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# Crash reduction potential of connected vehicles in South Australia

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## TITLE

Crash reduction potential of connected vehicles in South Australia

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## 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. Central to the methodology employed to achieve this was the application of a collision avoidance system model to simulations of real world crashes investigated by CASR to determine the change in impact speed. The collision avoidance system model was used for this project to not only model sensor based AEB systems but comparable connected vehicles systems to determine the additional crash reduction potential of connected vehicles above that provided by AEB. A literature review was conducted and found that connected vehicles have many safety related applications that can address the South Australian crash types of right angle, right turn, rear end, hit pedestrian, side swipe and head on, though technical difficulties exist for hit pedestrian and head on crashes. Importantly, crash types that are poorly addressed by AEB, right angle and right turn crashes and certain pedestrian crashes, can be addressed by connected vehicle applications. It was found that connected vehicle technology could 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 hit pedestrian or head on crashes can not be addressed by connected vehicles the additional reduction is 14 to 18 percentage points and 7 to 12 percentage points for injury and fatal crashes respectively. The potential of connected vehicles to reduce crashes in South Australia is therefore considerable and the uptake of such technology should be encouraged in ways that are shown to be cost effective.

## KEYWORDS

Vehicle-to-vehicle communication (V2V), injury risk, modelling, simulation, accident rate

# Summary


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 safety applications. The purpose of this report was to estimate the safety potential of connected vehicle technology in Australian conditions.

This technology, referred to generally as connected vehicle technology, is not currently included on any production vehicle. When connected vehicle technology enters the market it will likely be doing so at a time when Autonomous Emergency Braking (AEB) is becoming common on new vehicles. The advantage of connected vehicles over AEB is that it does not suffer from field of view and line of sight limitations. The clear disadvantage of connected vehicle technology, however, is that it needs both vehicles to have the technology while AEB is self contained.

A literature review was conducted and found that connected vehicles have many safety related applications that can address the South Australian crash types of right angle, right turn, rear end, hit pedestrian, side swipe and head on, though technical difficulties exist for hit pedestrian and head on crashes. Importantly, crash types that are poorly addressed by AEB, right angle and right turn crashes and certain pedestrian crashes, can be addressed by connected vehicle applications.

Much of the research found in the literature review proposed that connected vehicles would be used to compliment a sensor based AEB system to provide a comprehensive collision avoidance system. For this reason the natural place to start was the methodology of a project conducted by CASR in early 2012 that examined the potential benefits of AEB. Central to the methodology employed to achieve this was the application of a collision avoidance system model to simulations of real world crashes investigated by CASR to determine the change in impact speed. The collision avoidance system model was used for this project to not only model sensor based AEB systems but comparable connected vehicles systems to determine the additional crash reduction potential of connected vehicles above that provided by AEB.

Because simulations are time consuming it was important that they were focussed on crash types that were both relevant and important. Relevance to connected vehicle technology was judged by the information found in the literature on applications of connected vehicle technology. Importance was judged by the prevalence of a given crash type in South Australia.

Risk curves were used to determine the injury outcomes of the crashes at the new speed produced by the collision avoidance system. The percentage reductions within a crash type, severity and speed zone group were applied to the South Australian crash data to determine the overall crash reduction percentages.

It was found that connected vehicle technology could 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 hit pedestrian or head on crashes can not be addressed by connected vehicles the additional reduction is 14 to 18 percentage points and 7 to 12 percentage points for injury and fatal crashes respectively. The potential of connected vehicles to reduce crashes in South Australia is therefore considerable and the uptake of such technology should be encouraged in ways that are shown to be cost effective.

# Contents

# 1 Introduction

Vehicle safety developments are often divided into two categories, primary safety and secondary safety. Primary safety refers to safety features that assist the driver in avoiding a crash while secondary safety refers to safety features that attempt to mitigate the consequences of a crash. Vehicle safety ratings and standards have historically focussed on secondary safety but have begun to mandate or encourage primary safety features as more and more such features are developed, electronic stability control being a prime example.

In recent years primary safety features have been developed that augment a driver's vision and reactions by automatically braking the vehicle if a hazard is detected. These system are referred to as autonomous emergency braking (AEB) systems. AEB systems currently use sensors of varying types to detect objects. These sensors suffer from some of the same limitations as human eyes; they have a limited field of view (perhaps even more limited than human eyes) and they require a line of sight to detect objects. Nevertheless AEB systems have been shown to have great potential to reduce crashes and injury (Anderson *et al.*, 2012; Insurance Institute for Highway Safety, 2012; Hummel *et al.*, 2011; Rosén *et al.*, 2010; Grover *et al.*, 2008) and increasingly manufacturers are adding such systems to their vehicles.

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 information that is sent from a vehicle is sometimes referred to as the 'basic safety message' or 'here I am' signal. The format of this basic safety message has been formalised in a Society of Automotive Engineers (SAE) standard SAE J2735 (SAE, 2009). It contains information such as the position (including elevation), positional accuracy, current speed, heading, steering wheel angle, acceleration and brake status. There is also potential for transmission of a short path history and a predicted path of the vehicle. SAE J2735 also provides standards for other information such as that from a dedicated intersection safety system.

For the purpose of primary safety applications the exchange of information between connected vehicles can be used to detect risks or potential collisions and warn the driver and/or autonomously intervene to avoid the collision.

Though connected vehicle technology is not currently included on any production vehicle it appears that this may occur in the near future. For example the National Highway Traffic Safety Administration (NHTSA) is set to make an agency decision on connected vehicles by 2013 which may include regulation or inclusion in the New Car Assessment Program (RITA website, 24 July 2012). 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 does not suffer from the same field of view and line of sight limitations. The clear disadvantage of connected vehicle technology, however, is that it needs both vehicles to have the technology while AEB is self contained.

The purpose of this report was to estimate the safety potential of connected vehicle technology in Australian conditions. This will be accomplished by determining what crash types can be addressed by connected vehicle technology and how effective it will be at reducing injury and fatal crashes of these types.

# 2 Literature review

Over the past two decades there has been a considerable amount of research conducted relating to connected vehicles. This research has accelerated in recent years. The research can be broken down into several general topics; development of the communication technology, development of applications for the communication technology, proof of concept tests of technology and/or applications, ensuring security, user acceptance tests, benefit costs analyses and large scale trials known as Field Operational Tests (FOTs). A comprehensive FOT should represent the last step before deployment. Many research projects have concentrated on several of these general topics.

The literature review will consider the applications that have been developed that have a safety focus (as opposed to a mobility focus), cost benefit analyses, and the FOTs that have been conducted. Estimates of efficacy and willingness to pay will also be examined. Other areas of research will be discussed where they provide context to the areas of focus. The bulk of the research in these areas has been conducted separately in three regions; the United States of America, the European Union and Japan.

Many safety applications for connected vehicle technology were proposed, developed and tested in the research work. The applications found can be put into two loose categories; those that can have a direct crash avoidance effect and those that may have an indirect crash avoidance effect. The applications are listed in Table 2.1 along with a description. Note that the operation of a given application may vary between research projects while still generally fitting the description. Mobility applications were not considered.

Table 2.1
Connected vehicle applications found in the research literature

| Application | Description |
|---|---|
| ***The applications that may have an direct crash avoidance effect*** | |
| 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 |
| 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 |
| Emergency Electronic Brake Lights | Warns the driver that a vehicle ahead is undergoing heavy braking |
| Forward Collision Warning | Warns the driver of impending collision with a vehicle in front (focussed on rear end crashes) |
| Blind Spot Warning (Lane Change Warning) | Warns the driver of vehicles present in their blind spot, especially when they intend to change lanes |
| Do Not Pass Warning | Warns the driver of vehicles in the oncoming traffic lanes, especially when they are about to perform a passing manoeuvre |
| Intersection Movement Assist | Warns the driver when it is not safe to enter an intersection due to high collision probability with other vehicles |
| 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) |
| 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). |
| Pedestrian Detection | Little information on this application is available, but detection is likely to be via the pedestrian's mobile phone |
| Bicycle Collision Prevention | Little information on this application is available, but detection is likely to be via the pedestrian's mobile phone |
| Loss of Control Warning | Warns surrounding vehicles of a vehicle that has lost control and may therefore pose a threat to them |
| ***The applications that may have an indirect crash avoidance effect include:*** | |
| Curve Speed Warning | Warns the driver if they are entering a corner too fast |
| Accident / Incident Warning | Warns the driver that an accident has occurred ahead of them |
| Weather Condition / Visibility Warning | Warns they driver that they are approaching bad weather, especially weather that might reduce visibility such as fog |
| Congestion Warning | Warns the driver that they are approaching the end of a slow or stationary traffic queue |
| In-vehicle Signage | Traffic sign information is communicated to the vehicles for display or notification |
| Intelligent Speed Assist with links to infrastructure | Informs the driver of the current speed limit including variable speed zones |
| Slippery Road Warning | Warns drivers of slippery road ahead either by infrastructure or by relaying information from other vehicles control systems |
| Road Works Warning | Provides advanced warning of road works and potentially the applicable road work speed limit |
| Car Breakdown Warning | Warns the driver that they are approaching a broken down vehicle |
| Approaching Emergency Vehicle Warning | Warns vehicles of approaching emergency vehicles |
| Green Light Optimal Speed Advisory | Signal phases of traffic lights are communicated to vehicles in order to inform the drivers about the optimal speed to pass traffic lights at green |
| Wrong Way Warning | Little information on this application is available |
| Merging Assist | Little information on this application is available |

Table 2.2 shows the applications that were included in each research project that is discussed in the following sections. The most common applications included in the research projects were signal violation warning and intersection movement assist. Europe is the only region that focussed more on the indirect safety applications than the direct safety applications.

Table 2.2
Applications found in the research literature by project

| Application | US Research | | | | | European Research | | | | | Japanese Research | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | VII | VSC-A | Safety Pilot Driver Clinics | Safety Pilot Model Deploy. | CICAS-V | COOPERS | CVIS | SAFESPOT | PReVENT | DRIVE C2X | Driving Safety Support System | Smartway | ASV |
| ***The applications that may have an direct crash avoidance effect*** | | | | | | | | | | | | | |
| Signal Violation Warning | ✓ | | | ✓ | ✓ | | | ✓ | ✓ | | ✓ | | ? |
| Stop Sign Violation Warning | | | | ✓ | ✓ | | | ✓ | ✓ | | ✓ | | ? |
| Emergency Electronic Brake Lights | | ✓ | ✓ | ✓ | | | | | | ✓ | | | |
| Forward Collision Warning | | ✓ | ✓ | ✓ | | | | ✓ | | | ✓ | | ? |
| Blind Spot (Lane Change) Warning | | ✓ | ✓ | ✓ | | | | ✓ | | | | | |
| Do Not Pass Warning | | ✓ | ✓ | ✓ | | | | ✓ | | | | | |
| Intersection Movement Assist | | ✓ | ✓ | ✓ | | | | ✓ | ✓ | | ✓ | | ? |
| Left Turn Assist | | | ✓ | ✓ | | | | | | | ✓ | | ? |
| Right Turn in Front Warning | | | | ✓ | | | | ✓ | ✓ | | ✓ | | ? |
| Pedestrian Detection | | | | ✓ | | | | ✓ | | | ✓ | | ? |
| Bicycle Collision Prevention | | | | | | | | ✓ | | | ✓ | | ? |
| Loss of Control Warning | | ✓ | | | | | | | | | | | |
| ***The applications that may have an indirect crash avoidance effect include:*** | | | | | | | | | | | | | |
| Curve Speed Warning | | | | ✓ | | | | ✓ | | | | | |
| Accident / Incident Warning | | | | | | ✓ | ? | ✓ | | ✓ | | | |
| Weather Condition / Visibility Warning | | | | | | ✓ | ? | | ✓ | ✓ | | | |
| Congestion Warning | | | | | | ✓ | ? | | ✓ | ✓ | | ✓ | ? |
| In-vehicle Signage | ✓ | | | | | ✓ | ? | | | ✓ | | | |
| Intelligent Speed Assist (V2I) | | | | | | ✓ | ? | ✓ | | ✓ | ✓ | | |
| Slippery Road Warning | | | | | | | | ✓ | ✓ | | ✓ | | |
| Road Works Warning | | | | | | | | | | ✓ | | | |
| Car Breakdown Warning | | | | | | | | | | ✓ | | | |
| Approaching Emergency Vehicle Warning | | | | | | | | ✓ | | | | | |
| Green Light Optimal Speed Advisory | | | | | | | | | | ✓ | | | |
| Wrong Way Warning | | | | | | | | | | | ✓ | | |
| Merging Assist | | | | | | | | | | | | ✓ | ? |

? is used when it is not known directly what applications were included in a project but inferences can be made

The individual research projects are discussed in the following sections by the region they were conducted in.

## 2.1 US Research

In the US the public and private sector have worked together to undertake a considerable amount of research and development of connected vehicles. The public sector has been led by the United States Department of Transportation's Research and Innovative Technology Administration (RITA) with substantial input also coming from the Michigan Department of Transportation. The key private input has come from vehicle manufacturers in the form of the Crash Avoidance Metrics Partnership (CAMP). Private research groups have also been involved, particularly Universities in Michigan and the Virginia Tech Transportation Institute (VTTI).

The research and development program for connected vehicles in the USA was initially referred to as the Vehicle Infrastructure Integration (VII) Initiative but was later renamed IntelliDrive. Another major connected vehicle project conducted in the USA was Safe and Efficient Travel through Innovation and Partnerships for the 21$^{st}$ Century (Safe Trip-21), however this project was focussed on mobility applications and therefore is not discussed in the present report.

### 2.1.1 Vehicle Infrastructure Integration (VII)

The VII program was launched in 2003 with a vision to "use wireless communication with and between vehicles to achieve dramatic safety and mobility improvements" (RITA, 2010). While its vision implied that that it would focus on V2V and V2I, in practice V2I was the primary focus of the program as it was thought that V2I could achieve safety benefits sooner than V2V (RITA, 2010).

The major piece of research conducted under the VII program was the VII Proof of Concept conducted between October 2005 and December 2008. The research was conducted by the VII consortium, consisting of vehicle manufacturers Ford, Nissan, BMW, Honda, Toyota, General Motors, Volkswagen, Mercedes Benz and Chrysler. The VII consortium was formed "for the specific purpose of actively engaging in the design, testing and evaluation of a deployable VII system for the United States" (Andrews and Cops, 2009). Seven applications were tested aimed at testing the core functionality of the system rather than developing specific production ready functions. Of these applications the 'heartbeat', a message containing speed and position data sent at typical interval of 100 ms, is arguably the most relevant to future safety applications and appears to be a forerunner to the basic safety message. The applications were tested in a lab environment, on test tracks and in open road environments. The tests showed that the vision of VII was technically feasible while also identifying areas where performance could be improved and concepts refined (Andrews and Cops, 2009).

A benefit-cost analysis was also conducted under the VII program to examine the economic impact of a nationwide deployment of the VII vision (RITA, 2008). Of the 14 applications included in the analysis only four were directly related to safety. These were; 'Signal Violation Warning', 'Stop Sign Violation Warning', 'Curve Speed Warning' and 'Electronic Brake Lights'. The estimates of efficacy of these applications used in the analysis were based upon the initial results of the Japanese SKY project conducted by Nissan (see Section 2.3). Not all of the applications were included in the SKY project, however the authors reasoned that applying these results was valid as they represented the approximate level of driver behavioural change from warnings. In all four cases 25% efficacy was used. The safety applications contributed the vast majority (95%) of the overall system benefit of $US44.2B. The cost of a roadside equipment installation was estimated and varied from US$9,600 to US$37,100, depending on the location (urban / rural) and type of installation (power source, communications components). On-board equipment was estimated to cost US$50 per vehicle. The benefit cost ratio was found to be 1.6. Sensitivity testing of various parameters was also undertaken to understand how the various inputs to the analysis affect the result. The BCR was most sensitive to the assumptions regarding the on-board equipment and efficacy with a doubling of the on-board equipment costs reducing the BCR to 1.1 and a reduction in efficacy rate to 15% reducing the BCR to 1.0.

### 2.1.2 IntelliDrive

In 2009 the USDOT rebranded the VII program IntelliDrive. The IntelliDrive program shares the same vision as the VII program but changed the approach to achieving the vision. This largely came about through the rapid adoption of new wireless technologies, such as the 3G network, and location services (GPS) opening up new possibilities for safety and mobility through wireless technology. Furthermore the VII approach, focussed on V2I, had produced three major questions that had not previously been resolved (RITA, 2010):

- Which is installed first: vehicles or infrastructure?
- How can market penetration into the vehicle fleet be accelerated to realise early benefits?
- How can the financial and logistical challenges be overcome to achieve sufficient infrastructure deployment?

IntelliDrive's new approach sought to overcome these hurdles in the ways described below and shown diagrammatically in Figure 2.1:

- The VII approach focussed on V2I, however research by NHTSA (Najm *et al.* 2010) revealed the huge potential of V2V and provided a compelling reason for IntelliDrive to aggressively pursue V2V implementation while also pursuing V2I. NHTSA has stated a V2V regulatory decision will be made in 2013, which could include mandating the installation of V2V technology in new vehicles and therefore resolving the question of the order of installation.
- The IntelliDrive program aims to accelerate market penetration by embedding DSRC in navigation systems and other aftermarket devices that emit a 'here I am' message for use by vehicles equipped with a full V2V system.
- With the focus of IntelliDrive being on the large benefits of V2V, and hence requiring little roadside infrastructure, it was proposed that infrastructure spending be prioritised for spot safety applications at high risk locations.

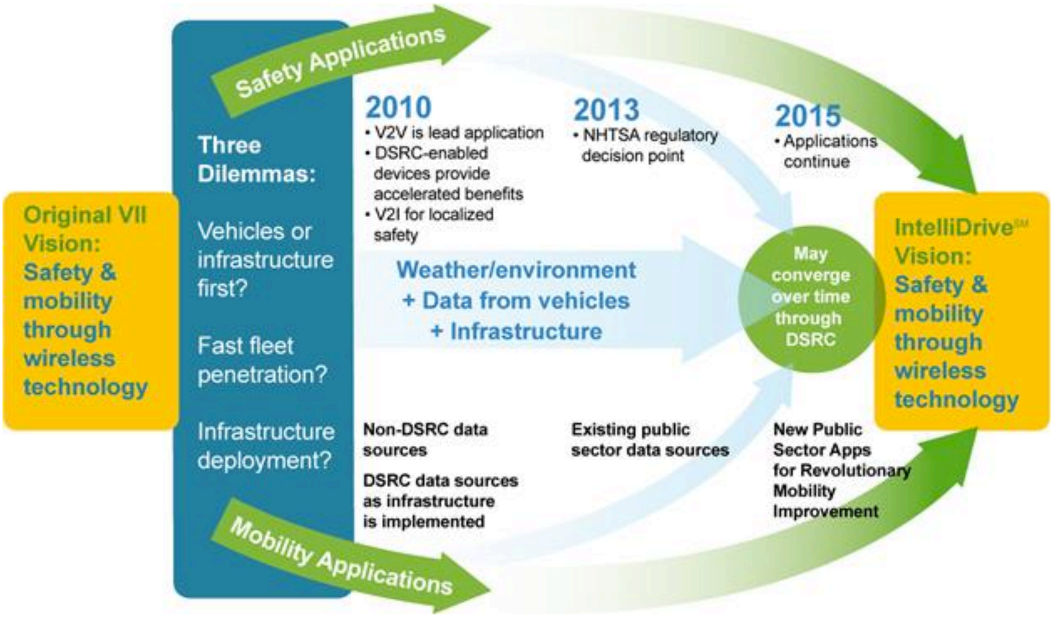


Figure 2.1 Achieving the IntelliDrive vision – the full concept (RITA, 2010)

The IntelliDrive V2V safety application research plan is shown in Figure 2.2. According to the plan, much of this research should be complete or nearing completion. However, because publicly available research reports are often only released a year or more after completion of the research, only limited information is available. The following sections detail what was available at the time of writing and is relevant to this report.

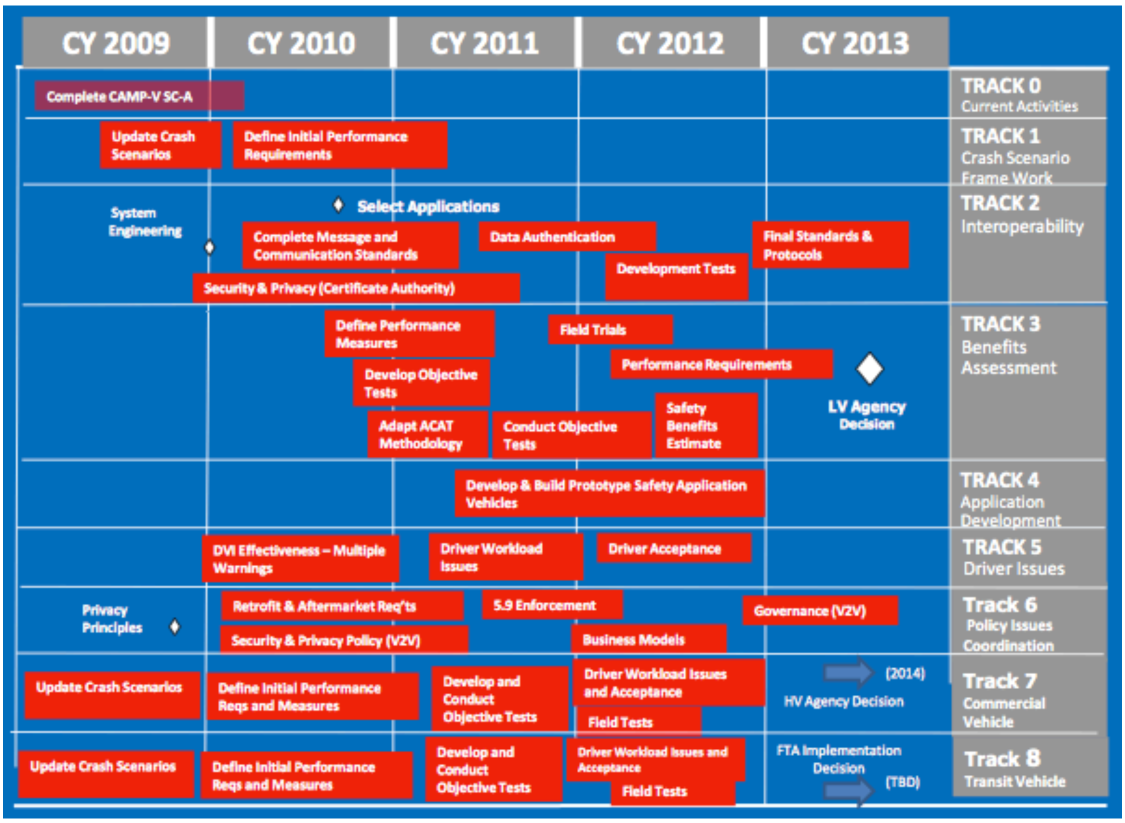


Figure 2.2
IntelliDrive V2V Safety application research plan roadmap (USDOT, 2011)

## Vehicle Safety Communications – Applications (VSC-A)

The VSC-A project aimed to develop and test connected vehicle safety systems to determine if dedicated short range communications (DSRC), combined with vehicle positioning, could improve upon AEB systems and/or enable new safety applications not possible with systems that only utilize vehicle based sensors such as radar, lidar or cameras (Ahmed-Zaid *et al*., 2011). The work conducted in VSC-A largely fits into the categories of development of communication technology, development of applications for the communication technology and proof of concept tests of technology and applications.

Data from the 2004 National Automotive Sampling System's General Estimates System crash database was used to determine a ranking for pre-crash scenarios based on frequency, cost and years of life lost. Seven scenarios were chosen to be the focus of the VSC-A project (See Table 2.3). Notable exclusions from Table 2.3 were 'Vehicle(s) Not Making a Manoeuvre – Opposite Direction' and 'Road Edge Departure without Prior Vehicle Manoeuvre'. Both were deemed not to be viable scenarios to be addressed by V2V. These crash types appear to be equivalent to head on crashes where the driver was not overtaking and vehicles that left the road; either out of control or simply drifting into the oncoming lane or off the road. 'Vehicle(s) Making a Manoeuvre – Opposite Direction', which appears to refer to vehicles preforming an overtaking manoeuvre, was selected purely to test the path prediction method in the oncoming direction.

Table 2.3
VSC-A selected crash imminent scenarios (Ahmed-Zaid *et al*., 2011)

| Crash Imminent Scenario | Crash Category | | |
|---|---|---|---|
| | High Frequency | High Cost | High life years lost |
| Lead Vehicle Stopped | ✓ | ✓ | ✓ |
| Control Loss without Prior Vehicle Action | ✓ | ✓ | ✓ |
| Vehicle(s) Turning at Non-Signalised Junctions | ✓ | ✓ | |
| Straights Crossing Paths at Non-Signalised Junctions | | | ✓ |
| Lead Vehicle Decelerating | ✓ | ✓ | |
| Vehicle(s) Changing Lanes – Same Direction | ✓ | | |
| Vehicle(s) Making a Manoeuvre – Opposite Direction | | | |

✓ Denotes top five ranking for the crash category

The list of selected pre-crash scenarios was then used to develop V2V safety application concepts: Emergency Electronic Brake Lights, Forward Collision Warning, Blind Spot Warning (Lane Change Warning), Do Not Pass Warning, Intersection Movement Assist and Loss of Control Warning (Ahmed-Zaid *et al*., 2011).

After the applications had been chosen, the potential of a system that combined a small field of view radar with a DSRC unit with positioning system (connected vehicle) was investigated. A vehicle fitted with both technologies was used to compare sensor output in six scenarios that were focussed on known situations where the radar sensor was limited. After conducting these tests the authors concluded that:

> In-vehicle testing shows that DSRC+Positioning can address several known limitations with autonomous sensing safety systems. Thus, the operational envelope for autonomous systems could be extended by associating targets identified with autonomous sensors with targets identified via DSRC+Positioning. For situations where no autonomous sensor target exists,

which can be associated with a corresponding DSRC+Positioning target, standard autonomous applications are still possible using the information received from a DSRC+Positioning only system. Likewise, for situations where no DSRC+Positioning target is possible (e.g., fixed targets, people, animals, etc.), autonomous sensors are necessary. What is likely is a "mixed-environment" with vehicles being equipped with an autonomous sensing and a DSRC+Positioning sensing safety system. (Ahmed-Zaid *et al.*, 2011).

## Safety Pilot Driver Clinics

Following the VSC-A project the CAMP members developed manufacturer-specific pre-production versions of the connected vehicle applications chosen in the VSC-A project, with the notable substitution of 'control loss warning' for 'left turn assist' (LTA). The Safety Pilot Driver Clinics aimed to obtain feedback on these connected vehicle applications for a representative sample of drivers and promote the safety benefits of V2V technology, while also assessing the performance and reliability of the systems. The Safety Pilot Driver Clinics therefore combined proof of concept tests of technology and applications with user acceptance tests.

Eight connected vehicles were driven in six test track locations by 688 drivers through 12 scenarios that demonstrated the six applications. Manufacturer specific human machine interfaces were used with audio, visual and/or haptic warnings to alert the driver to danger: the vehicles did not autonomously intervene. The clinics took place between August 2011 and January 2012.

A comprehensive report has not yet been released though a press release detailing the overall results (Green, 2012) and a presentation of the results (Lukuc, 2012) are available. The following results are taken from the presentation. When asked if they would like to have V2V communication on their personal vehicle 90% agreed, with 73% strongly agreeing. Of the specific applications drivers rated intersection movement assist (IMA) the most useful feature in terms of real world safety (96% positive) and LTA the least useful (84%). These results were closely mirrored in the driver's assessment of the effectiveness of the applications at alerting the driver to a specific threat, with IMA being rated the most effective (93% positive) and LTA the least (85% positive). A willingness-to-pay type question was asked to the drivers: "at what price level might you begin to feel this collective group of safety applications is too expensive to consider purchasing" (Lukuc, 2012). The majority of the drivers (58%) chose the highest value given, more than $250.

## Safety Pilot Model Deployment

The Safety Pilot Driver Clinics were conducted in a controlled test track environment. The Safety Pilot Model Deployment is a real world model of a national deployment of connected vehicles. It aims to determine effectiveness of the safety applications at reducing crashes and determine how real world drivers will respond to the safety applications. It began in August 2012 and it is planned to continue for one year.

The model deployment consists of 2,836 vehicles, including trucks and transit vehicles, and 73 lane miles (118 km) of roadway with 29 roadside equipment installations. Of the vehicles, only 386 can receive messages with the remainder simply transmitting the 'basic safety message'. The roadside equipment installations were located at 21 signalised intersections, three curves and five freeway sites. The V2V applications included in the deployment were the six used in the driver clinics with the addition of a 'Right Turn in Front Warning'. The V2I applications included were 'Cooperative Intersection Collision Avoidance Systems - Violations', 'Curve Speed Warning' and 'Pedestrian Detection' (Bezzina, 2012).

### Cooperative Intersection Collision Avoidance Systems Violations (CICAS-V)

The CICAS-V is a prototype V2I system designed by CAMP that aims to prevent vehicles from violating a traffic signal or stop sign at an intersection. The roadside equipment at the intersection broadcasts a geographical intersection description, local corrections for a GPS and the current state of the traffic signals. The on-board equipment uses this data, data from the vehicle and its own GPS to determine the lane of travel and, if required, ability to stop without excessive deceleration. If the system determines that the vehicle may be in danger of violating the traffic signal or stop sign the driver is warned by visual, audio and haptic alerts (Brewer, Koopmann and Najm, 2011).

Objective tests of the system were conducted in a test track environment in July 2008 to determine the readiness of the system to deliver timely warnings when there is real potential for a violation to occur, yet not produce false alarms. Test speeds ranged from 25 to 55 mph (40 to 89 km/h). The results of the objective tests showed the system functioned as desired, even when the vehicle was positioned near the edge of the lane, the vehicle shifted between lanes, or there were multiple intersections within the range of the on-board equipment. The objective tests also found that the system was capable of operating under severely inhibited line of sight conditions.

Following the success of the objective test a pilot test was conducted on public roads and on a test track with naïve drivers. The pilot test consisted of two tests, a pseudo- naturalistic test and test track tests. In the pseudo-naturalistic component 93 drivers drove a pre-planned route in a vehicle equipped with several advanced safety features, one of which was CICAS-V. The route included a total of 20 manoeuvres at signalised intersections and 32 manoeuvres at intersections with stop signs, all of which were equipped with CICAS-V roadside equipment. In total, data was obtained from 1,455 signalised intersection crossings and 2,618 stop controlled intersection crossings. The test track tests consisted of distracting 23 drivers on the approach to an intersection just as the traffic signal changed from green to amber. If sufficiently distracted the driver would receive a warning from the CICAS-V system. The driver would also be closely followed by another vehicle on the approach to the intersection.

The pseudo naturalistic portion of the pilot test demonstrated that the system reacted correctly in most cases, however some shortcomings in the system when the approach is on a steep incline were discovered and rectified. Incorrect warnings were also issued due to an error in a geographical intersection description and phasing changes being made due to an emergency vehicle priority protocol. The CICAS-V system correctly warned three drivers who may have driven through a stop sign because it was partially obscured on approach to the intersection and one driver who may have otherwise run a red light. The test track portion of the pilot test showed that CICAS-V appropriately warned distracted drivers, causing most of them to avoid running a red light despite being closely followed by another vehicle (one of 18 proceeded through the red light). It was concluded that while CICAS-V demonstrated promising capability further fine-tuning would be needed before a field operational test is undertaken.

It can be assumed that the further fine-tuning of the system has taken place, as the system has been included in the Safety Pilot Model Deployment described earlier.

## 2.2 European Research

A significant body of research and development has also been conducted in Europe with research beginning over a decade ago. This section will only discuss the more recent research projects. The bulk of the research has been funded by the European Commission and it's various framework programmes, with involvement of many vehicle manufacturers, equipment suppliers and research institutes.

Three of the major EC funded projects that ran in parallel were the Cooperative Systems for Intelligent Road Safety project (COOPERS), the Cooperative Vehicle-Infrastructure Systems project (CVIS), and the SAFESPOT project. These three projects were designed to be complementary, though they do overlap. The focus of the projects and how they complement each other is shown diagrammatically in Figure 2.3. Other projects included the PReVENT project and the DRIVE C2X project. All of the European projects discussed were very large and incorporated many, if not all, of the general topics.

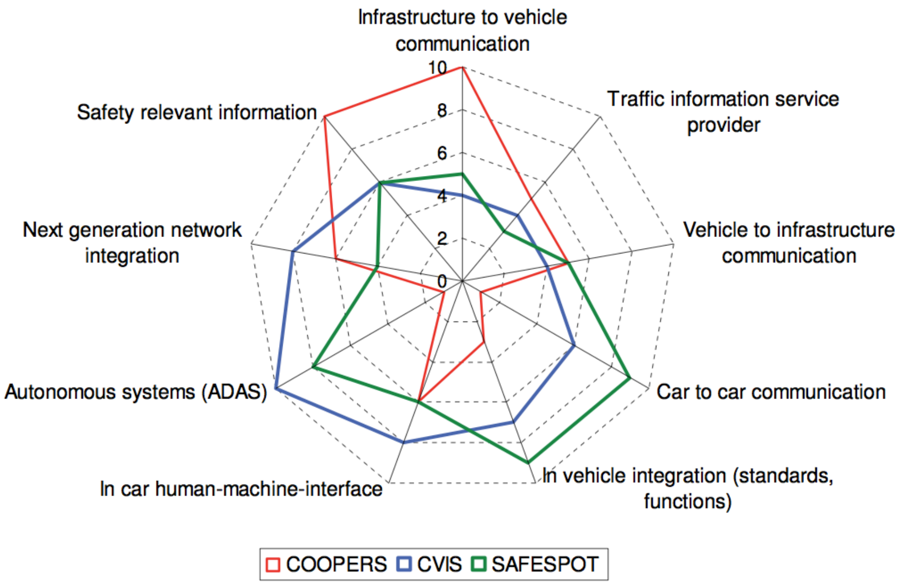


Figure 2.3
Focus of three of the EC funded projects on connected vehicles (Pfliegl, 2010)

## Cooperative Systems for Intelligent Road Safety (COOPERS)

The stated goal of the COOPERS project is "the enhancement of road safety by direct and up to date traffic information communication between infrastructure and motorised vehicles on a motorway section" (COOPERS website, 27 July 2012). While the stated goal of the project was to improve safety, the applications chosen all have an indirect crash avoidance effect (See Table 2.2). Essentially, the system developed in the project would operate as a fast acting variable message board that transmits its message to the vehicle for display and warning. The primary safety benefit of the system would be in the reduction of rear end accidents (COOPERS, 2008). Simulation and demonstration sites' results showed that the system would reduce mean speeds on the approach to traffic congestion or fog.

## Cooperative Vehicle-Infrastructure Systems (CVIS)

The objectives of the CVIS project were to create a wireless network and platform for V2I and V2V services, thereby increasing road efficiency and safety through vehicle-infrastructure cooperation (Kompfner, 2010). The applications developed were primarily focussed on mobility with only one application, Enhanced Driver Awareness (EDA), focussed on safety. EDA appears to be an umbrella term for applications that will inform the driver of the traffic situation ahead by V2I or V2V, similar to the V2I applications of COOPERS. User acceptance surveys and a study of costs, benefits and business models were also undertaken as part of the CVIS project.

The user acceptance surveys found that the CVIS applications were generally rated favourably, with the only safety application (referred to as Road Status Report in the user acceptance surveys) rated very or quite useful by 71% of the respondents. While users generally thought the applications would be useful they were less willing to pay for them, with only 45% quite or very willing to pay for the same application.

The costs, benefits and business models work undertaken did not arrive at a BCR but rather gave recommendations on factors that might lead to implementation of the CVIS system. One such recommendation was that the implementation of CVIS should focus on safety applications that have a highly beneficial effect. This recommendation came after it was found that safety benefits represented 93% of the total potential benefits. The recommendations also noted that user acceptance was one of the highest risks in terms of deployment and cost effectiveness. While no BCR was calculated, total benefits and costs were reported. For example, the scenarios in which the public (meaning public institutions) pays lists the total benefits as €2.1B and the total costs as €1.4B, from which a BCR of 1.5 can be inferred.

The authors concluded “that a public and private participation will be needed to implement these services and the necessary infrastructure” (Berger *et al.,* 2010).

### SAFESPOT

The objectives of the SAFESPOT project were (SAFESPOT website, 27 July):

- Use the infrastructure and the vehicles as sources and destinations of safety-related information and develop an open, flexible and modular architecture and communication platform.
- Develop the key enabling technologies: ad-hoc dynamic network, accurate relative localisation, dynamic local traffic maps.
- Develop and test scenario-based applications to evaluate the impacts on road safety.
- Define a sustainable deployment strategy for cooperative systems for road safety, evaluating also related liability, regulations and standardisation aspects.

To achieve these objectives eight sub-projects were undertaken. As can be seen in Figure 2.3, of the three parallel EC projects, SAFESPOT was the most focussed on V2V technology and applications. It was also the most focussed on direct safety applications (see Table 2.2).

Many of the applications appear to be focussed on situations where an AEB system’s functionality will be limited. In some cases it was proposed to use V2V to relay information from one vehicles AEB system to another vehicle in order to facilitate early warning even when a vehicles view is obstructed (Brignolo *et al.,* 2008).

The V2I applications were evaluated at six test sites and in traffic simulation environments. The tests conducted showed that, overall, warnings were delivered correctly and in time. The nature of the tests did not allow for a robust estimate of their safety impact but rather demonstrated that the safety applications are technically achievable (Fakler *et al.* 2010).

A user acceptance survey comprising 1,825 respondents was also conducted as part of the SAFESPOT project (Francano *et al.,* 2010). Of the applications that respondents were asked about, rear or frontal collision warning was rated as the most useful, with 92% of respondents rating it very useful (69%) or useful (23%). On-vehicle road sign provision was rated the lowest, with 20% rating it as very useful and 37% as useful. A majority of the respondents thought that rear or frontal collision warning systems, pedestrian protection and safety distance warning should become mandatory (65%, 61% and 54% respectively). Fewer respondents were willing to pay for the applications than had rated them useful, though the majority were willing to pay for rear or frontal collision warning and pedestrian detection. Almost 80% preferred to pay for the system when they purchased a car rather than an annual, monthly or per kilometre fee. The majority of these would prefer it to be a standard feature and were willing to pay between €150 and €350 for the whole system (individual prices were not put on specific applications).

A cost benefit analysis was also undertaken for selected V2V and V2I safety applications (Luedeke *et al.,* 2010). Much of the benefit calculations, particularly the estimates of efficacy, were taken from a previous project call eIMPACT. Table 2.4 shows the efficacy estimates used in the analysis.

Table 2.4
Estimates for behavioural mechanism effects for selected applications and bundles based on relevant aggregated accident statistics (Luedeke *et al.,* 2010)

| Application | Sub-application | Aim | Safety impact | |
|---|---|---|---|---|
| | | | Fatalities (%) | Injured (%) |
| V2V | | | | |
| Lateral collision (LATC) | Road intersection safety/Obstructed view at intersections | Left-turn assistant | -0.7 | -2.2 |
| Road departure (RODP) | Road condition status /Slippery road | Warning about slippery road only | -1.0 | -0.5 |
| Longitudinal Collision (LONC) | Speed limitation and safe distance | Information about speed limit and keeping safe distance | -7.5 | -6.1 |
| V2I | | | | |
| Intelligent Cooperative Intersection Safety system (IRIS) | Basic application | Identify potential red light violators, support drivers turning right and left turn assistant | -3.1 | -4.8 |
| Hazard and Incident Warning (H&IW) | Abnormal weather conditions | Warning about slippery road and reduced visibility | -1.6 | -0.7 |
| Speed Alert (SpA) | Legal Speed Limit | Information about speed limit | -7.1 | -4.9 |
| Bundles | | | | |
| V2V bundle | Road intersection safety and Speed limitation and safe distance | Left-turn assistant and information about speed limit and keeping safe distance | -8.1 | -8.3 |
| V2I bundle | Intersection Safety system and Speed Limit | Identify potential red light violators, support drivers turning right and left turn assistant and Information about speed limit | -10.2 | -9.7 |

The estimated costs of the V2V systems and the infrastructure are shown in Tables 2.5 and 2.6. One of the V2V components listed is a long range radar, usually associated with sensor based AEB systems. The authors stated “the inclusion of the LRR [long range radar] in the V2V bundle is made to align the system under analysis with the current implementations available in the SAFESPOT test sites” (Luedeke *et al.,* 2010). However, it is not clear if the proposed applications rely on the radar. If the radar were not included the cost of the V2V system would be more than halved.

Table 2.5
Total component and system costs per penetration rate for V2V (Luedeke *et al.*, 2010)

| Penetration rate | Component costs (EUR) | | | | Sum (EUR) | System costs including implementation (EUR) |
|---|---|---|---|---|---|---|
| | Dual freq. GPS | Digital maps | Warning module | Long range radar | | |
| 4.2% | 20 | 30 | 10 | 84 | 144 | 151 |
| 11.3% | 5 | 20 | 10 | 84 | 119 | 125 |

Table 2.6
Infrastructure costs for V2I in EUR (Luedeke *et al.*, 2010)

| Component | Costs (incl. installation) | Operation and maintenance costs | Lifetime (years) | Annuity rate | Yearly costs |
|---|---|---|---|---|---|
| Roadside unit incl. antenna | 6,500 | 130 | 10 | 0.117 | 1,549 |
| Existing CCTV video cameras | 1,200 | 1,139 | 10 | 0.117 | 1,280 |
| Automatic ice detection system | 8,275 | 441 | 10 | 0.117 | 1,411 |
| Laser scanner | 3,515 | 441 | 10 | 0.117 | 853 |

A benefit cost analysis was carried out using several key assumptions; that there would be no V2V benefit before a fleet penetration level of 4.2% and equipping 50% of roads with infrastructure (installed every 1.5km) will cover almost all the crashes relevant to the V2I applications. For the V2V applications the BCR was found to be between 1 and 1.1 for penetration rates of between 6.1 and 8.7%, and various investment models. For the V2I applications the BCR ranged from 0.21 to 0.36 for vehicle penetration rates between 5.4 and 9.5%. However, the authors suggest a highly targeted infrastructure approach may achieve a BCR of, or above, 1.

## PReVENT

The PReVENT project was a large European research and development project that aimed to develop and demonstrate a suite of safety functions that would complement each other to produce an electronic safety zone around the vehicle, as shown in Figure 2.4 below (Schulze *et al.,* 2008).

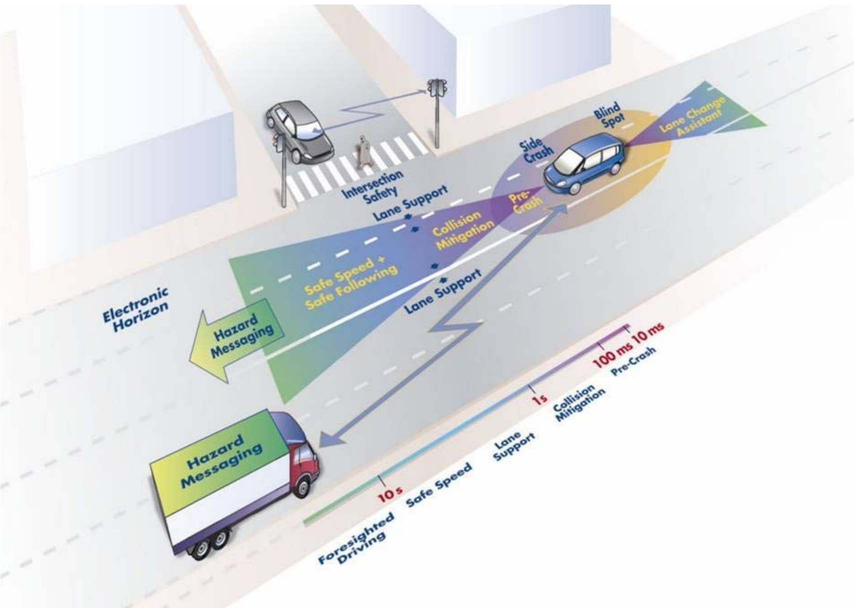


Figure 2.4
PReVENT vision of a safety zone around the vehicle realised by complimentary safety functions (Schulze *et al.,* 2008)

The safety functions envisioned and developed used both typical sensors as well as connected vehicle technology. Two of the proposed safety functions relied purely on connected vehicle technology; the 'wireless local danger warning system', a communication based cooperative driving system that extends the driver's horizon and warns the driver of dangerous situations ahead, and the 'intersection driving support system', a driver warning system that will know the status of the relevant traffic signals, the relative positions of other vehicles and the predicted path of other vehicles at intersections.

The PReVENT wireless local danger warning system relays information that can be obtained from the vehicles control systems, rather than passing on information from the sensor based systems. This limits the warnings to stopped vehicle ahead warnings, road condition warnings derived from stability control systems and reduced visibility warnings derived from the vehicles lights and wipers.

The intersection driving support system was developed to assist with turning left through oncoming traffic (equivalent to right in Australia), warn of laterally approaching vehicles and provide the status of traffic signals. System tests produced 7%, 0% and 10% false alarm rates respectively, though no false negatives occurred. User acceptance tests were also conducted.

Evaluations of the potential effectiveness of the systems were undertaken (Scholliers *et al.*, 2008) however the results for the connected vehicle applications appear to be largely based on subjective estimates. Only the left turn assist aspect of the intersection driving support system was included in the effectiveness evaluation. It was estimated to reduce fatalities by 0.6% and injuries by 1.5%.

### DRIVE C2X

DRIVE C2X is a large field trial of connected vehicle technology being conducted in seven European countries.  It represents the next step in European connected vehicle research, and possibly the final step before implementation. It began at the beginning of 2011 and is scheduled to take three years (Schulze, 2011); therefore it is approximately half way to completion at the time of writing.

While 26 functions were defined in the preliminary stage (known as Pre-Drive C2X) only nine were selected for full impact assessment based on several criteria; global traffic safety, individual safety and impact on road fatalities, deployment and time to market, traffic efficiency, quality of evaluation, and test site involvement. The chosen functions were, road works warning, traffic jam ahead warning, car breakdown warning, weather warning, emergency electronic brake light, approaching emergency vehicle warning, post crash warning, in-vehicle signage & regulatory and contextual speed limit, and green-light optimal speed advisory (Mäkinen et al. 2011).

All but one of the applications are applications that may only have an indirect effect on safety, despite the use of several safety based selection criteria. The applications will be tested in two ways, naturalistic tests in real driving conditions and controlled tests on closed circuits.

The cost of the system was estimated to be €400, of which €150 is for the components and the rest to cover overheads (Schulze, 2012).

A number of the test sites involved in the project are essentially running their own FOTs that provide inputs to the overall DRIVE C2X project. In Germany this project is referred to as simTD. SimTD will also internally evaluate an intersection and cross traffic assistant feature that will warn motorists when they are about to fail to give way at an intersection (simTD website, 2011). The system seems similar to that developed and evaluated in PReVENT.

France also has a stand alone project that is part of C2X known as SCORE@F. This project also has specific applications that are not part of DRIVE C2X, namely wrong way vehicle warning, approaching vehicle, stop sign violation warning and third party on collision course warning (FOT-Net Wiki website, viewed 24 July 2012). Definitions of approaching vehicle and third party on collision course warning were not provided.

## 2.3 Japanese Research

Connected vehicle research and development began in Japan in the 1990's and has involved the Ministry of Land, Infrastructure, and Transportation, the National Police Agency and vehicle manufacturers. It has been conducted in three separate streams; the SmartWay project, Driving Safety Support System (DSSS) program and the Advanced Safety Vehicle program (ASV). Figure 2.5 shows the timing and focus of these three projects streams. Of note is that the ASV project only began to focus on connected vehicles (referred to as V-V comm. in Figure 2.5) in the third stage of the ASV project (Fukushima and Suzuki, 2010). Information on these projects was difficult to obtain: what is known about them is described in the following sections.

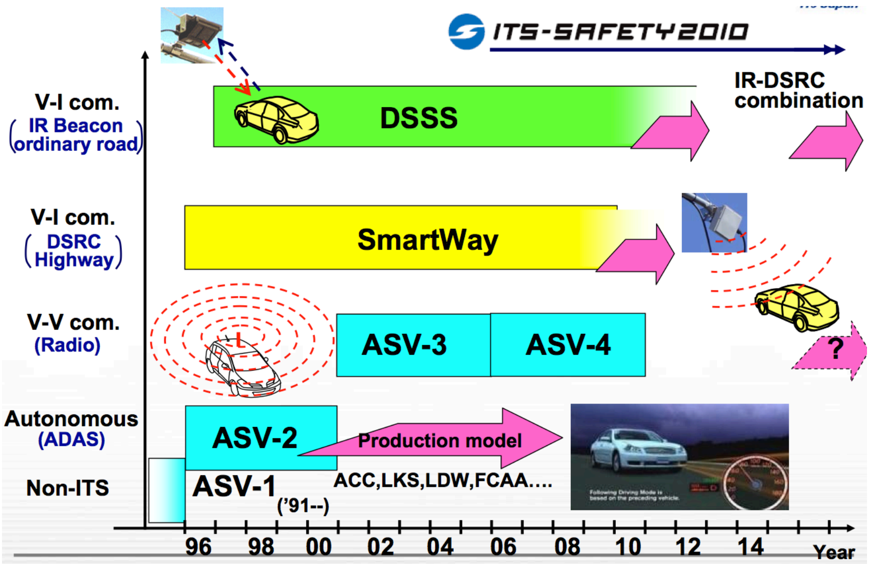


Figure 2.5
History and road map of connected vehicles in Japan (Fukushima and Suzuki, 2010)

### Driving Safety Support System

The exact scope of the work encompassed under this program is not clear, however it is known that it is based upon V2I technology on ordinary roads (see Figure 2.5 above). The bulk of the information available appears to be derived from work conducted by Nissan. The DSSS applications are reported to include, right-turn collision prevention, crossing pedestrian recognition enhancement, left-turn collision prevention, signal recognition enhancement, crossing collision prevention, crossing bicycle collision prevention, stop sign recognition enhancement and rear-end collision prevention.

Specific information on how all these systems achieve their goals could not be obtained, however it appears that the general method was to use roadside infrared beacons to detect the presence and speed of road users. Warnings would then be transmitted to vehicles based on this information.

A FOT was carried out involving 2,000 naïve drivers for a period of almost two years to test the signal and stop sign recognition enhancement applications and the crossing collision prevention application (Fukushima, 2011). Complete results were not available, however vehicles equipped with the system came to a complete stop at one of the stop signs 76% of the time, compared to 41% of the time for vehicles without the system. The percentage of vehicles that were exceeding the speed limit on the approach to the intersection was also reduced from 41% to 23% with the system. For the traffic signal warning, the rate of speeding on the approach reduced from 70% to 56%. For the crossing collision prevention application the rate of 'crash unavoidable vehicles' reduced from 38% to 22%, though it is unclear what 'crash unavoidable vehicle' means (Fukushima, 2011).

Further work was conducted privately by Nissan and is referred to as the SKY (Start ITS from Kanagawa, Yokohama) project. The safety applications tested in SKY were intersection collision avoidance (2,000 vehicles), intelligent speed advisory (2,000 vehicles), pedestrian traffic safety using GPS mobile phones (700 people), skid incident information service (100 vehicles) and opposite direction driving prevention on highway (Fukushima and Suzuki, 2010; Fukushima, 2011). The pedestrian traffic safety application appears to only alert drivers to the presence of a pedestrian in the general vicinity of the vehicle rather than alerting the driver to an imminent collision. It seems that the trials included in SKY have been completed though no results could be found.

### SmartWay

The vision of the SmartWay project is a road system that allows the exchange of information between road users. It is essentially a road infrastructure focussed V2I project. The safety related applications included in the SmartWay field operation tests were limited to congestion and obstacle warnings and merging assistance (Arno, 2007). The project appears to have been aimed at high volume roads. A FOT began in 2007 but no results could be found.

### Advanced Safety Vehicle (ASV)

The advanced safety vehicle program involves the Japanese Ministry of Land, Infrastructure and Transportation and Japanese car manufacturers. The ASV program has been conducted in several stages, with connected vehicle technology only included from the third stage, with earlier stages focusing more on ADAS systems, including AEB. It appears, however, that connected vehicles were only seriously considered for the ASV4 program that ran from 2006 to 2010. The desired role of connected vehicle technology in the project was to cover events that would not be seen by a sensor based ADAS system (Wani, 2006).

The ASV4 project aimed to trial V2V and V2I applications from 2007 with a target of partial market introduction in 2010 (Wani, 2006). The precise applications that were included in the trial are not known, and neither are the results of the trial.

The ASV5 project aims to further develop connected vehicle technology and further study the practical use of V2V and include vehicle to pedestrian communication (Wani, 2012). The current progress of ASV5 is unknown.

## 2.4 Summary and Discussion

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. In 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. Mobile phones may be placed in a position that interrupts the GPS signal when not in use, such as the bottom of a handbag.

Very little research on the effect of the applications is available at this point in time. 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 (appears to be a combination of several intersection collision prevention applications) applications: vehicles coming to a complete stop at a stop sign rose by 85% from 41% to 76%, vehicles that were exceeding the speed limit on the approach to an intersection was reduced from 41% to 23% and 'crash unavoidable vehicles' reduced from 38% to 22% (though it is unclear what 'crash unavoidable vehicle' means). The European research project COOPERS found that traffic congestion warnings and fog warnings did reduce the approach speed of drivers based on simulator and demonstration site results. Another European research project, SAFESPOT, also reported some application effects, however these do not appear to be based on experimental results.

Several benefit-cost analyses were performed despite the lack of efficacy data available. The results of these analyses should therefore be treated as preliminary and could be subject to change 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%. 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. 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. 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.

It is also 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% respectively).

The costs of the connected vehicle technology were detailed in two of the research projects, be it the in-vehicle technology or roadside technology. The VII project estimated the cost of the in-vehicle technology to be $50. The roadside technology ranged from $9,600 to $37,100. The SAFESPOT project estimated the in-vehicle technology to cost between €125 and €151, though this included a long range radar. If the cost of the radar was excluded then the cost is reduced to between €41 and €67. The cost of a roadside unit was €6,500. The C2X project estimated the cost of the system to be €400, €150 for components and €250 for overheads. This is considerably higher than the other estimates.

Willingness to pay is often used as an assessment of the likely take up of a new technology: if the cost of the object is below what someone is willing to pay for it they will likely purchase it, given an opportunity. The majority (58%) of the participants in the Safety Pilot Driver Clinics, conducted as part of the US IntelliDrive program, stated they would feel the connected vehicle applications were too expensive if they were more than $250, the highest value given. The CVIS project included a very basic willingness to pay question, with participants reporting their level of willingness rather than a dollar value. Only 45% of the participants stated they were quite willing or very willing to pay for the safety application termed Road Status Report, though this appears to be a weak safety application. A user acceptance survey that was conducted as part of the SAFESPOT project found that the majority of respondents would prefer to pay for the technology when they purchased a new vehicle and would also prefer that it was a standard feature rather than an option. They were willing to pay between €150 and €350. Based on these willingness to pay values and the in-vehicle technology cost estimates it appears that people would be willing to pay the price of the in-vehicle equipment estimated in the VII and SAFESPOT projects, but not the cost given in the C2X project.

A theme that was common to several of 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 will be used to compliment a sensor based AEB system too provide a comprehensive collision avoidance system.

# 3 Background and objectives of the present research

In early 2012 the Centre for Automotive Safety Research was commissioned by the Queensland Department of Transport and Main Roads and the Australian Department of Infrastructure and Transport to undertake research into the potential benefits of AEB (referred to as forward collision avoidance technology in the subsequent report). Central to the methodology employed to achieve this was the simulation of real world crashes investigated by CASR and the application of a model of AEB systems to the crashes to determine the change in impact speed. This study found that AEB could be highly effective at reducing crashes: potential injury and fatal crash reductions were found to be between 30 and 50% and 20 and 40% respectively (Anderson *et al.*, 2012).

Much of the research discussed in the literature review (Section 2) highlighted that connected vehicles would not enter the market in isolation, rather it would be used to compliment a sensor based AEB system too provide a comprehensive collision avoidance system. This idea was found in research in all three of the main regions of connected vehicle research; the US, Europe and Japan. For this reason the natural place to begin the methodology of this project was with the aforementioned AEB project and its methodology.

One obvious disparity between the connected vehicle applications that have reportedly been developed and AEB is that the connected vehicle applications appear to simply warn the driver whereas AEB, by definition, autonomously intervenes to avoid the crash. Warnings alone have been found to have a lesser effect than autonomously intervening systems (Georgi *et al.* 2009; Insurance Institute for Highway Safety, 2012). The reason may be that they can not warn the driver any sooner than an autonomous system would intervene because false warnings would be annoying, similar to false autonomous interventions. Since the driver can not react as quickly to the warning as an autonomous system can, the driver will intervene later than an autonomous system. However, the fact that the current applications of connected vehicles only include warnings does not mean they will not autonomously intervene in the near future. Warning systems often evolve into autonomous systems in time: AEB was the natural evolution of forward collision warning systems. Furthermore, if connected vehicle technology's future path is, as proposed by several researchers, to compliment a sensor based AEB system, it seems likely that the information received by a connected vehicle will be used in conjunction with the information from the sensors to autonomously brake the vehicle when required. Taking this into consideration the methodology of the AEB project (Anderson *et al.*, 2012) could be applied directly to the current work examining connected vehicles by simply taking into account the extra information that is available from the connected vehicle technology.

The objective of this approach was to determine the additional benefit, in terms of fatal and injury crash reductions, of connected vehicles above that provided by a sensor based AEB system. This will provide an estimate of the crash reduction potential of connected vehicles in the vehicle safety environment they are likely to encounter when they enter the market.

# 4 Method

## 4.1 Methodology

The focus of the methodology adopted from Anderson *et al.* (2012) was to simulate crashes to determine what the outcome 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 additional benefit of connected vehicles.

It was thought that simulating real world crashes would give the most accurate indication of the effect of the collision avoidance systems. To simulate a 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). Data collected by at scene in-depth crash investigations do contain the necessary level of detail, though they may not provide a representative sample. To overcome these shortcomings, both datasets were used; the in-depth crash data was used to simulate crashes within a crash type and the mass data was used to weight these results to determine the overall effect.

The outcome of the crash with the collision avoidance system is elementary if the simulation shows that the crash would have been avoided completely. However, if the collision avoidance system reduces the impact speed but does not avoid the crash altogether, determining the outcome of the crash is more complex, though still important as a reduction in impact speed may have a considerable effect of the degree of injury suffered in the crash. A number of risk curves have been produced by researchers that provide information on the likely injury outcome at a given impact severity. Such curves were used to determine the injury outcomes in cases were the collision avoidance system was not able to avoid the crash but did reduce the impact speed.

Because simulations are time consuming it is important that they are focussed on crash types that are both relevant and important. Relevance to connected vehicle technology can be judged by the information in the literature review on the applications of connected vehicles. Importance can be judged by the prevalence of a given crash type in the mass data.

It was also thought to be important to differentiate between crashes occurring in different speed zones 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. However, to break the simulations down into individual speed zones and crash types would either mean a very large number of simulations or very few simulations in each grouping. It was decided that grouping speed zones into typical groups (50/60, 70/80/90 and 110/110) would provide appropriate differentiation of speed limits while still providing for a reasonable number of simulations in each individual group without conducting excessive simulations.

## 4.2 Overview

The method can be summarised as follows:

- Literature was reviewed to determine what crash types are relevant, or potentially relevant to connected vehicles
- Mass crash data was used to select the important types of injury and fatal crashes that are relevant, or potentially relevant, to connect vehicles by speed zone group

- Cases from CASR's in-depth crash investigation database were randomly selected for the relevant and important crash types in each speed zone group
- The selected in-depth cases were simulated to determine trajectories and closing speeds
- The specification (general performance) of several AEB systems and equivalent connected vehicle systems were parameterised
- A collision detection and intervention model based on these parameters was applied to the simulations of in-depth cases to determine the new closing speed with the collision avoidance system
- New crash outcomes were determined in each crash based on a relationship between closing speed and injury or fatal crash risk
- The percentage reductions within a crash type, severity and speed zone group were applied to the mass data to determine the overall crash reduction percentage
- The additional crash reduction percentage produced by connected vehicle was calculated by summing the positive differences between the crash reductions of the connected vehicle system and its equivalent sensor based AEB system and dividing by the total number of crashes

## 4.3 Identification of relevant and important crash types

The literature review identified the potential applications of connected vehicle technology. By matching these with crash types found in the mass data, it can be determined what crash types are relevant. Note that only the applications that were thought to have a direct effect on crashes were appropriate for this purpose.

The South Australian mass crash database, TARS, uses its own system of crash type classification. The crash types contained in TARS are much broader than the Definition for Coding Accidents (DCA codes) used in some other states, with only 13 crash types in total compared to the 88 DCA codes. The DCA codes that are covered by each TARS crash type and the applications that apply to each crash type are shown in Table 4.1. The crash types that might be addressed by connected vehicle applications were right angle, rear end, right turn, hit pedestrian, side swipe and head on crashes.

Table 4.1
The DCA codes covered by each TARS crash type

| TARS crash type | DCA codes | Relevant applications |
|---|---|---|
| Hit fixed object | 703-704/803-804 | - |
| Right angle | 101-109 | signal violation warning ,stop sign violation warning, intersection movement assist |
| Rear end | 301-304 | emergency electronic brake lights, forward collision warning |
| Right turn | 202-207 | right turn in front warning, intersection movement assist, signal violation warning, stop sign violation warning, forward collision warning |
| Roll over | 705/805 | - |
| Hit pedestrian | 001-003 | pedestrian detection |
| Side swipe | 305-307/308-309 | blind spot (lane change) warning |
| Head on | 201/501 | Do not pass warning, loss of control warning |
| Hit parked vehicle | 401-402/601, 604 | - |
| Left road - out of control | 701-702/706-707/801-802 | - |
| Hit animal | 703-704/803-804 | - |
| Hit object on road | 605-610 | - |
| Other | x00 | - |

The numbers of crashes by crash type, speed zone group and severity between 2001 and 2010 are shown in Table 4.2. The five most prevalent crash types in each sub-category were deemed to be the important crash types and would become the focus of the simulation work (shown in red). The five most prevalent crash types in either level of severity were generally similar across the speed zone groups, with rear end, hit fixed object, right angle, head on, hit pedestrian, rollover and right turn often among the most prevalent. The exceptions were rollover crashes in 50 and 60 km/h zones and hit pedestrian and right turn crashes in 100 and 110 km/h zones, which were outside of the five most prevalent crash types.

The five most prevalent crash types accounted for about 85% (ranging from 83 to 90%) of all the crashes within a given speed zone group and severity level.

Note that not all of the top five most prevalent crash types can be addressed by connected vehicles. For example, hit fixed object crashes, which cause the most fatal crashes of all crash types are not addressed by connected vehicles.

Table 4.2
Crashes by crash type, speed zone group and severity: 2001 to 2010
(top five are shown in red)

| 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 |
| Rear End | 15,836 | 13 | 2,753 | 13 | 743 | 23 |
| Hit Fixed Object | 5,742 | 117 | 1,805 | 76 | 3,581 | 235 |
| Side Swipe | 3,126 | 11 | 445 | 5 | 347 | 19 |
| Right Angle | 9,843 | 58 | 1,263 | 27 | 730 | 59 |
| Head On | 956 | 20 | 369 | 19 | 572 | 105 |
| Hit Pedestrian | 3,595 | 102 | 148 | 19 | 63 | 17 |
| Roll Over | 1,155 | 13 | 511 | 11 | 2,640 | 112 |
| Right Turn | 5,088 | 34 | 598 | 13 | 114 | 6 |
| Hit Parked Vehicle | 1,683 | 11 | 53 | 0 | 32 | 2 |
| Hit Animal | 38 | 0 | 46 | 0 | 288 | 6 |
| Hit Object on Road | 74 | 0 | 40 | 1 | 85 | 1 |
| Left Road Out of Control | 142 | 0 | 94 | 1 | 372 | 8 |
| Other | 389 | 2 | 44 | 0 | 65 | 2 |
| Total | 47,667 | 381 | 8,169 | 185 | 9,632 | 595 |

## 4.4 Selection of crashes for simulation

At scene in-depth crash investigations can provide a much more complete picture of the circumstances of a crash than is available in the mass crash data. CASR has been conducting such investigations for over four decades. However, the data used in this report was limited to investigations taking place between 1995 and 2011. During this time 1,145 cases were investigated, and of these cases, 364 had been reconstructed so that travel and impact speeds were known, information that is required to simulate the crash.

Crash types that are relevant and important in either severity level within a speed zone group were selected for simulation. 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 can be seen in Table 4.3. The selected cases are shown in Table 4.4 by the severity of the crash; 17 were 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 4.3
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 |

Table 4.4
Number of simulated cases by crash severity 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 | |
| Injury | 57 | 12 | 25 | 94 |
| Fatal | 4 | 6 | 7 | 17 |
| Total | 61 | 18 | 32 | 111 |

## 4.5 Simulations

In this project, extensive use was made of software called PreScan (Tass, Netherlands). PreScan is a simulation environment for primary safety technologies, and many types of sensor can be simulated, as can the response of a vehicle to sensor signals in many types of environmental conditions.

The trajectory, speeds, braking and impact configuration of the selected in-depth cases were replicated in the PreScan software. 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.

An example of how an in-depth crash investigation case was replicated in the PreScan software is shown in Figure 4.1. The site diagram from the original crash is shown on the left and the same scenario replicated 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.

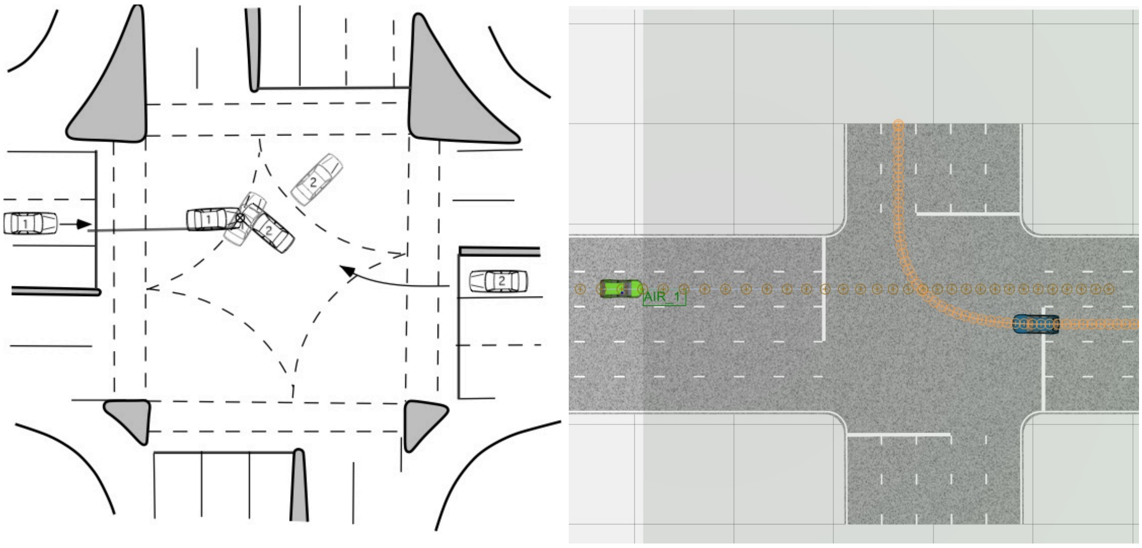


Figure 4.1
Site diagram of in-depth crash investigation case CN172 (left) and corresponding PreScan scenario (right)

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 with several variable attributes. By assigning values to these attributes, variations of sensor based systems and connected vehicle systems and their response during specific crash scenarios was modelled. The model attributes are discussed in Appendix A, as are the operation of the model and the model limitations.

A three step process was employed to determine attribute values for the systems. Firstly a baseline sensor based system was defined. The values for the attributes in this system were chosen to reflect a typical long range sensor system. The next step was to define variations to the system to examine the effect of changing key variables. The variations that were chosen were, a shorter time to collision (TTC), a lower system deceleration and a restricted view. It should be noted that this system uses the simplified collision prediction method that is only based on the longitudinal position and velocity of the crash partner (see Appendix A for further information). This simplified prediction method was the basis for selecting a lower computation time than other systems. The final step was to define attribute values for the connected vehicle system that were equivalent to the sensor based system in system response, yet provided the greater detection area of a connected vehicle system. All attribute values were based on information from published literature and provided by vehicle and system manufacturers.

The sensor based systems have a limited field of view and have a typical 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 where detected within the range of the system. The range used was only 100 metres. While, in reality, a connected vehicle can communicate with another vehicle at a range greater 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 represent that the computation time would have already past by the time the vehicles are within 100 metres of each other.

The attribute values that were selected to represent these sensor and connected vehicle based systems are shown in Tables 4.5.

Table 4.5
Attribute values for the sensor and connected vehicle system variations

| | Baseline | | Short TTC | | Low system deceleration | | Restricted view | |
|---|---|---|---|---|---|---|---|---|
| Attribute | 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 |

Note: see Appendix B for detailed descriptions of the attributes

A visual example of the collision avoidance simulation results are shown in Figure 4.2. 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.

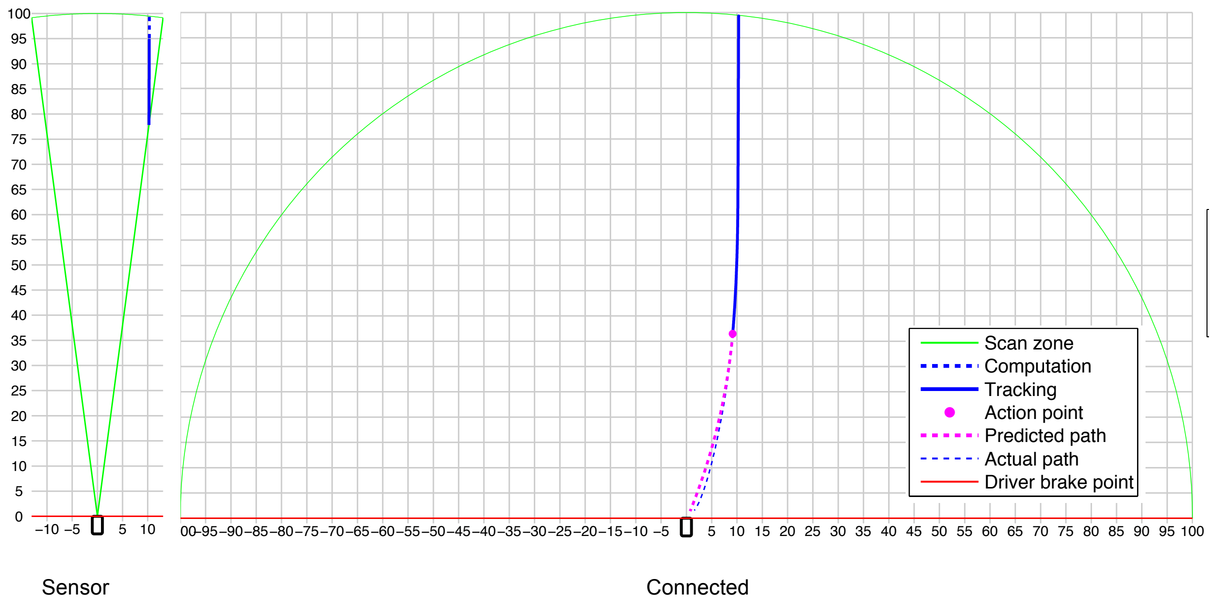


Figure 4.2
Collision avoidance model response to a right turn crash with the baseline sensor based AEB system and the connected vehicle system

## 4.6 Injury risk analysis

Risk curves were used to determine the injury outcomes of the crashes at the reduced speed produced by the collision avoidance system. Separate risk curve sets were used for vehicle crashes (NHTSA, 2005) and pedestrian crashes (Davis, 2001) that included risk curves for non-injury, injury and fatal injury. For the purpose of examining the benefit of the collision avoidance systems, the probability, or risk, of injury or death at various speeds was considered with respect to the actual crash injury outcome. The result for each crash was a new probability of no injury, injury and fatality. Detailed information on the full process of injury risk analysis, along with a discussion of its limitations, largely taken from Anderson *et al.* (2012), can be found in Appendix B.

## 4.7 Calculating the crash reductions

The probabilities of injury and fatal crashes calculated in the injury risk analysis in each group of speed zones, severity and crash type were summed and divided by the number of crashes in the corresponding group in the actual in-depth crashes to produce crash reduction factors.

The crash reduction factors were multiplied by the number of crashes found in the mass data in the corresponding category to determine the number of crashes that could be reduced with a given collision avoidance system. In some categories there were no fatal crashes in the sample. In these instances the effect on injury crashes was applied to the fatal crashes.

It should be noted that certain crash types relevant to sensor based AEB systems but not connected vehicles, such as hit fixed object crashes, were not included. The calculation of the number of crashes reduced with an AEB system, and subsequent calculations, was performed purely for comparison with the connected vehicle percentage to determine the additional benefit of connected vehicles.

The total number of crashes reduced with a given collision avoidance system was divided by the total number of crashes (Table 4.2) to determine the crash reduction percentages.

The additional crash reduction percentage produced by connected vehicle was calculated by summing the positive differences between the crash reductions of the connected vehicle system and its equivalent sensor based AEB system and dividing by the total number of crashes. The additional crash reduction percentage produced by connected vehicles was also calculated excluding the effect of the systems on pedestrian and/or head on crashes due to the doubt over the technical feasibility of applications addressing these crash types noted in Section 2.4.

# 5 Results

The crash reduction factors by speed zone, severity, crash type and system are shown in Table 5.1. The additional crash reductions produced by the connect vehicle systems are clearly evident in right angle, right turn crashes and pedestrian crashes. The effect of the connected vehicle systems on head on crashes in relation to the sensor based AEB systems was varied. There were, at best, very little additional crash reductions in rear end crashes with a connected vehicle system.

Table 5.1
Crash reduction factors to be applied to rates of crash involvement

| Speed limit | Crash severity | Type | Crash reduction factors by system with conversion of fatal to injury crashes in parenthesis | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Baseline | | Short TTC | | Low system deceleration | | Restricted view | |
| | | | Sensor | Connected | Sensor | Connected | Sensor | Connected | Sensor | Connected |
| 50/60 | Injury | Head on | 0.71 | 0.73 | 0.71 | 0.73 | 0.71 | 0.73 | 0.19 | 0.73 |
| | | Pedestrian | 0.56 | 1.00 | 0.27 | 0.90 | 0.56 | 1.00 | 0.83 | 0.90 |
| | | Rear end | 0.83 | 0.84 | 0.60 | 0.61 | 0.82 | 0.82 | 0.73 | 0.61 |
| | | Right angle | 0.00 | 0.74 | 0.00 | 0.54 | 0.00 | 0.72 | 0.03 | 0.54 |
| | | Right turn | 0.39 | 0.95 | 0.37 | 0.87 | 0.36 | 0.88 | 0.11 | 0.87 |
| | Fatal | Head on | 0.00 (-0.00) | 0.95 (-0.95) | 0.00 (-0.00) | 0.95 (-0.95) | 0.00 (-0.00) | 0.95 (-0.95) | 0.00 (-0.00) | 0.95 (-0.95) |
| | | Pedestrian | 0.51 (-0.21) | 0.84 (-0.21) | 0.46 (-0.46) | 0.79 (-0.46) | 0.51 (-0.21) | 0.84 (-0.21) | 0.92 (-0.92) | 0.79 (-0.46) |
| 70/80/90 | Injury | Head on | 0.47 | 0.80 | 0.47 | 0.80 | 0.32 | 0.64 | 0.63 | 0.80 |
| | | Pedestrian | 1.00 | 1.00 | 0.00 | 0.51 | 1.00 | 1.00 | 0.44 | 0.51 |
| | | Rear end | 1.00 | 1.00 | 0.86 | 0.86 | 1.00 | 1.00 | 0.86 | 0.86 |
| | | Right angle | 0.20 | 0.92 | 0.00 | 0.53 | 0.19 | 0.82 | 0.11 | 0.53 |
| | | Right turn | 0.16 | 0.64 | 0.16 | 0.32 | 0.16 | 0.64 | 0.21 | 0.32 |
| | Fatal | Head on | 0.00 (0.00) | 0.00 (-0.00) | 0.00 (-0.00) | 0.00 (-0.00) | 0.00 (-0.00) | 0.00 (-0.00) | 0.00 (-0.00) | 0.00 (-0.00) |
| | | Pedestrian | 1.00 (0.00) | 1.00 (0.00) | 0.96 (-0.75) | 0.96 (-0.75) | 0.96 (-0.75) | 0.96 (-0.75) | 0.83 (-0.83) | 0.96 (-0.75) |
| | | Right angle | 0.00 (-0.00) | 0.97 (-0.47) | 0.00 (-0.00) | 0.90 (-0.90) | 0.00 (-0.00) | 0.90 (-0.90) | 0.47 (-0.47) | 0.90 (-0.90) |
| | | Right turn | 0.95 (-0.95) | 0.95 (-0.95) | 0.34 (-0.34) | 0.79 (-0.79) | 0.95 (-0.95) | 0.95 (-0.95) | 0.12 (-0.12) | 0.79 (-0.79) |
| 100/110 | Injury | Head on | 0.65 | 0.96 | 0.64 | 0.94 | 0.48 | 0.80 | 0.50 | 0.94 |
| | | Rear end | 1.00 | 1.00 | 0.38 | 0.38 | 0.76 | 0.76 | 0.42 | 0.38 |
| | | Right angle | 0.31 | 0.76 | 0.09 | 0.48 | 0.21 | 0.60 | 0.16 | 0.48 |
| | Fatal | Head on | 0.96 (-0.68) | 0.96 (-0.68) | 0.83 (-0.79) | 0.83 (-0.79) | 0.85 (-0.85) | 0.87 (-0.87) | 0.50 (-0.47) | 0.83 (-0.79) |
| | | Right Angle | 0.00 (-0.00) | 0.98 (-0.43) | 0.00 (-0.00) | 0.88 (-0.88) | 0.00 (-0.00) | 0.79 (-0.79) | 0.34 (-0.34) | 0.88 (-0.88) |

Table 5.2 shows the total crash reduction percentages and the additional percentage reduction achieved by connected vehicles in addition to sensor based AEB by speed zone, severity and system. The key result, the overall additional percentage reduction achieved by connected vehicles, is 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 5.2
Crash reduction percentages of connected vehicles

| | Crash severity | Baseline equivalent | | Short TTC equivalent | | Low system deceleration equivalent | | Restricted view equivalent | |
|---|---|---|---|---|---|---|---|---|---|
| Speed limit | | Total | Additional | Total | Additional | Total | Additional | Total | Additional |
| 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% |

The additional crash reduction factors excluding pedestrian crashes and/or head on crashes are shown in Table 5.3. These are reported because it is possible that these crash types will not be appropriately addressed by connected vehicle technology (see Section 2.4). 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 5.3
Additional 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% |

# 6 Discussion and limitations

## 6.1 General

Previous research has highlighted that a sensor based AEB system has a very limited effect 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 and beyond that of 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 also have some additional benefit in head on crashes.

If technical limitations mean that pedestrian and head on crashes cannot be addressed by connected vehicle technology, the additional benefit remains substantial, albeit reduced from its full potential. The changes are large enough to suggest that pursuing 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, especially if the NHTSA decision in 2013 is to mandate connected vehicle technology on all new vehicles in the near future. 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 4.2 can be used rather than the additional crash reductions.

## 6.2 Simulations

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, which will produce an underestimate of the additional 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 future fleet penetration of these systems becomes sufficiently high 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. It is not clear, however, what effect this would have on the additional benefit of connected vehicle technology above that given by sensor based AEB systems.

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 additional benefit of connected vehicle technology above that given by sensor based AEB systems.

Similar comments can be made in respect to warnings. As discussed in Section 3, crash imminent warnings, which by design will be annoying enough to attract the drivers attention quickly, will not be able to be issued any earlier than an autonomous system would intervene. However, subtle warnings such as visual warnings, may be able to be used much earlier with connected vehicle technology than sensor based systems such as AEB. Connected vehicles benefits may therefore be greater still.

As the results have been expressed as an additional 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 additional 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 systems 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.

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 effects of some AEB systems.

## 6.3 Injury risk

With respect to the risk reductions based on the simulation results, some caution must be exercised, not because of the simulation results themselves, but because 111 crashes were used to represent all relevant crashes. Hence, confidence is highest when speed changes in individual crashes are considered. When converted to change in average risk over all crashes, confidence is highest when the results are aggregated after weighting to reflect the incidence of each crash type in the mass data (thus minimising random effects in estimated risk reductions in individual crash types). We would recommend caution with the use of changes in risk that have been estimated for any one crash type and speed zone in this study, as relatively few crashes may be used to generate the average change in risk in each category. More robust individual risk reductions would be obtained with further simulations of more crashes.

The risk curve that was used in the analysis of occupant injury was based on US crash data from 1995-1999. Given that crashworthiness of vehicles has been found to increase with model year

(Anderson, Doecke and Searson, 2009; Newstead, Watson and Cameron, 2011), it is probable that the chance of injury or fatality, at a given speed, is less in current and future cohorts of vehicles than the risk curves would suggest. As relative changes in risk are used in this study, errors in absolute risk levels are likely to be attenuated when estimating relative changes in risk.

# 7 Conclusions and recommendations

Connected vehicles were found to:

- have many safety related applications that can potentially address the South Australia 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 in South Australia is therefore considerable and the uptake of such technology should be encouraged in ways that are shown to be cost effective.

# 8 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 calculated for South Australia 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.

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# Appendix A – Collision detection and intervention model

## Model attributes

### Scan zone

The scan zone of a collision avoidance system defines the area, forward of the host vehicle, in which an object can be detected.

A sensor detection system scans an area in a cone shape by sweeping back and forth through a certain number of degrees. Some sensor detection systems however, restrict the area in which an detected object may trigger the collision avoidance algorithm to a rectangle so as to ignore objects that are not directly in front of the vehicle.

A connected vehicle can detect vehicles all around at a range that is dependant upon the transmission environment.

The collision avoidance system model defines a scan zone using three attributes *scan shape*, *range* (in metres), and *angle/width* (in degrees/metres) as shown in Figure A.1.

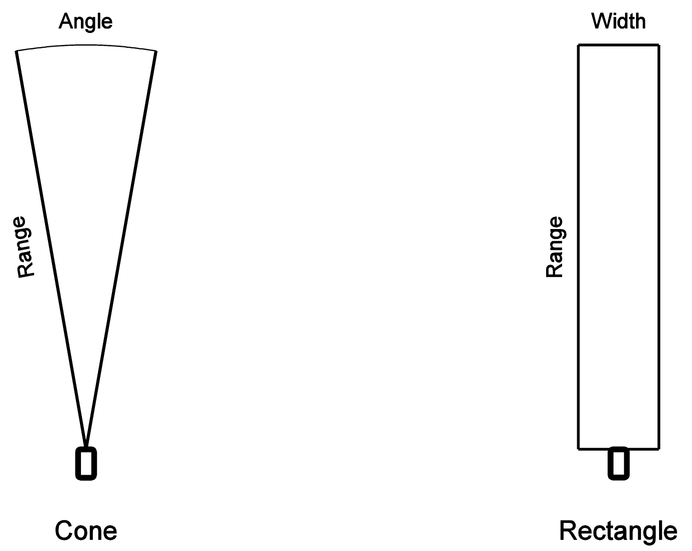


Figure A.1
The two types of scan shape that can define the scan zone

### Object tracking and collision detection

There are several ways in which a collision avoidance system detects and tracks objects. The technique used depends in part on the detection technology used. Furthermore, techniques may differ between systems that use similar detection technologies.

Some systems predict a collision based solely on the distance and relative speed of the object. Other systems use more sophisticated techniques to predict the future motion of objects based on their current position, speed, and acceleration. Connected vehicles may possibly receive path prediction information as part of the message received from the other vehicle.

For the collision avoidance system model it is assumed that, within the scan zone, an object can be detected, tracked, and its future motion predicted with enough accuracy as to enable potential collisions to be identified.

The two attributes *computation time* and *prediction method* were used to define the characteristics of the model's object tracking and motion prediction ability. The *computation time* (in seconds) is used to represent the amount of time required by the system to observe an object before its future motion can be successfully predicted. The *prediction method* then defines whether an advanced or simple motion prediction algorithm is used.

The advanced prediction method calculates the position of an object at $t$ seconds into the future in both the longitudinal ($x$) and lateral ($y$) direction, based on the object's current position, velocity, and acceleration, as shown in the equations below (subscript $i$ denotes the current logittudinal/lateral position, velocity, and acceleration and subscript $f$ denotes the future longitudinal/lateral position).

$$x_f(t) = x_i + \dot{x}_i t + \frac{\ddot{x}_i t^2}{2}$$

$$y_f(t) = y_i + \dot{y}_i t + \frac{\ddot{y}_i t^2}{2}$$

The simple prediction method calculates the position of an object at $t$ seconds into the future based on the object's current longitudinal ($x$) position and velocity, while ignoring the object's current lateral ($y$) motion, as shown in the equations below, where subscript $i$ denotes the current longitudinal/lateral position and velocity and subscript $f$ denotes the future longitudinal/lateral position.

$$x_f(t) = x_i + \dot{x}_i t$$

$$y_f(t) = y_i$$

A potential collision is identified by calculating a future position that intercepts with the host vehicle. The collision avoidance system must then decide when to respond. The system cannot respond too early, as trajectories may change such that the collision is no longer likely. But the system must respond with enough time to reduce the severity of the collision. Lee and Peng (2005) detail some early collision warning and collision avoidance algorithms. In this study the collision avoidance system model uses a simple time to collision (TTC) value. The attribute *TTC action* (in seconds) defines at what length of time before a predicted collision the system will take braking action.

## System response

Once a collision avoidance system has identified a potential collision there are many responses possible. ADAC (2011) tested six production passenger vehicles fitted with an AEB system and tracked their warning and braking responses during an identical frontal collision scenario. All systems triggered a warning and then applied some level of final braking. However, the time at which the warning and braking was applied and the severity of the braking was different for each system. Additionally, some systems applied some level of partial braking between the warning and final braking.

In this study, the collision avoidance system model is designed to take braking action automatically once a potential collision has been detected within the *TTC action* time. It will also cooperate with the braking actions of the driver: if the driver brakes after a potential collision has been detected, then their deceleration is increased from the 0.7g that was used in the in-depth crash study reconstructions to a higher value.

The braking action of the model is defined by two attributes: *system deceleration* and *driver deceleration*. The *system deceleration* (in g) defines the amount of deceleration from braking the system applies automatically by itself. The *driver deceleration* (in g) defines the amount of deceleration from braking the system applies when the driver is pushing the brake pedal.

The reduction in speed achieved by the *system deceleration* or *driver 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.

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

## Model operation

The operation of the collision avoidance model is explained diagrammatically in Figure A.2. For an object to be successfully tracked, it must enter the scan zone defined by the *scan shape*, *range*, and *angle/width* attributes and must remain within the zone for a length of time specified by the *computation time* attribute. Once an object is being tracked it must stay within the scan zone in order for it to continue being tracked.

The future motion of the object is then predicted using an algorithm selected by the *prediction method* attribute. The system continuously updates the predicted future motion of the object and calculates whether the object is predicted to collide with the host vehicle in less than the time specified by the *TTC action* attribute. If the object is predicted to collide with the host vehicle within the *TTC action* time then the collision speed reduction benefit is calculated based on the system's braking response.

Three braking response scenarios are possible depending on the actions of the driver; the driver brakes before the collision avoidance system responds, the driver brakes after the collision avoidance system responds, or the driver does not brake at all.

If the driver brakes before the system responds, then the speed reduction is calculated in two steps. A speed reduction is calculated using a deceleration of 0.7g over the distance between where the driver started braking and where the system responds. A further speed reduction is then calculated using the *driver deceleration* attribute value over the remaining distance to the collision point.

If the system brakes before the driver, then the speed reduction is again calculated in two steps. A speed reduction is calculated using the *system deceleration* attribute value over the distance between where the system responds and where the driver brakes. A further speed reduction is then calculated using the *driver deceleration* attribute value over the remaining distance to the collision point.

If the driver does not brake at all, then the speed reduction is calculated using only the *system deceleration* attribute value over the distance from where the system responds to the collision point.

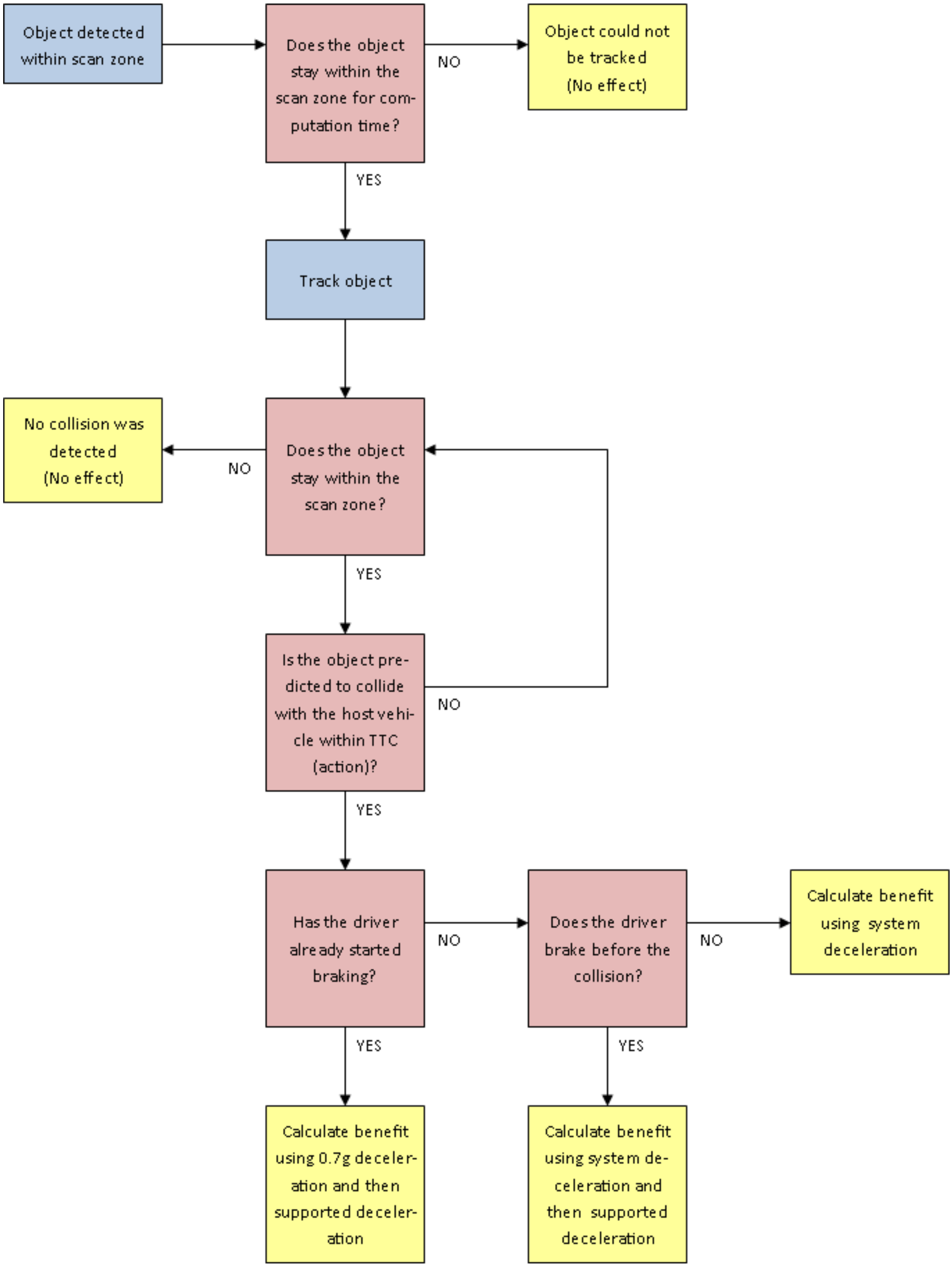


Figure A.2
Flow diagram of collision avoidance system model

## Model limitations

Apart from the assumptions mentioned above, and the usual limitations of simulating a real system with a model, the collision avoidance system model has two major limitations that should be noted.

The first is that the value for the *TTC action* attribute is static and does not dynamically adjust based on the conditions of the host vehicle. At faster travelling speeds the *TTC action* value should be increased to account for the increase in the time required to bring the host vehicle to a stop (or a collision speed that has been deemed acceptable). This limitation is mitigated slightly by the different TTC in systems variations.

The second major limitation is that no vehicle dynamics are taken into account once braking begins. That is, the model simply calculates the new travelling speed at the original collision point. What this does not take into account however is the change in vehicle relative trajectories as a result of system braking. Because of this the model cannot identify crashes where a change in trajectory prevents a collision from occurring. This is unlikely to be important for rear end, head on and pedestrian crashes. Intersection crashes where a vehicle is travelling across the path of another vehicle are most likely to be affected by this limitation. This may produce an underestimate of the effectiveness of the systems that will depend on the speed reduction the system produces and the rate at which the struck vehicle crosses the path of the unit with the system.

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# Appendix B – Injury risk analysis

## Injury categories

The CASR in-depth crash studies include several levels of injury severity. These levels are:

- No injury
- Minor injury (no ambulance transport)
- Transport to Hospital (no hospital treatment)
- Hospital Treatment (treatment of casualty without hospital admission)
- Hospital Admission (treatment exceeds 4 hours)
- Fatality (death resulting form crash occurs within 30 days of crash)

Table B.1 shows the different definitions for injury as used in this analysis.

Table B.1
Categories of injury severity

| Analysis Degree of Crash | CASR In-depth Crash Severity | MAIS Severity | MAIS Description |
|---|---|---|---|
| No Injury | No Injury, Minor Injury (No Ambulance Transport) | MAIS 0 - 1 | No injury - Minor injury |
| Injury | Ambulance Transport, Hospital Treatment/Admission | MAIS 2 - 5 | Moderate - Critical Injury |
| Fatal | Fatal | Fatal | Fatal |

MAIS 1 was grouped with MAIS 0 for the purpose of this analysis as 'no injury', as it was assumed to correspond most closely with a no-injury crash in the mass data.

## Vehicle speed and injury risk

Several studies have attempted to relate crash vehicle impact speed or delta-v to risk of occupant or pedestrian injury in the form of a speed-injury risk relationship.

### Vehicle speed and injury to vehicle occupants

NHTSA (2005) included an analysis of the risk of occupant injury or fatality in crashes from 1995-1999, "for all passenger vehicle occupants involved in crashes where at least one passenger vehicle used brakes". NHTSA (2005) derived individual probability risk functions for MAIS 0, MAIS 1+, MAIS 2+, MAIS 3+, MAIS4+, MAIS 5+ and fatal injuries.

The NHTSA injury probability risk functions were chosen for the analyses as they were considered the most appropriate model for the particular analysis. Using the NHTSA delta-v injury risk functions for MAIS 0-1, MAIS 2-5 and fatal, risk curves were generated for these injury categories consistent with the definitions in Table B.1

Figure B.1 shows the absolute risk of a particular injury (relative to the other injuries), adapted from NHTSA (2005) for the three defined injury categories. This presentation of the risk curves considers the individual risks of MAIS 0-1, MAIS 2-5 and fatality at each delta-v as a proportion of 100 per cent. For example, the risk at a delta-v of 0 km/h of MAIS 0-1 is 100 per cent, and zero for MAIS 2-5 and fatal injuries respectively. At a delta-v of 50 km/h the risk of a MAIS 0-1 is 45 per cent, the risk of MAIS 2-5 is 52 per cent, and the risk of a fatal injury is three per cent.

This graph can also be drawn as a cumulative risk of injury as shown in Figure B.2. According to Figure B.2 at a delta-v of 50 km/h the cumulative risk of a fatality is three per cent, the cumulative risk of fatality or injury (MAIS 2+) is 55 per cent, which is the sum of the individual risks for fatality and injury at the delta-v of 50km/h.

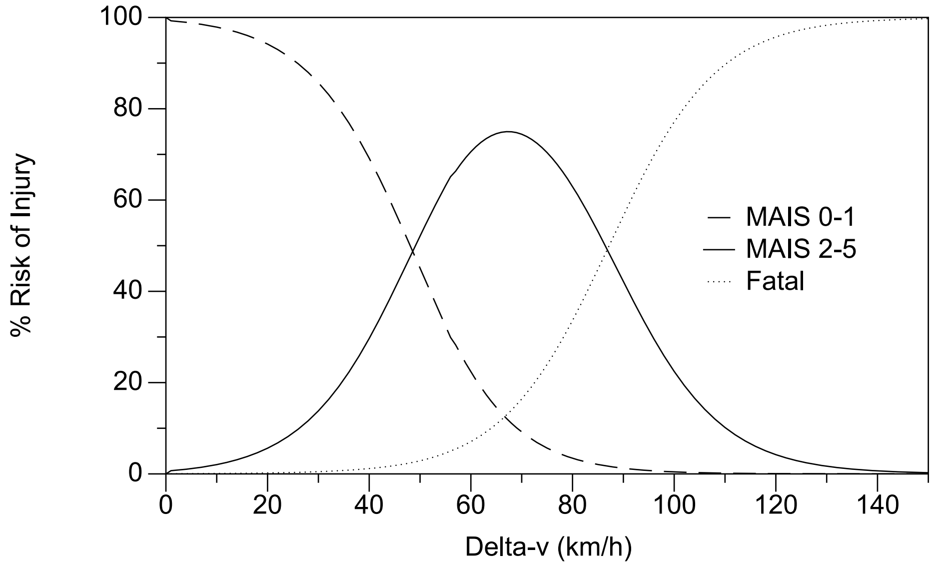


Figure B.1
Maximum occupant injury risk curves adapted from NHTSA (2005), for MAIS 0-1, MAIS 2-5 and fatal injuries.

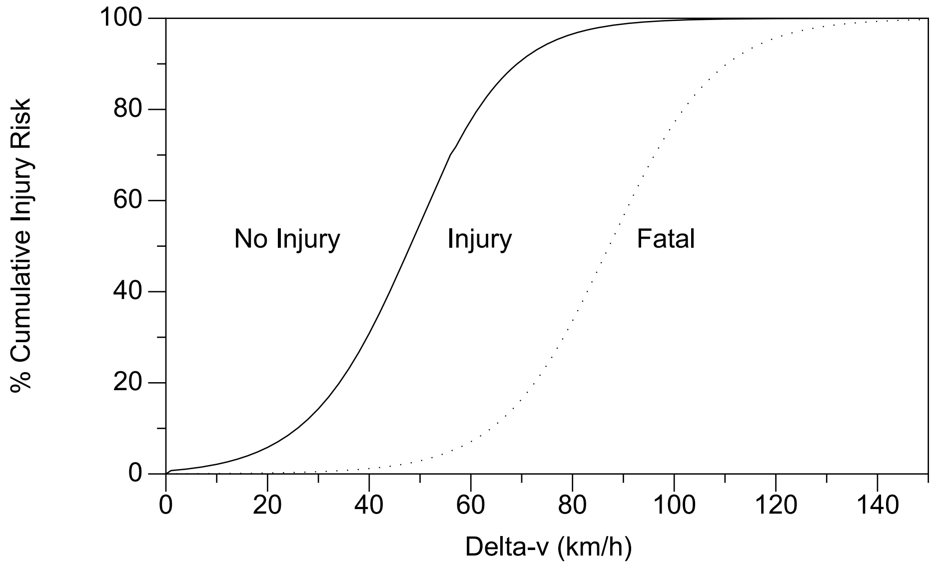


Figure B.2
Cumulative occupant injury risk curves derived from NHTSA (2005), showing the proportion of no injury, injury and fatal at each delta-v.

## Vehicle speed and injury to pedestrians

Rosen (2009), considered German Crash Data (GIDAS) from 1997-2007, resulting in a total sample of 490 pedestrian crashes and 36 fatalities for pedestrians aged 15 years and over. Rosen (2009) developed a risk function for vehicle impact speed and risk of fatality.

Davis (2001) derived similar risk curves by analysing crash data from previous studies. Additionally, he generated injury risk functions for slight, serious and fatal collisions. Although the crash data is older than that from Rosen (2009) these injury risk functions were selected for the analysis, as it is able to represent the risks of the three injury levels considered in this analysis.

Note that the fatal risk curve from Rosen (2009) correlates reasonably well with the fatal risk curve from Davis (2001), particularly for impact speeds less than 60km/h.

Figure B.3 shows the absolute risk of injury for the three defined injury categories from Davis (2001). This graph can also be drawn as a cumulative risk of injury as shown in Figure B.4.

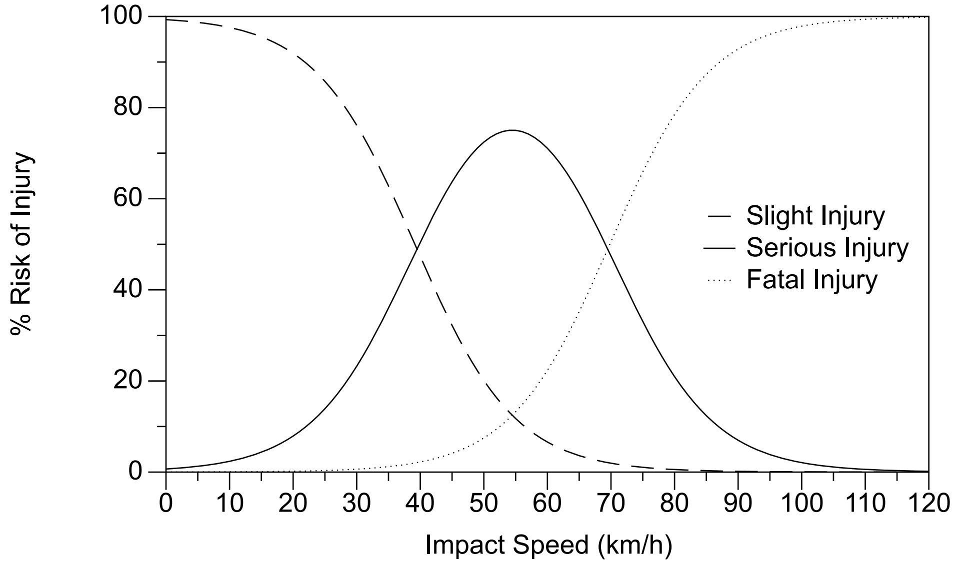


Figure B.3
Pedestrian collision risk curves from Davis (2001), for slight injury, serious injury and fatal injury.

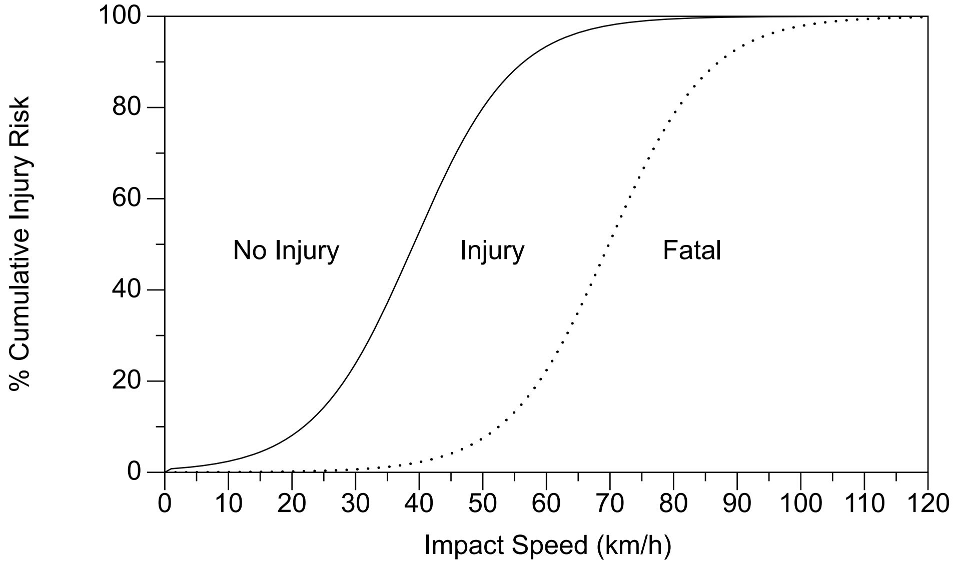


Figure B.4
Cumulative pedestrian injury risk curves adapted from Davis (2011), showing the proportion of no injury, injury and fatal at each impact speed.

## Determining injury risk based on speed modification

Pedestrian injury risk is presented as a function of the vehicle impact speed, which is the velocity of the vehicle relative to the velocity of the pedestrian, immediately prior to the collision.

Vehicle occupant injury risk is posed in terms of delta-v. The delta-v is a function of the closing speed, the masses of both vehicles and the coefficient of restitution in the collision. As the collision avoidance model determines a longitudinal closing speed, a general relationship between delta-v and longitudinal closing speed was used to estimate the delta-v that would be produced in each relevant crash scenario.

From the CASR in-depth crash studies, the individual speed reconstructions yield a longitudinal closing speed and a corresponding delta-v. Considering a number of crash configurations and generalising, the relationships for delta-v and longitudinal closing speed were derived as shown in Table B.2.

Table B.2
Estimated relationship between longitudinal closing speed and delta-v

| Crash Type | Delta-v Functions |
|---|---|
| Head-on collisions | Delta-v = 0.5 x closing speed |
| Right turn | Delta-v = 0.6 x closing speed |
| Right angle | Delta-v = 0.6 x closing speed |
| Rear end | Delta-v = 0.6 x closing speed |

## Determining crash injury outcomes

The process for determining the effect of an individual collision avoidance system on risks of a poor crash outcome is as follows:

For the original crash

- The actual crash closing speed was converted to a delta-v according to Table B.2 (no adjustment for pedestrian crashes).
- The probability of fatality, injury or no injury was determined from the appropriate risk functions.

For the collision avoidance system case

- The new closing speed was adjusted according to Table B.2 (no adjustment for pedestrian crashes).
- The probability of fatality, injury or no injury was determined from the appropriate risk functions for the revised delta-v, given the original severity of the crash.

To determine new risks, given the speed reductions produced by the collision avoidance system, the crash severity was “redistributed” into the probabilities of the crash being in the original severity category or a lower category, according to the risk curves and the new and original speeds.

If the collision avoidance system has no effect on the vehicle closing speed, then the predicted injury outcome is the same as the original injury outcome. If the collision avoidance system reduces the closing speed then the following process was applied.

For a crash where the outcome was an injury, the injury risks are found by equations 1 and 2. The definitions for the variables used are shown in Table B.3.

$$P_{System\ Speed}\ (injury|crash\ was\ injury) = \frac{1-P_{crash\ speed}(fatal)-P_{System\ Speed}(none)}{P_{crash\ speed}(injury)} \quad (1)$$

$$P_{System\ Speed}\ (none|crash\ was\ injury) = 1 - P_{System\ Speed}\ (injury|crash\ was\ injury) \quad (2)$$

In some cases, a collision avoidance system can produce a probability that no injury would occur. This occurs when the collision avoidance system speed has been reduced to zero and the collision is theoretically avoided or when:

$$P_{System\ Speed}\ (none) > 1 - P_{crash\ speed}(fatal)$$

In these cases, the injury is redistributed completely to no injury (none).

Table B.3
Nomenclature for Equations

| Risk Function Predictors | Crash Speed | Collision Avoidance System Speed |
|---|---|---|
| Probability of no injury | $P_{crash\ Speed}\ (none)$ | $P_{System\ Speed}\ (none)$ |
| Probability of slight/serious injury | $P_{crash\ Speed}\ (injury)$ | $P_{System\ Speed}\ (injury)$ |
| Probability of Fatal | $P_{crash\ Speed}\ (fatal)$ | $P_{System\ Speed}\ (fatal)$ |

For example, consider a scenario where an injury resulted from a single vehicle that crashed with a delta-v of 60 km/h. At a delta-v of 60 km/h the injury risk curve in Figure B.2 predicts a risk of injury in the crash ($P_{60}(injury)$) to be 70.6 per cent. Figure B.5 shows the individual no injury, injury and fatal predicted distributions at 60km/h. The 70.6 per cent injury risk is depicted by the $P_{60}(injury)$ interval in the injury area of Figure B.5 Now consider the effect of a collision avoidance system that reduces the delta-v of the vehicle to 50 km/h. The predicted injury distributions are shifted, as indicated in Figure B.5, and the injury is redistributed according to equation 1 and 2, as shown in Figure 5.6.

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

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

As a result, the injury has been redistributed to 0.68 injuries and 0.32 no injuries.

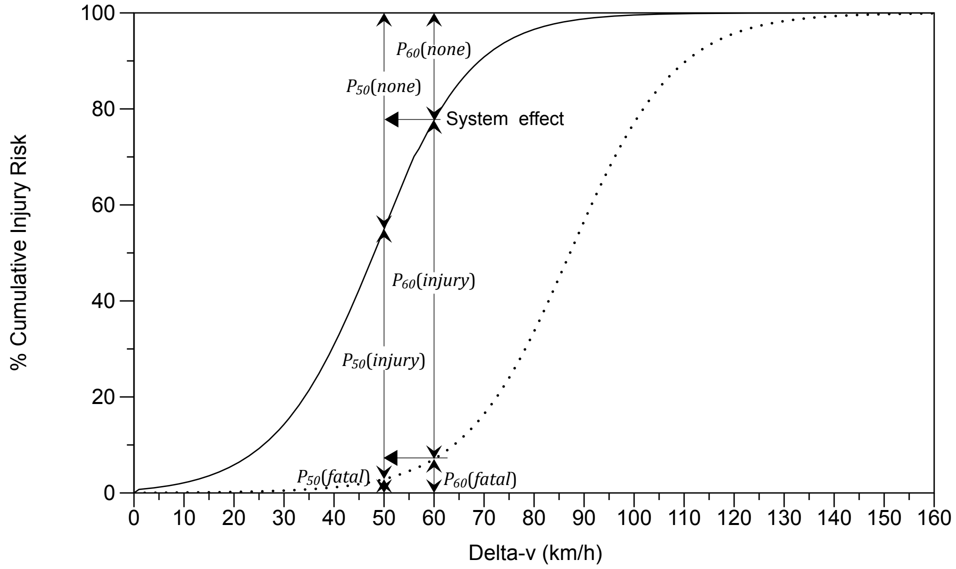


Figure B.5
An example of the redistribution of an injury from a delta-v of 60km/h to a collision avoidance system reduced delta-v of 50km/h

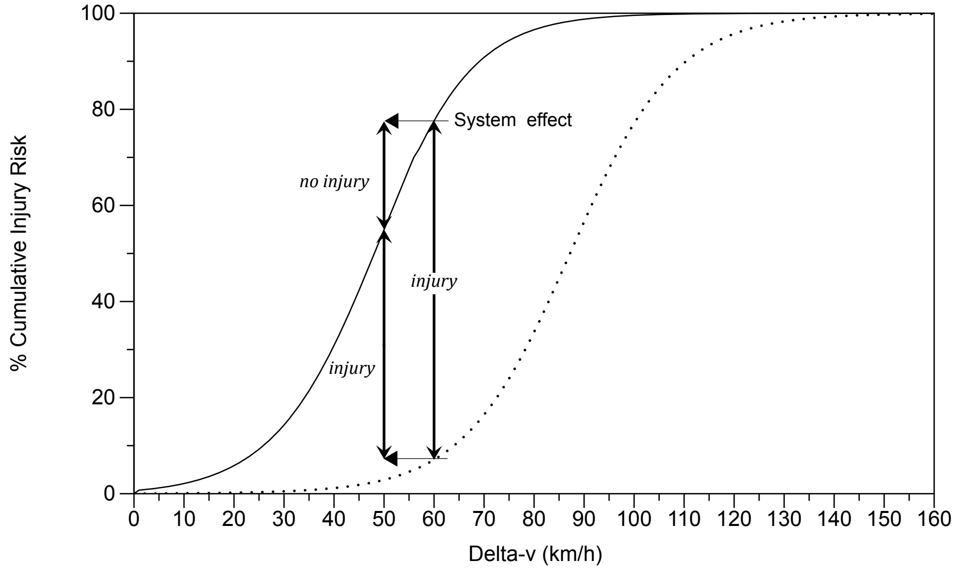


Figure B.6
The injury from a crash delta-v of 60km/h to a collision avoidance system reduced delta-v of 50km/h has been redistributed to injury and no injury

In the case of a fatal crash, the severity is also redistributed based on the predicted risks (at the actual crash delta-v and the collision avoidance system reduced delta-v); in the majority of cases, the fatality is re-distributed into probabilities of fatal and injury outcomes according to equation 3 and 4.

$$P_{Systen\ Speed}\ (fatal|crash\ was\ fatal) = \frac{P_{System\ Speed}(fatal)}{P_{crash\ speed}(fatal)} \quad (3)$$

$$P_{Systen\ Speed}\ (injury|crash\ was\ fatal) = \frac{P_{crash\ speed}(fatal) - P_{System\ Speed}(fatal)}{P_{crash\ speed}(fatal)} \quad (4)$$

Consider a scenario where a fatality resulted from a single vehicle that crashed with a delta-v of 80 km/h. Figure B.7 shows the no injury, injury and fatal predicted distributions at 80km/h. At a delta-v of 80 km/h, the fatality risk according to Figure B.2 is 33.6 per cent. This 33.6 per cent fatality risk is depicted by the $P_{80}(fatal)$ interval in the fatal area of Figure B.7. Consider now the effect of an collision avoidance system that reduces the delta-v to 60 km/h. The predicted no injury, injury and fatal distributions are shifted, as indicated in Figure B.7, and the fatality is redistributed according to equation 3 and 4 and shown schematically in Figure B.8.

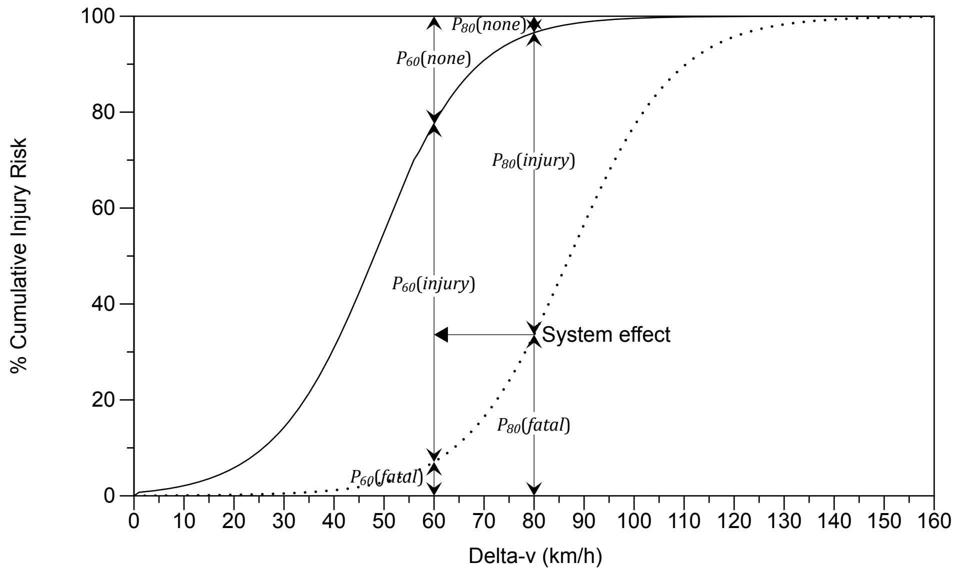


Figure B.7
An example of the redistribution of a fatality from a crash speed of 80km/h to a collision avoidance system reduced speed of 60km/h.

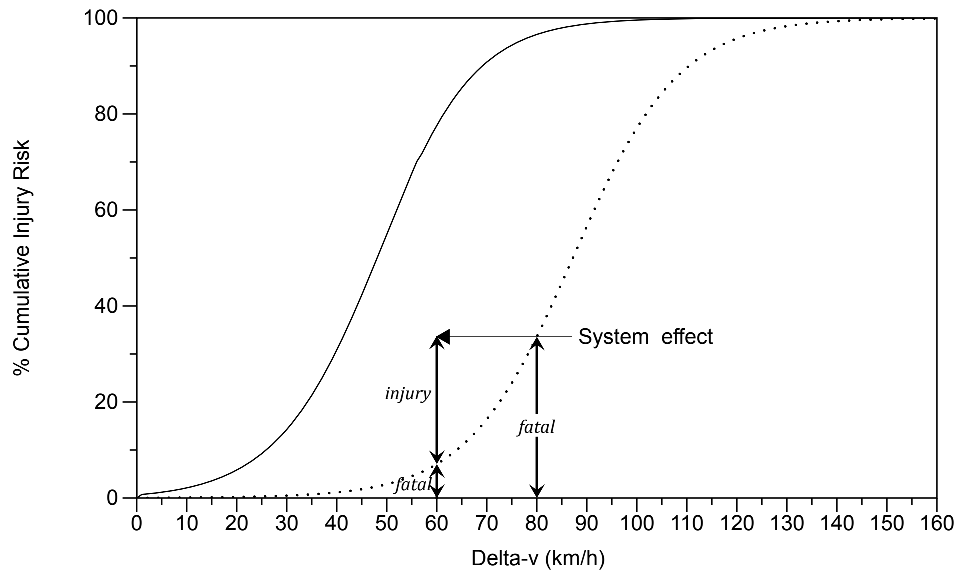


Figure B.8
The fatality from a crash delta-v of 80km/h to a collision avoidance system reduced crash delta-v of 60km/h has been redistributed to fatality and injury.

Then according to equation 3 and equation 4.

$$P_{60}(fatal|crash\ was\ fatal) = \frac{P_{60}(fatal)}{P_{80}(fatal)} = \frac{0.071}{0.336} = 21\%$$

$$P_{60}(injury|crash\ was\ fatal) = \frac{P_{80}(fatal) - P_{60}(fatal)}{P_{80}(fatal)} = \frac{0.336 - 0.71}{0.336} = 79\%$$

The risk redistribution results in 0.21 fatalities and 0.79 injuries.

In some cases, a collision avoidance system can produce a probability that no fatality or injury would occur. This occurs when the collision avoidance system speed has been reduced to zero and the collision is theoretically avoided. In some cases a fatality is redistributed as a fatality, injury and no injury, this occurs when:

$$P_{System\ Speed}\ (none) > 1 - P_{crash\ speed}(fatal)$$

In this case equation 5 replaces equation 3 and equation 6 is used to calculate the probability of no injury.

$$P_{System\ Speed}\ (injury|crash\ was\ fatal) = \frac{P_{System\ Speed}\ (injury)}{P_{System\ speed}(fatal)} \quad (5)$$

$$P_{System\ Speed}\ (none|crash\ was\ fatal) = \frac{P_{crash\ speed}(fatal) - P_{System\ Speed}(fatal) - P_{System\ Speed}\ (injury)}{P_{crash\ speed}(fatal)} \quad (6)$$

This process was applied to each individual crash and for each individual collision avoidance system.

## Limitations

The risk curves used refer to a vehicle-based measure of severity, whereas we have used them to indicate severity in a crash. Theoretically, it might be appropriate to adjust the risk curves accordingly. The more units involved in a crash, the greater the likelihood that the severity will be higher due to random effects. However, no adjustment was made on the following grounds:

- In at least half of injury crashes and in the majority of fatal 2-car crashes, the outcome is asymmetrical and a single unit determines the severity. No adjustment is necessary in these cases.
- Adjusting the risk curves would have inflated the risks in multi-unit crashes. Given the curves are based on injury outcomes in much older vehicles (circa 1990), we felt that any adjustment that would inflate the risks would be over-stating risks in a future fleet of vehicles.

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