The safety potential of connected vehicles

Doecke, S. D., Anderson, R. W. G.

Centre for Automotive Safety Research

Abstract

Connected vehicle technology allows vehicles to send and receive information to and from one another, other road users and infrastructure. Although it is not yet available on any production vehicle, on-road trials are well under way. It is likely that connected vehicle technology will enter the market at a time when autonomous emergency braking (AEB) is becoming more common on new vehicles. The purpose of the present research was to estimate the safety benefits of connected vehicle technology in Australian conditions over and above what could be provided by AEB. The applications and limitations of connected vehicle technology were assessed by reviewing literature and consulting with a local developer of the technology. It was found that crash types that are poorly addressed by AEB such as right angle and right turn crashes and certain pedestrian crashes, are more likely to be addressed by connected vehicle applications. The safety benefits were calculated by applying a collision avoidance system model to simulations of real world crashes to determine the change in impact speed. It was found that the potential of connected vehicles to reduce crash risk is considerable, even in the presence of a sensor-based AEB system, and the uptake of such technology should be encouraged in ways that are shown to be cost effective.

Introduction

For well over a decade technology has been under development to allow vehicles to send and receive information to and from one another, other road users and infrastructure. Many uses for such technology have been conceptualised, including primary safety applications. This emerging technology is known by several names: vehicle-to-vehicle communication (V2V), vehicle to infrastructure communication (V2I), V2X (when generally considering communication between vehicles and another entity), car-to-car (C2C) and the associated C2I and C2X acronyms, inter-vehicle communication, cooperative driving and connected vehicles. It may also be known by one of the favoured methods of communication, Dedicated Short Range Communication (DSRC). To avoid confusion we will use the umbrella term ‘connected vehicles’ in most instances but on occasion when referring to a particular type of connected vehicle technology we may use the more specific terms V2V or V2I.

The exchange of information between connected vehicles can be used to detect risks or potential collisions and could be used to trigger a vehicle response such as providing a warning to the driver and/or to autonomously intervene using the vehicle’s braking or steering systems. When connected vehicle technology enters the market it will likely be doing so at a time when AEB is becoming common on new vehicles. The advantage of connected vehicles over AEB is that it is not limited by a sensor’s field of view and does not require a clear line of sight between the vehicle’s sensor and the target. The clear disadvantage of connected vehicle technology, however, is that it (generally) needs both vehicles to have the technology, while AEB requires only the host vehicle to be equipped with the technology. Hence, while AEB effectiveness is limited at the population level by its prevalence, V2V effectiveness is limited by the prevalence squared.

The purpose of the present research was to estimate the safety potential of connected vehicle technology, particularly the marginal benefits over and above the benefits of regular sensor-based AEB. This will be accomplished by determining the crash types that are addressed by connected vehicle technology and how effective the technology will be at reducing injury and fatal crashes of these types.

Literature review

A literature review was conducted that focused on connected vehicle applications that have a safety focus (as opposed to a mobility focus). The review covered published cost benefit analyses, and Field Operational Tests (FOTs). Estimates of efficacy and willingness-to-pay were also examined. The bulk of the research in these areas has been conducted in the United States, the European Union, and Japan. Note that the literature review was conducted in late 2012 therefore more recent research is not included here.

Two-broad categories of safety-related connected vehicle applications were identified in the literature; those that have a direct crash avoidance effect and those that have an indirect crash avoidance effect. The direct crash avoidance applications are listed in Table 1.

Table 1. Connected vehicle direct crash avoidance applications found in the research literature

Application	Description	References
Signal Violation Warning	Warns the driver that they are about to violate a red traffic signal if the application decides the driver has not recognised the signal	Andrews and Cops, 2009; Bezzina, 2012; Brewer, Koopmann and Najm, 2011; Brignolo et al., 2008; Fakler et al. 2010; Schulze et al., 2008; Fukushima, 2011
Stop Sign Violation Warning	Warns the driver that they are about to violate a stop sign if the application decides the driver has not recognised the sign	Bezzina, 2012; Brewer, Koopmann and Najm, 2011; Brignolo et al., 2008; Fakler et al. 2010; Schulze et al., 2008; Fukushima, 2011
Emergency Electronic Brake Lights	Warns the driver that a vehicle ahead is undergoing heavy braking	Ahmed-Zaid *et al*., 2011; Lukuc, 2012; Bezzina, 2012; Mäkinen et al. 2011
Forward Collision Warning	Warns the driver of impending collision with a vehicle in front (focussed on rear end crashes)	Ahmed-Zaid *et al*., 2011; Lukuc, 2012; Bezzina, 2012; Brignolo et al., 2008; Fakler et al. 2010; Fukushima, 2011
Blind Spot Warning (Lane Change Warning)	Warns the driver of vehicles present in their blind spot, especially when they intend to change lanes	Ahmed-Zaid *et al*., 2011; Lukuc, 2012; Bezzina, 2012; Brignolo et al., 2008; Fakler et al. 2010
Do Not Pass Warning	Warns the driver of vehicles in the oncoming traffic lanes, especially when they are about to perform a passing manoeuvre	Ahmed-Zaid *et al*., 2011; Lukuc, 2012; Bezzina, 2012; Brignolo et al., 2008; Fakler et al. 2010
Intersection Movement Assist	Warns the driver when it is not safe to enter an intersection due to high collision probability with other vehicles	Ahmed-Zaid *et al*., 2011; Lukuc, 2012; Bezzina, 2012; Brignolo et al., 2008; Fakler et al. 2010; Schulze et al., 2008; Fukushima, 2011
Left Turn Assist	Little information on this application is available, may be warning of an insufficient gap to complete a left turn across traffic (right turn in Australia)	Lukuc, 2012; Bezzina, 2012; Fukushima, 2011
Right Turn in Front Warning	Little information on this application is available, may be warning of a vehicle in front turning right (left in Australia).	Bezzina, 2012; Brignolo et al., 2008; Fakler et al. 2010; Schulze et al., 2008; Fukushima, 2011
Pedestrian Detection	Little information on this application is available, but detection is likely to be via the pedestrian’s mobile phone	Bezzina, 2012; Brignolo et al., 2008; Fakler et al. 2010; Fukushima, 2011
Bicycle Collision Prevention	Little information on this application is available, but detection is likely to be via the pedestrian’s mobile phone	Brignolo et al., 2008; Fakler et al. 2010; Fukushima, 2011
Loss of Control Warning	Warns surrounding vehicles of a vehicle that has lost control and may therefore pose a threat to them	Bezzina, 2012

While most of the applications have made it through some form of proof of concept testing, not all have been part of an FOT to validate their operation in a natural environment.

Very little research on the effectiveness of safety-related connected vehicle applications has been done to-date. The Japanese research project DSSS and its derivative SKY have produced some results for their Signal Violation Warning, Stop Sign Violation Warning and Crossing Collision Prevention applications: vehicles coming to a complete stop at a stop sign increased from 41% to 76%; the number of vehicles exceeding the speed limit on the approach to an intersection was reduced from 41% to 23%; and 'crash unavoidable vehicles' (though it is unclear what the authors meant by 'crash unavoidable vehicle') reduced from 38% to 22% (Fukushima, 2011). The European research project COOPERS found that traffic congestion warnings and fog warnings did reduce the approach speed of drivers based on the results of simulator studies and from effects at a demonstration site (COOPERS, 2008). The European research project, SAFESPOT, also reported some application effects, however these do not appear to be based on experimental results (Luedeke *et al.,* 2010).

Several benefit-cost analyses have been published, despite the lack of efficacy data available. The results of such analyses should therefore be treated as preliminary and it might be expected that the results will be modified as more robust efficacy results become available. The VII program in the US found a BCR of 1.6 using a blanket effectiveness rate of 25% (RITA, 2008). They noted that this would drop to 1 if the effectiveness rate dropped to 15%. The European CVIS project did not specifically calculate a BCR but did calculate benefits and cost from which a BCR of 1.5 can be inferred (Berger *et al.,* 2010). The European SAFESPOT project determined BCRs separately for the V2V and V2I applications it considered. The V2V applications were found to have a BCR between 1 and 1.1 but the BCR for the V2I applications was 0.21 to 0.36 (Luedeke *et al.,* 2010). These analyses show that it is possible that connected vehicle applications will be cost effective. Of particular note is the US finding that an efficacy rate of 15% or more will enable it to be so.

Note however that a limitation of studies, which are often based on historical crash rates, is that they are prone to double-counting of benefits given the general reductions in crash risk that are already built in to the new vehicle fleet. Hence, it will become increasingly important when estimating benefits and costs to understand the marginal nature of the benefits of connected vehicle technology. It is interesting to note that two of three studies that looked at benefits and costs, VII and CVIS, found that the vast majority of the benefit comes from safety applications rather than mobility applications (95 and 93%).

A theme that was common to several research projects across all three regions was the relationship between sensors based AEB systems and connected vehicle technology. The authors of the report on the US research project, VSC-A, concluded that connected vehicle technology can address several known limitations of sensor based AEB systems and it is likely that vehicles will be equipped with both technologies (Ahmed-Zaid *et al*., 2011). The European PReVENT project sought to develop an electronic safety zone around a vehicle that would utilise both typical AEB sensors as well as connected vehicle technology (Schulze et al., 2008). The Japanese ASV project also considered the relationship between the two technologies and stated that the desired role of connected vehicle technology was to cover events that would be invisible to a sensor based AEB system (Wani, 2006). Furthermore the SAFESPOT project included a radar sensor in its system costing to match what was used at their test sites (Luedeke et al., 2010). The consensus among the research projects that did consider the relationship between sensor based AEB systems and connected vehicle technology is that connected vehicle technology can be used to compliment a sensor based AEB system to provide a comprehensive collision avoidance system, and the marginal benefits of connected vehicle technologies are likely to be worthwhile.

Method

The methodology used in this study was adopted from Anderson *et al.* (2012) in which simulation was used to determine what the outcome of individual crashes would have been had an AEB system been installed on the striking vehicle. This study will extend that methodology to examine the effect that connected vehicle technology would have on the crash outcome and compare this against the effect a comparable AEB system would have had to determine the marginal benefit of connected vehicle technology over and above that of an AEB system.

To simulate each crash, information on the vehicles trajectory, speed, braking location and impact location were required. This information is not available from the mass data routinely collected by police such as that contained in the South Australian Traffic Accident Reporting System (TARS). However, data collected by at-scene in-depth crash investigations do contain the necessary level of detail. A disadvantage of in-depth data is that they may not provide a representative sample of crashes. However, it was assumed for the purposes of this study that crashes of a particular type in the dataset (e.g. fatal head-on crashes in 100 km/h zones) do broadly represent crashes that are similar in respect of the definition of the crash type in TARS. Hence, an approximation of benefits across all crashes could be made by disaggregating the in-depth data to the level of crash type, severity and speed zone, examining benefits of connected vehicles for each grouping, and then weighting the results according to the relative frequency of each crash type in the TARS database.

Simulations were focussed on crash types that are likely to be both relevant and important. Relevance to connected vehicle technology was judged by the information in the literature review on the applications of connected vehicles. Importance was judged by the prevalence of a given crash type in the mass data.

It was also important to differentiate between crashes occurring in different speed zone groups for three reasons: the effect of the collision avoidance system may be different at different speeds, the crash types that are important may differ by speed zone and crashes within the crash type may differ by speed zone.

The objective was to simulate between 10 and 20 cases from each crash type within a speed zone group. This proved particularly difficult in the less common speed zones of 70, 80 and 90 km/h.

A total of 111 crashes were chosen for simulation. The number of cases in each crash type and speed zone group can be seen in Table 2. The crashes included 17 fatal crashes and the remaining 94 were injury crashes. The proportion of crashes that were fatal was much lower in 50 and 60 km/h zones than in higher speed zones (as would be expected).

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

Crash Group	**Speed zones**			**Total**
	50 and 60 km/h	**70, 80 and 90 km/h**	**100 and 110 km/h**	
Rear End	13	1	2	16
Right Angle	20	7	20	47
Head On	6	4	10	20
Hit Pedestrian	12	2	NA	14
Right Turn	10	4	NA	14
Total	61	18	32	111

The trajectory, speeds, braking and impact configuration of the selected in-depth cases were replicated in software known as PreScan(TASS, Netherlands). While the PreScan software 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 plot of the trajectory of the struck vehicle from the viewpoint of the vehicle with the collision avoidance system. This plot was then used as a basis for determining changes in closing speed with the inclusion of a collision avoidance system.

Each crash trajectory was analysed to determine how collision speeds might have been affected by a collision avoidance system. To do this, a generic collision avoidance system model was developed in MatLab with several variable attributes; scan zone, computation time, collision prediction method and the system response. The scan zone is an area projecting from the front of a vehicle within which other vehicles can be detected. It is defined by a scan shape, a range and an angle or width.

The computation time represents the amount of time required by the system to observe an object before it can be identified and its future motion predicted. We assume that some systems may predict a collision based solely on the distance and relative speed of the object. Other systems may use more complex techniques to predict the future motion of objects based on their current position, speed, and acceleration. The system response includes the time to collision (TTC) at which the system begins to intervene, the rate at which the system will decelerate noting that the system might decelerate the vehicle at different rates depending on whether the vehicle is decelerating completely autonomously or whether the system is supporting the braking initiated by the driver.

The reduction in speed achieved by the deceleration is calculated as shown in the equation below, where S_f is the resulting travel speed, S_i is the initial travel speed, A is the deceleration value, and D is the distance over which the deceleration occurs.

$$S_f = \sqrt{S_i^2 - 19.62AD}$$

By assigning values to these attributes, variations of sensor based systems and connected vehicle systems and their response during specific crash scenarios was modelled. All attribute values were based on information from published literature and provided by vehicle and system manufacturers.

The attribute values that were selected to represent these sensor-based and connected vehicle-based systems are shown in Table 3. The sensor-based systems have a limited field of view and were assigned a computation time of 0.2 seconds. To represent the connected vehicle based system that can see all around a field of view of 180 degrees was used, which in effect meant that all the crash partners modelled in the simulations were detected within the range of the system. The range used was only 100 metres. While a connected vehicle can communicate with another vehicle at much greater ranges than 100 metres, this range is adequate for the system to act as soon as the TTC criteria is met within the simulation. The computation time is set at zero to allow for this attenuated range and to represent that the computation time would have already passed by the time the vehicles are within 100 metres of each other.

Table 3. Attribute values for the sensor and connected vehicle system variations

Attribute	**Baseline**		**Short TTC**		**Low system deceleration**		**Restricted view**	
	Sensor	**Connected**	**Sensor**	**Connected**	**Sensor**	**Connected**	**Sensor**	**Connected**
Scan shape	Cone	Cone	Cone	Cone	Cone	Cone	Rectangle	Cone
Range (m)	100	100	100	100	100	100	40	100
Angle/width (deg/m)	15	180	15	180	15	180	4	180
Computation time (s)	0.2	0.0	0.2	0.0	0.2	0.0	0.1	0.0
Prediction method	Advanced	Advanced	Advanced	Advanced	Advanced	Advanced	Simple	Advanced
TTC action (s)	2.0	2.0	1.0	1.0	2.0	2.0	1.0	1.0
System deceleration (g)	0.8	0.8	0.8	0.8	0.4	0.4	0.8	0.8
Driver supported deceleration (g)	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8

A site diagram from an in-depth crash investigation and the corresponding simulation are shown in Figure 1.

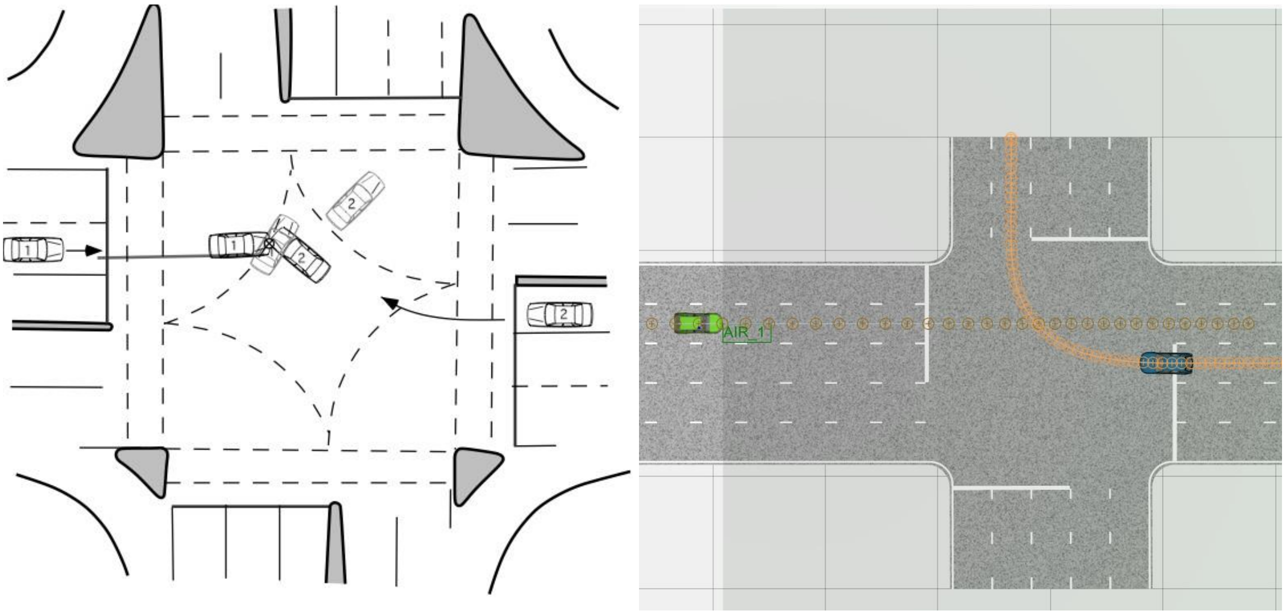


Figure 1. Site diagram of in-depth crash investigation (left) and corresponding simulation (right)

The simulation results for the case shown above are shown in Figure 2. The difference between the scan zones can be clearly seen. The collision partner moves outside the scan zone of the sensor based AEB system when the vehicles are still about 80 metres apart. The connected vehicle system, that can see the collision partner from 100 metres away right up to the impact point, takes action when the other vehicle is 37 metres away. The sensor based AEB system does not take action, as the collision partner is not on a collision course during the time that it is within the limited field of view of the system. Note that in the actual crash the driver did not brake at all prior to the collision.

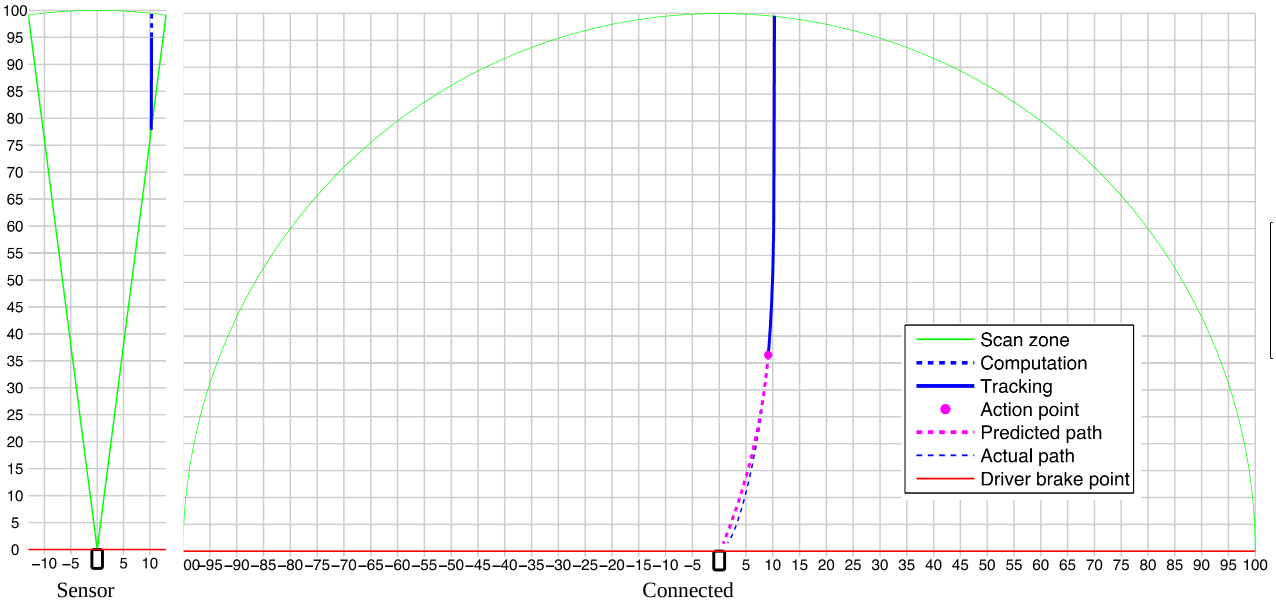
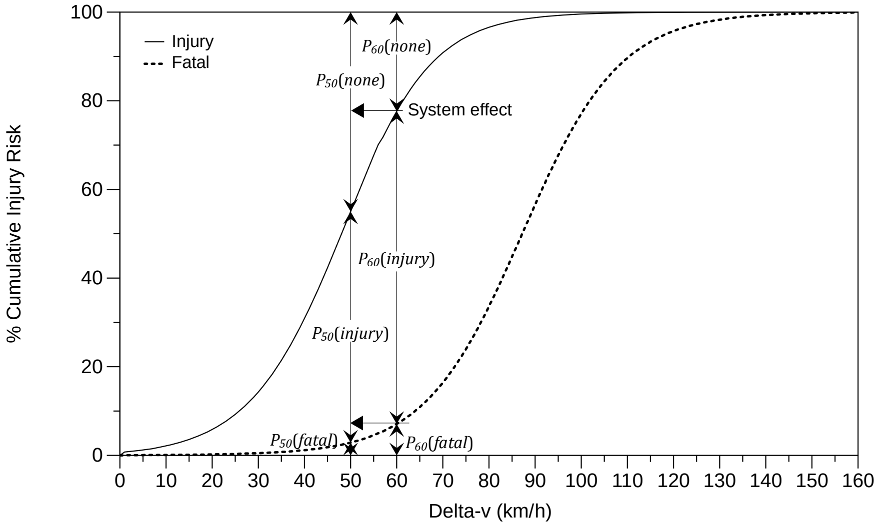


Figure 2. Collision avoidance model response to a right turn crash with the baseline sensor based AEB system (left) and the connected vehicle system (right)

Some simulations predicted that a crash would be avoided altogether with the benefit of the crash avoidance system. In other simulations it was predicted that the actions of an autonomous braking system would have resulted in a reduced collision speed. Sets of risk curves (that estimate the probability that a crash would have resulted in no injury, injury or fatality) were then used to determine the reduction in injury risk as a result of the reductions in collision speed. Separate risk curve sets were used for vehicle crashes (NHTSA, 2005) and pedestrian crashes (Davis, 2001).

The risk curve for vehicles is relative to the change in velocity of the vehicle (delta-V) while the risk curve for pedestrian crashes is relative to impact speed. For the purpose of examining the benefit of the collision avoidance systems, the relative risk of injury or death at various speeds was considered with respect to the original crash injury outcome.

An example of such a calculation for an injury crash that originally had a delta-V of 60 km/h reduced to 50 km/h is shown in Figure 3. The delta-V reduction resulted in the chance of injury being 68%. Further examples and explanation of the method can be found in Appendix B of Anderson *et al.* (2012).



$$P_{50}(injury|crash\ was\ injury) = \frac{1-P_{60}(fatal)-P_{50}(none)}{P_{60}(injury)} = \frac{1-0.071-0.45}{0.71} = 68\%$$

$$P_{50}(none|crash\ was\ injury) = 1-P_{50}(injury|crash\ was\ injury) = 1-0.68 = 32\%$$

Figure 3: An example of the redistribution of an injury from a delta-v of 60km/h to a collision avoidance system reduced delta-v of 50km/h

For each collision avoidance system, the probabilities of injury or death in each crash were summed over the sample of crashes and divided by the number of injury and fatal crashes to calculate a percentage reduction in number of deaths and injuries produced by that particular system. This was done separately for each category of crash according to speed zone, severity and crash type (as shown in equation below).

$$\%\ injury\ crash\ reduction = \frac{\sum new\ probability\ of\ injury}{No.of\ injury\ crashes}$$

The reductions in each category were weighted according to the proportion of crashes found in the in the corresponding category of mass crash data, as seen in the equation below. This provided an estimate of the overall reduction in the number of crashes produced by a given collision avoidance system. In some categories there were no fatal crashes in the sample and the effect on injury crashes was applied to the fatal crashes.

$$\%\ system\ injury\ reduction = \sum_{i=type,speed\ zone} \%injury\ crash\ reduction_i \times \%\ of\ crashes_i$$

The marginal benefit was calculated by simply subtracting the benefit of the sensor based AEB systems from the benefit of the connected vehicle systems.

It should be noted that certain crash types that are not relevant to connected vehicle systems (such as hit fixed object crashes) were not included in the analysis. Hence, the calculation of the number of crashes reduced with an AEB system, and subsequent calculations, were performed solely to determine the marginal benefit of connected vehicle systems.

Results

Table 4 shows the total crash reductions and the marginal reductions achieved by connected vehicle crash avoidance systems by speed zone, severity and system. The key results (the overall marginal reduction achieved by connected vehicles) are shown in red. The additional crash reduction percentage ranged from 16 to 21 percentage points for injury crashes and 12 to 17 percentage points for fatal crashes. The total and additional percentage reductions both decrease as the speed limits increase.

Table 4. Crash reduction percentages of connected vehicles

Speed limit	**Crash severity**	**Baseline equivalent**		**Short TTC equivalent**		**Low system deceleration equivalent**		**Restricted view equivalent**	
		Total	Marginal	Total	Marginal	Total	Marginal	Total	Marginal
50/60	**Injury**	62.3%	25.0%	48.6%	21.6%	60.5%	24.0%	48.6%	20.2%
	Fatal	47.4%	29.5%	39.3%	23.5%	47.0%	29.2%	39.3%	13.7%
70/80/90	**Injury**	58.0%	16.0%	43.7%	11.7%	55.6%	14.7%	43.7%	8.2%
	Fatal	38.2%	14.2%	34.6%	16.3%	36.7%	13.1%	34.6%	12.3%
100/110	**Injury**	18.4%	5.3%	11.3%	4.7%	14.2%	4.8%	11.3%	4.7%
	Fatal	30.5%	9.7%	24.8%	8.8%	26.1%	8.2%	24.8%	11.1%
Overall	**Injury**	55.3%	21.0%	42.5%	17.9%	53.1%	20.0%	42.5%	16.4%
	Fatal	37.3%	16.9%	31.1%	14.8%	34.7%	15.9%	31.1%	12.2%

After speaking to a local manufacturer of connected vehicle technology, it became apparent that applications to prevent head on crashes in environments where vehicles normally travel in close proximity to oncoming traffic (an undivided road) are technically challenging at this stage of development. This is due to the position information (GPS) not always having the required accuracy to differentiate between a compliant oncoming vehicle and one that is crossing into oncoming traffic. Similar challenges with pedestrian applications were noted, as they will most likely rely on position information from a mobile phone.

The marginal crash reductions excluding pedestrian crashes and/or head on crashes are shown in Table 5. These are reported because it is possible that these crash types will not be appropriately addressed by connected vehicle technology. If these crash types are not included the effect of connected vehicles is reduced by between 1.6 and 4.1 percentage points in injury crashes and between 4.6 and 4.8 percentage points for fatal crashes. Despite this the additional crash reduction percentages remain sizeable.

Table 5. Marginal crash reduction percentages produced by connected vehicles relative to sensor based AEB systems

Crash types	Crash severity	Difference			
		Baseline	**Short TTC**	**Low sys. dec.**	**Restricted view**
Without pedestrian	**Injury**	18.6%	14.3%	17.5%	16.0%
	Fatal	14.0%	11.9%	12.9%	11.9%
Without head on	**Injury**	20.6%	17.4%	19.5%	15.2%
	Fatal	15.3%	13.2%	14.0%	9.2%
Without both	**Injury**	18.1%	13.8%	17.1%	14.8%
	Fatal	12.3%	10.2%	11.1%	7.4%

Discussion

Previous research has highlighted that sensor based AEB systems may have very limited effects on right angle, right turn and pedestrian crashes where the pedestrian emerges from parked vehicles (Doecke *et al.*, 2012). The benefit of connected vehicle technology above that of a sensor based AEB found in this report is promising. The results confirmed that connected vehicle technology can address these crash types not addressed by sensor based AEB systems, and may also have some additional benefit in head on crashes. Note though that the limitations brought about by the need to avoid false-positive interventions will apply equally to AEB and connected vehicle systems, and it is not possible to say from these results to what extent such limitations will significantly impact on the benefits of any given system.

If technical limitations mean that pedestrian and head on crashes cannot be addressed by connected vehicle technology, the marginal benefits are likely to remain substantial, albeit reduced from the full potential of the technology. The reductions in benefit are large enough to suggest that pursing connected vehicle technology applications that can address these crash types is worthwhile, especially as the effect of not addressing these crashes is greater for fatal crashes than injury crashes.

An assumption of this study is that AEB will already be fitted to every vehicle that production versions of connected vehicle technology are also fitted to. This assumption was based on the conclusions and general direction of research projects surveyed in the literature review and on the knowledge that AEB systems are becoming available in more and more new vehicles while connected vehicle technology is still in the development phase. It is, of course, still possible that connected vehicles may overtake the take-up of sensor based AEB when it is production ready. The possibility of retrofitting connected vehicle technology in used vehicles may also mean that connected vehicle technology is fitted to vehicles that are not fitted with AEB. Retrofitting is much more likely for systems that only warn and send information rather than autonomous systems. If it does come to pass that connected vehicle technology is fitted to vehicles without AEB the total crash reductions shown in Table 4 can be used rather than the marginal crash reductions.

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 pass without a collision occurring. This is most likely to affect right angle crashes. This limitation of the model contributes an underestimate of the effectiveness of the collision avoidance system. Because it is most likely to affect right angle crashes that are not affected by AEB but are by connected vehicles, this will produce an underestimate of the marginal benefit of connected vehicles.

When conducting the simulations it was assumed that only one vehicle, the striking vehicle, was equipped with a collision avoidance system, though for the connected vehicle system to operate the collision partner must at least be sending the relevant data. This represents the most likely situation in the near future. If fleet penetration of these systems becomes sufficiently high in future years that two vehicles crashing are likely to both have a collision avoidance system, a benefit beyond what has been accounted for in this study could be realised. The assumption of only the striking vehicle being equipped with a collision avoidance system was originally made when only sensor based AEB was considered as it was thought to be unlikely that an AEB system on the struck vehicle would have any effect. Connected vehicle systems, with the ability to detect vehicles at any angle, may have an effect on the struck vehicle. For example, the struck vehicle may not even move into an unsafe gap when crossing traffic, or at least brake before they enter the cross traffic lane. This assumption may therefore produce an underestimate of the marginal benefit of connected vehicle technology above that given by sensor based AEB systems.

As the results have been expressed as an marginal benefit above that given by AEB any inaccuracy in the estimate of the benefit of AEB will affect these results. There are two areas that may have produced an overestimate of the benefit of AEB and therefore an underestimate of the marginal benefit of connected vehicles. The first is that the computation times used for the AEB systems may be optimistic. The second is that limitations of the sensors used for AEB in certain weather and lighting conditions were not taken into account. It should be remembered, however, that connected vehicles technology will most likely not be fitted to production vehicles for several years, by which point AEB system will likely have improved.

The system model used in this analysis is a simplification of complex technology that is still evolving. One of the greatest challenges facing manufacturers of collision avoidances systems is to correctly identify collision threats and avoid false alarms in complex environments. Connected vehicles do not have to the overcome the problem of identification of objects faced by sensor based AEB system but a large challenge for connected vehicles may be processing the wealth of information that they can receive. Connected vehicles could potentially receive information from hundreds of vehicles in heavy traffic from which they are required to determine if a real threat of collision exists.

Conclusions

Connected vehicles were found to:

- have many safety related applications that can potentially address the crash types right angle, right turn, rear end, hit pedestrian, side swipe and head on, though technical difficulties exist for hit pedestrian and head on crashes

- have the potential to address important crash types that are poorly, if at all, addressed by AEB; right angle and right turn crashes and certain pedestrian crashes

- reduce injury and fatal crashes by an additional 16 to 21 percentage points and 12 to 17 percentage points respectively above the percentage reduction of sensor based AEB if all crash types mentioned above can be addressed by connected vehicles

- reduce injury and fatal crashes by an additional 14 to 18 percentage points and 7 to 12 percentage points respectively above the percentage reduction of sensor based AEB if hit pedestrian and head on crashes can not be addressed by connected vehicles

The potential of connected vehicles to reduce crashes is therefore considerable and the uptake of such technology should be encouraged in ways that are shown to be cost effective.

Further Work

It was concluded that the uptake of connected vehicle technology should be encouraged in ways that are shown to be cost effective. Further work could be conducted to examine the cost effectiveness of connected vehicle technologies and methods of encouraging their uptake. The sample of simulations could also be expanded, particularly with regard to fatal crashes, to provide for more robust results within the categories of crash type, speed zone and severity.

The potential crash reductions were based on South Australia data only. Further work could be conducted to examine potential crash reductions in other states that use more specific crash types and may have a different distribution of crashes within the crash types.

The collision avoidance system model used is theoretical only. Further work is currently underway to use a production collision avoidance system from a connected vehicle collision avoidance product rather than the theoretical model. This will improve the accuracy of the results.

References

Ahmed-Zaid F, Bai F, Bai S, Basnayake C, Bellur B, Brovold S, Brown G, Caminiti L, Cunningham D, Elzein H, Hong K, Ivan J, Jiang D, Kenney J, Krishnan H, Lovell J, Maile M, Masselink D, McGlohon E, Mudalige P, Popovic Z, Rai V, Stinnett J, Tellis L, Tirey K and VanSickle S (2011) Vehicle Safety Communications – Applications (VSC-A) Final Report. DOT HS 811 492A. Farmington Hills: Crash Avoidance Metrics Partnership on behalf of the Vehicle Safety Communications 2 Consortium

Anderson RWG, Doecke SD, Mackenzie JRR, Ponte G, Paine D, Paine M (2012) Potential benefits of forward collision avoidance technology. CASR106. Adelaide: Centre for Automotive Safety Research

Andrews S, Cops M (2009) Final report: Vehicle infrastructure integration proof of concept. FHWA-JPO-09-003. Novi: VII Consortium

Arino M (2007) ITS Policy in Japan and Smartway [presentation] October

Brewer J, Koopmann J and Najm W (2011) System Capability Assessment of Cooperative Intersection Collision Avoidance System for Violations (CICAS-V). Cambridge: Research and Innovative Technology Administration, United States Department of Transportation

Berger A, Verweij F, Saleh P, Omasitis D, Schade H, Arneodo F, Cocozza M, Annoni M, Enricobena D Barnett L, Hoose N, Konstantinopoulou L and Booiman H (2010) Cooperative vehicle-infrastructure: costs, benefits and business models. D.DEPN 5.1. ERITCO – ITS Europe

COOPERS (2008) Co-operative Networks for Intelligent Road Safety: Summary report on safety standards, indicators to improve the safety roads. WP2000 D5 – A 2100. COOPERS

Davis GA (2001) Relating Severity of Pedestrian Injury to Impact Speed in Vehicle-Pedestrian Crashes, Transportation Research Record, 1773, pp. 108-113.

Doecke SD Anderson RWG, Mackenzie JRR and Ponte G (2012) ‘The potential of autonomous emergency braking systems to mitigate passenger vehicle crashes’, in Proceedings of Australasian Road Safety Research, Policing and Education Conference, Wellington, New Zealand, 4 - 6 October 2012

Fukushima M (2011) ‘The latest trend of v2x driver assistance systems in Japan’. Computer Networks, 55 (2011), pp. 3134-3141.

Fukushima M, Suzuki S (2010) ITS-Safety 2010. Cooperative safety driving challenge in Japan [presentation]

Lukuc M (2012) Light vehicle driver acceptance clinics: preliminary results [presentation] May 21

Mäkinen T, Schulze M, Krajzewicz D, Gaugel T, Koskinen S (2011) DRIVE C2X methodology framework. D22.1. DRIVE C2X

Najm WG, Koopmann J, Smith JD, and Brewer J (2010) Frequency of target crashes for IntelliDrive safety systems. DOT HS 811 381. Washington DC: National Highway Traffic Safety Administration.

NHTSA (2005) Tire Pressure Monitoring System FMVSS No. 138 – Final Regulatory Impact Analysis. Washington DC: National Highway Traffic Safety Administration.

RITA (2008) Vehicle-Infrastructure Integration (VII) initiative: benefit-cost analysis. Washington D.C.: Research and Innovative Technology Administration, United States Department of Transportation

RITA (2010) Achieving the vision: from VII to IntelliDrive. Policy white paper. Washington D.C.: Research and Innovative Technology Administration, United States Department of Transportation

Schulze M, Mäkinen T, Irion J, Flament M, Kessel T (2008) Final report. IP_D15. PReVENT

Schulze M (2011) DRIVE C2X @ simTD. DRIVE C2X: Overview – welcome [presentation] October 13

Schulze M (2012) DRIVE C2X @ DITCM. Deployment perspectives and potential pitfalls [presentation] July 5

Wani K (2006) ITS World Congress. The fourth phase of Advances Safety Vehicle project: technologies for collision avoidance [presentation] London