEB systems was parameterised.
- A collision detection and intervention model based on these parameters was applied to the simulations to determine how closing speed would be affected by an AEB system
- Average risk reduction in each crash type was estimated based on a relationship between closing speed and the risk of being injured or killed.

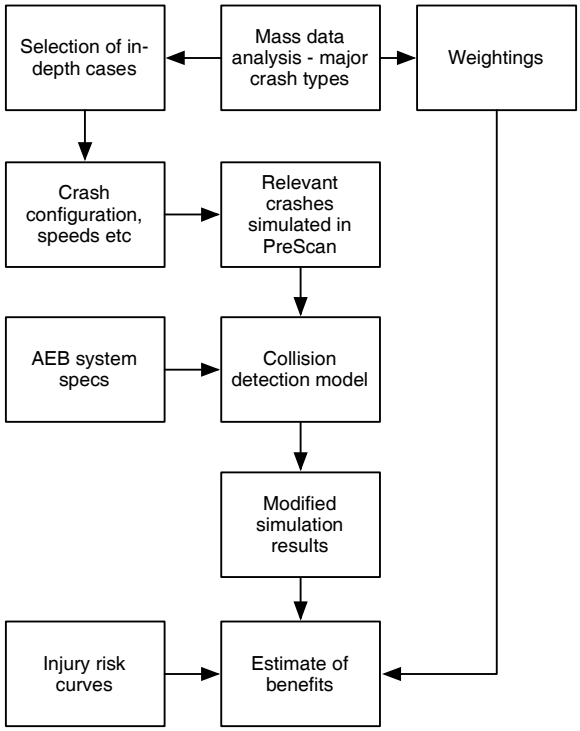

Figure 1. Methodological flow of calculating the safety benefit of AEB systems

Identification of relevant frontal collision crash configurations

Crashes that occurred in New South Wales between 1999 and 2009 causing injury or death were analyzed. Note that NSW crash data do not differentiate severity of injury in non-fatal injury crashes.

Crashes were grouped into similar types with respect to likely AEB effects, noting that little or no effects are expected for some crash types.

Proportions of crashes (injury and fatal) falling into each crash of several crash types were ranked. The top six categories were chosen, which covered approximately 90 percent of all crashes. Table 1

gives the percentages; those crash types that are most relevant to AEB systems are indicated by an asterisk.

These categories were used as a basis to select in-depth crash study cases for simulation. The percentages of all crashes that these crash types represent were also used to weight the results of the simulations, so that an estimate could be made of the overall effect of AEB systems on all crashes.

Table 1
Percentage of crashes within each crash group selected for simulation, disaggregated by speed zone group and severity

Crash Group	Speed Zones					
	50 and 60 km/h		70, 80 and 90 km/h		100 and 110 km/h	
	All injuries	Fatal	All injuries	Fatal	All injuries	Fatal
Intersection*	29.3	9.5	20.2	10.4	4.2	3.5
Rear end*	23.1	-	31.5	2.6	9.4	-
Pedestrian*	14.9	36.0	3.7	15.4	-	4.4
Hit fixed object*	15.5	30.9	22.8	34.7	46.0	41.1
Loss of control	-	3.6	-	-	12.3	7.1
Manoeuvre	4.7	2.7	-	-	-	-
Side swipe	-	-	4.9	2.5	-	-
Head on*	3.6	11.7	6.5	27.9	9.0	33.6
Off Path	-	-	-	-	8.3	3.6
Total	91.2	94.4	89.4	93.5	89.2	93.3

In depth crash data

The Centre for Automotive Safety Research (CASR) has an ongoing at-the-scene in-depth crash investigation activity in South Australia. Approximately 50 to 100 crashes are investigated annually, and a large database of crashes has been compiled over recent years.

A selection of crashes from CASR's in-depth crash investigation database was assembled to represent the circumstances of all crashes in the AEB relevant categories.

A total of 104 crashes were chosen for simulation. The number of cases in each crash type is given in Table 2. Twenty-one were fatal crashes and the remaining 83 were injury crashes requiring ambulance transportation.

Simulating the crash circumstances

Use was made of software called PreScan (Tass, Netherlands). PreScan is a simulation environment for primary safety technologies. The trajectory, speeds, braking and impact configuration of the vehicles in the selected in-depth cases were modeled in PreScan. While PreScan is capable of performing very detailed simulations of advanced driver assistance systems, these capabilities were not used in this study. Rather, PreScan was used to generate a time-based trajectory of the struck vehicle in the coordinates of the primary vehicle. This plot was then used as a basis for determining changes in closing speed with the inclusion of an AEB system in the primary vehicle.

Table 2
Number of simulated cases by crash type and speed zone group

Crash Group	Speed zones		
	50 and 60 km/h	70, 80 and 90 km/h	100 and 110 km/h
Intersection	15	11	10
Rear end	8	1	2
Pedestrian	12	2	1
Hit fixed object	8	4	16
Head on	5	4	5
Total	48	22	34

An example of how an in-depth crash investigation case was modeled in PreScan is shown in Figure 2. The site diagram from the crash is shown at the top of the figure and scenario modeled in PreScan is shown at the bottom. The colored lines in the PreScan diagram represent the trajectories of the vehicles with the spacing of the colored symbols representing the speed of the vehicle.

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 scan geometry, range, angle, computation time, time-to-collision (TTC) action time, system deceleration level and driver supported deceleration level.

- The *scan geometry* 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.

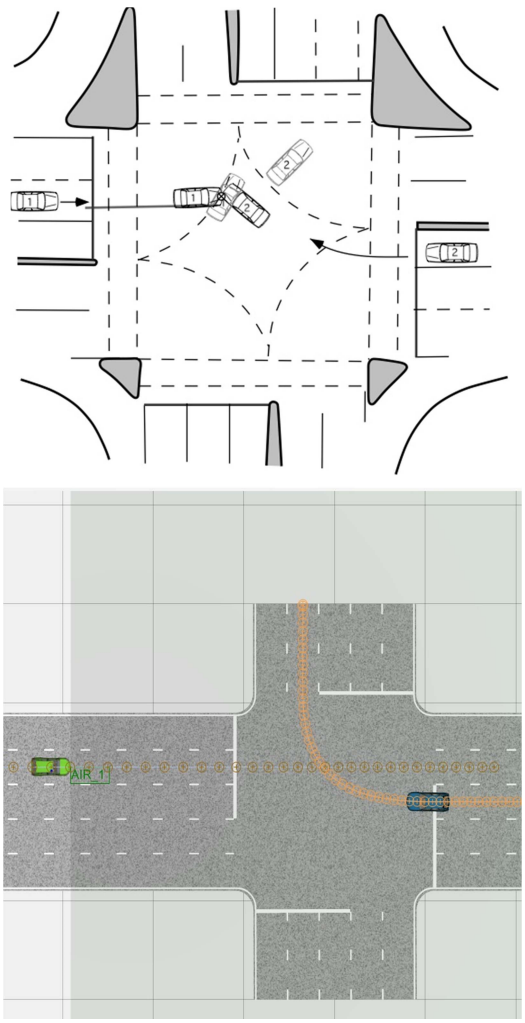

Figure 2. Site diagram of in-depth crash investigation case (top) and corresponding PreScan scenario (bottom)

- 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, average 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, and although we accept that this is possible over some period of braking, we opted for a more conservative increase in average braking level over the stopping distance).

During the simulation, when a vehicle/pedestrian 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 driver's response at that point in time in the real crash.

The parameters used to describe the different systems are shown in Table 3 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 may also produce a relatively large number of false alarms. The second and third systems describe variations of the baseline: 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; such a system minimises false alarms. It should be noted that this system uses a simplified collision prediction method that is only based on the longitudinal position and velocity of the crash partner, and did not track the path of the crash partner in order to estimate its future path. This simplified prediction method was the basis for selecting a computation time that was lower than other systems.

The AEB system model was only applied to the primary 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. a head on crash) the vehicle that was travelling straight ahead and had not crossed the centre-line of the road was chosen as the primary 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.

Table 3
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

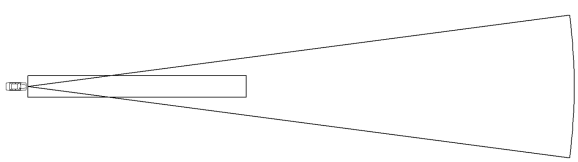

Figure 3. Fields of view of the AEB systems modelled: rectangle and cone

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. Note also that the crash phase was not simulated, and hence changes in velocity due to the crash and other crash parameters were not estimated explicitly.

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.

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

Estimating the reduction in injury risk based on reduction in impact speed

Each crash was scrutinised to determine the predicted effect of the AEB system being considered. For each of the individual crashes there were two relevant variables: impact speed and crash injury outcome. In some cases, the AEB system is likely to result in the crash being avoided. In that case, the effect is trivial to estimate. But in many other cases, the crash is not avoided, but mitigated through a reduction in impact speed, and here the effect on injury needs to be carefully evaluated.

Vehicle occupant injury risk is usually posed in terms of the change in speed during the crash: the delta-v. The delta-v is a function of the closing speed in a collision, the masses of both vehicles and the coefficient of restitution in the collision. As the simulations in this study only predicted a closing impact speed, a general relationship between delta-v and impact or closing speed was used to estimate changes in risk in each crash. For computational simplicity, the delta-v in the longitudinal axis of the primary vehicle was used to assess risk.

Average relationships between impact speed (as defined in this study) and delta-v were determined from CASR's in-depth crash reconstructions. The details of these reconstructions are not given here, but several hundred reconstructions have been performed based on matching simulated vehicle trajectories to forensic data at the scene, using the crash reconstruction software SMAC and HVE. Considering a number of crash configurations and

generalising, the following relationships were derived for the vehicle occupied by the most injured person.

- Head-on collisions
  - Delta-v = 0.5 x impact speed
- Hit fixed object
  - Delta-v = impact speed
- Intersection
  - Delta-v = 0.6 x impact speed
- Rear End
  - Delta-v = 0.6 x impact speed

Previous studies have attempted to quantify the relationships between impact speed or delta-v and the average risks of injury and death. These relationships provide a means of estimating the effects of AEB on fatal and injury crash risk in an individual case, and on average: in individual crashes where the speed and severity are known, the curves can be used to estimate the risk that the crash will be as severe, given a reduction in impact speed, and also to estimate the risk that the crash will fall into a lower severity category.

The curves that describe the risk of injury to a vehicle occupant are given in Figure 4. These curves are derived from NHTSA (2005) to cover the categories of injury severity used in this study.

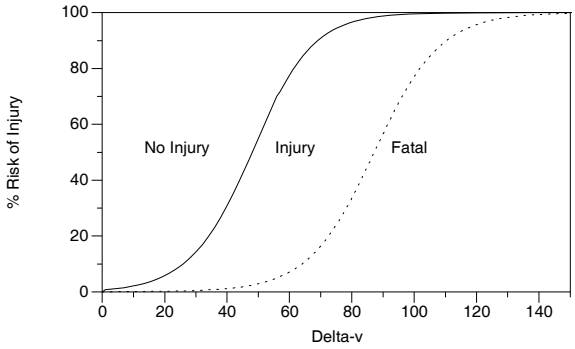

Figure 4. Maximum occupant injury risk curves derived from NHTSA (2005), showing the proportion of no injury, injury and fatal expected at each delta-v.

Pedestrian injury risk is usually expressed in terms of impact speed. The risk curves used in this study are based on Davis (2001) and are shown in Figure 5.

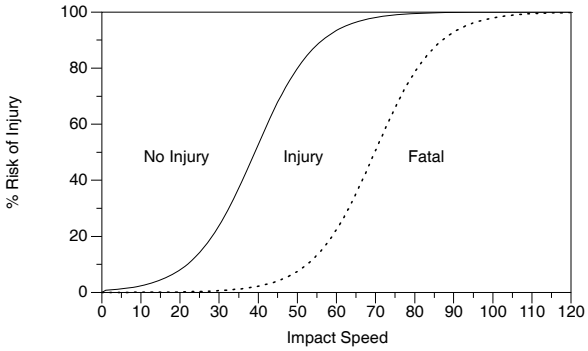

Figure 5. Injury risk curves adapted from Davis (2001), showing the proportion of no injury, injury and fatal expected at each impact speed.

The process for determining the effect of AEB on an individual crash was as follows:

- For occupant injury crashes, the actual crash closing speed was converted to a delta-v in the vehicle longitudinal direction.
- The probability of fatality, injury or no injury was determined from the appropriate risk functions.
- The effect of AEB on the crash was simulated
- For occupant injury crashes, the new closing speed was converted to a delta-v in the vehicle longitudinal direction
- The probabilities of fatality, injury or no injury were "redistributed" based on the revised delta-v (or impact speed in pedestrian crashes) and the original crash severity

For the redistribution of injury risk it was assumed that the crash would either remain in its original category of severity, or be reduced in severity, and that the probabilities of either of these outcomes are given by the original impact speed, the reduced impact speed and the risk curves illustrated above. The equations for doing so are not included here, but note that the usual result was that, for example in the case of a fatal crash, the fatal risk in the original crash (=1) was redistributed between a fatal risk (a) and a non-fatal injury risk (1-a). In some cases, speed was reduced to the point that a probability of no injury was also estimated.

This process was applied to each individual crash and for each variant of an AEB system considered. The individual probability outcomes in each crash were then averaged for each particular crash group and speed zone group.

RESULTS

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 6. Over-plotted on this data are areas corresponding to certain fields of view. The shaded areas correspond to widths of 4 and 6 metres. For a crash speed to be reduced toby the maximum extent possible, the crash partner must be in the field of view of the system at the relevant TTC action time plus any computation time. It might be noted how the position of the crash partner varies by crash type.

Figure 6 is useful as it illustrates the ranges and the angles of view required for a system to be sensitive to potential crashes. However, Figure 6 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 6 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 will be important to demonstrate that threats can be identified with high sensitivity and specificity.

Effect of AEB systems on crash speeds

The effect of the various AEB systems are summarised in Figure 7, which shows the average impact speed for each crash type according to AEB parameters.

Not all crash types were affected equally. AEB systems had a lesser effect in right angle crashes, whereas relative and absolute speed reductions were larger in other crash types. Pedestrian crash speeds were lower, but a detailed examination of those cases found that crashes in which the pedestrian was obscured prior to the crash were not affected except in the case of the restricted view system. The effectiveness of the restricted view system is due to a combination of a wider field of view at very close range and a shorter computation time. The relative effects of a shorter TTC and lower system deceleration vary between crash types.

The baseline system avoided 19 of 104 crashes while a shortened TTC avoided four. The reduced braking level system prevented 11/104 crashes. The system with a 1.0 s TTC and quick reaction time, but with a restricted view prevented 9 crashes.

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

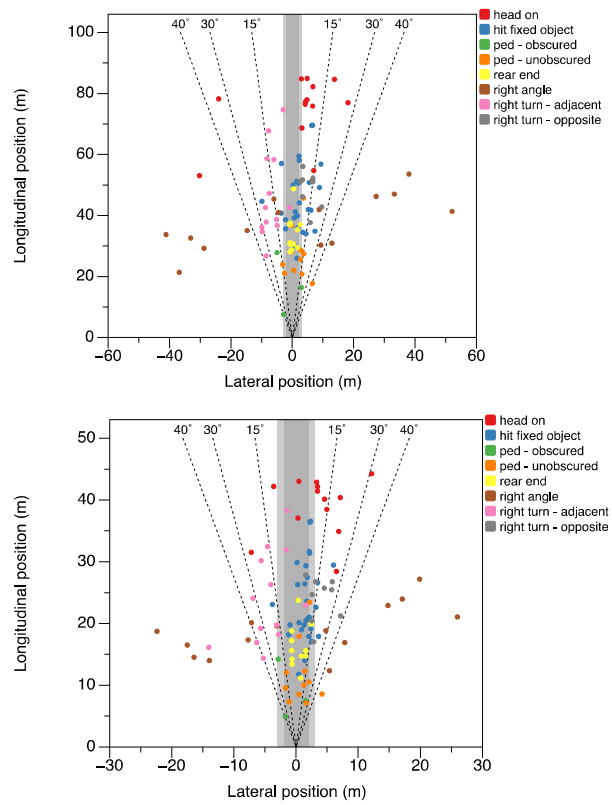

Figure 6. Location of crash partner at two (top) and one seconds (bottom) TTC by crash type

Effect of AEB systems on fatal crash risks and injury crash risks

Estimates of the effect of the speed reductions in each crash were made according to the method described previously:

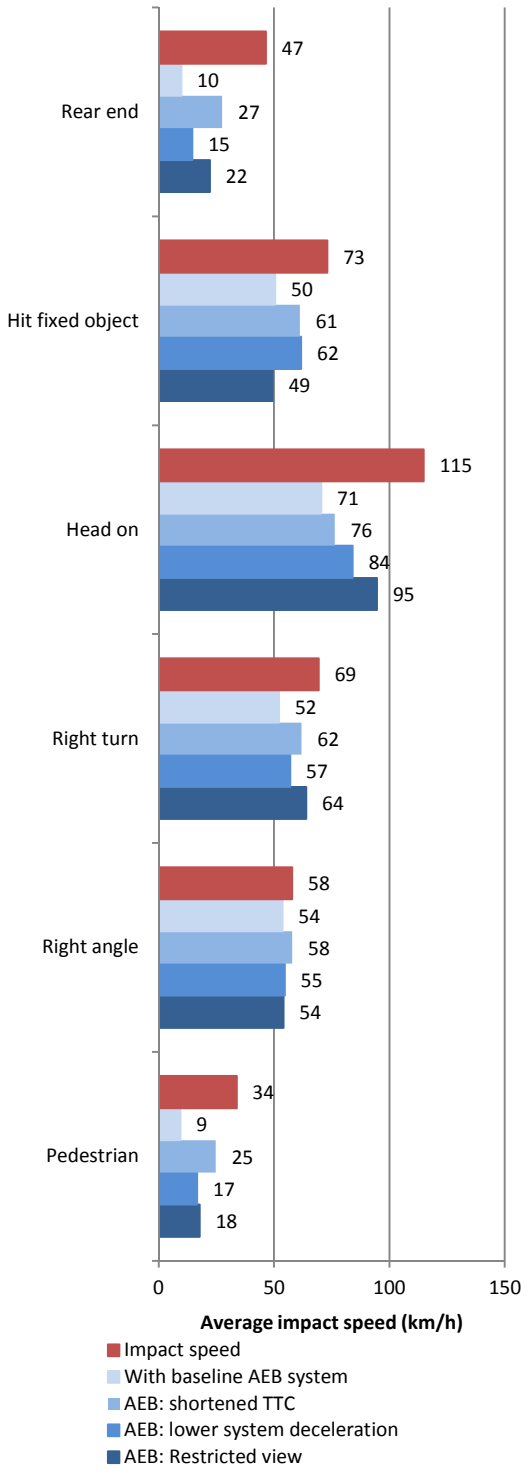

Figure 7. Average impact speeds by crash type and AEB system.

- Risks were modified in each crash as described in the method.
- The changes in risk were aggregated within each category of crash.
- These average changes in risk were then weighted according to the incidence of each crash subcategory in the mass-crash data (see Table 1 for the incidence of each category of crash.)
- The effect on all crashes was then totalled.

The results are shown in Table 4. Reductions are given for fatal crashes and injury crashes separately. Reductions are given as a reduction of all relevant forward collisions (see asterisked crash categories in Table 1) and also of all fatal and injury crashes.

Table 4
Percentage reductions crashes

System	Reduction (per cent)			
	Fatal		Injury	
	Forward crash	All crash	Forward crash	All crash
Baseline system	39	27	51	37
Shorter TTC	23	16	37	27
Lower deceleration	29	20	48	34
Restricted view	34	23	47	34

DISCUSSION

The results presented in this paper add support to other estimates that AEB will have a marked effect on crash risk. Other research has mainly examined effects on rear-end and pedestrian crashes; this study suggests that that AEB might be effective in a broad range of crash types, if systems are developed sufficiently to identify a broad range of potential crash risks.

The models of AEB used in this study are likely to be simplified representation of systems being developed by manufacturers. Hence, 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. The restricted view system presented in this paper attempts to represent this kind of system, but such a system might be made more effective by

preparing the vehicle systems or even applying partial braking before the crash partner is directly in line of the host vehicle. 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).

Nevertheless, these results do indicate that differences in the way that systems operate will make a material difference to their effectiveness, in terms of either speed reductions or injury risk. Reduced TTC and/or system deceleration reduced the effectiveness of the baseline AEB system. A wide field of view at very close range (represented by the rectangular field of view) and low system latency assisted in number of crash scenarios. A reduced TTC and restricted forward view represent potential countermeasures to any potential false-alarm problems with AEB systems. Furthermore, it has been assumed that the systems are active over the entire range of speeds that were extant in the crashes that were simulated.

The restricted view system was generally not as effective as the baseline system. Exceptions were hit fixed object crashes (mainly due to the inclusion of crashes occurring on a straight stretch of road) and right angle crashes. However it did still show average impact speed reductions of 16 km/h or more in all pedestrian, head on, rear end and hit fixed object crashes, and it was the second best system in terms of reductions in fatal and injury risks. These results show that such a system can still be effective in reducing impact speeds in a variety of crash types while avoiding the problems of false alarms that might arise through reacting to objects in a larger scan area.

The reductions in average impact speed found in the rear end, pedestrian crashes and head on crashes are notable. While no head on crashes would have been 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 designed to react only to objects within the vehicle's lane, Figure 6 shows that the vehicle would not have commenced braking in any of the head on crashes at two seconds TTC, and only to 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 of the AEB equipped vehicle's lane of travel (as was assumed for three of the four systems evaluated in this analysis).

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, the ability to function in inclement weather, and to have high sensitivity to crash potential. The effectiveness levels estimated in this report assume no failures to detect, and therefore need to be tempered by what might be known about system reliability in all crash conditions.

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.

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, higher autonomous deceleration and economical data processing.

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